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Cavitation and grain growth during superplastic forming

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Analysis and modelling

ABSTRACT

Purpose: The purpose of the paper is to study the cavitation and grain growth during superplastic forming.
Design/methodology/approach: Superplastic alloys exhibit the extremely large elongation to failure by their high strain rate sensitivity. Cavities have widely been observed during superplastic deformation of metals and alloys and lead to the degradation of material properties such as tensile, creep, fatigue and stress-corrosion behavior. In this work, a finite element method is developed, which considers the grain growth and the effect of material damage.
Findings: The effects of material parameters and deformation damage on the superplastic deformation process are numerically analyzed, and the means to control cavitation growth is discussed. The microstructural mechanism of grain growth during superplastic deformation is also studied. A new model considering the grain growth is proposed and applied to conventional superplastic materials The relationships between the strain, the strain rate, the test temperature, the initial grain size and the grain growth respectively in superplastic materials are discussed.
Practical implications: The effect of variation of strain rate sensitivity (m value) on the strain limit of the superplastic deformation is investigated, and the theoretically calculated values are compared with the experimental results.
Originality/value: A new microstructure model based on the microstructural mechanism of superplastic deformation has been proposed. This model has been successfully applied to analyze conventional superplastic materials.
Keywords: Finite Element Method; Cavitation; Grain growth; Superplastic deformation

1. Introduction

Superplasticity is the ability of certain polycrystalline materials to undergo extensive tensile plastic deformation under specific conditions. It is influenced by microstructural features, especially cavities and grain size, which is responsible for strength, ductility, toughness, corrosion resistance, and heat resistance. It is known that superplastic materials are generally sensitive to cavity formation. A fine grain is usually desirable for superplasticity because it has a lower material flow stress and its tensile elongation is larger. Grain size has also a significant influence on the strain rate and temperature during the superplastic deformation process [1, 2].

The development of superplastic-forming technology requires high accuracy in process control. It is necessary to build up a reliable constitutive equation for the flow law to analyze and optimize the forming process. Some investigators [3-7] have proposed models based on the mechanisms of superplastic deformation to describe the dominant structural features of superplasticity. They have indicated that the most important feature of superplasticity is grain-boundary sliding. However, little attention has been paid to the effects of dislocation motion, the diffusion in grains and the near-grain-boundary region on the superplastic forming process. These phenomena are usually required to maintain a continuous superplastic deformation. It is also important to take into account cavitation and/or grain growth that occurs during superplastic deformation, because it can lead to premature failure or significant strain hardening respectively, and result in a large deviation between prediction models and experimental results.

2. Superplasticity and cavitation

Cavitation can lead to the degradation of material properties such as tensile, creep, fatigue and stress-corrosion behavior. It is known that the superplastic materials are generally sensitive to cavitation formation. Moreover, the shape of cavities is irregular during superplastic deformation. Therefore, it is of importance to conduct the quantitative analysis of the cavitation volume to reveal the superplastic deformation mechanism. In this paper, a finite element method is developed, which considers the grain growth and the effect of material damage. The superplastic unaxial tensile tests for free bulging and constrained bulging processes are simulated. The simulation results are further compared with the experimental data. Furthermore, the effects of material parameters and deformation damage on the superplastic deformation process are numerically analyzed, and the means to control cavitation growth is discussed.

2.1. Cavitation growth and constitutive equation for superplasticity

Two main mechanisms of cavitation generation are widely accepted, i.e., vacancy diffusion controlled growth and plastic deformation controlled growth. It is considered that the mechanism of plastic deformation controlled growth is dominant during most of superplastic deformations. It is found that the number of cavitation f tends to increase with the increasing strain.

$$f = f_0 \exp(\bar{\beta}, \varepsilon) \quad (1)$$

where f_0 is the volume fraction of cavity at zero strain, $\bar{\beta}$ is the stress condition function and ε is the effective strain. The stress condition function can be expressed as,

$$\bar{\beta} = \beta D(\sigma) \quad (2)$$

where β is the material-dependent cavity coefficient and $D(\sigma)$ is the function related to stress condition [16], which is given by :

$$D(\sigma) = 0.558\sinh(X) + 0.008\xi\cosh(X) \quad (3)$$

$$X = \frac{1.5\sigma_m}{\sigma} = \frac{1.5(\sigma_m{}^0 + P_h)}{\sigma} \quad (4)$$

$$\xi = -3\dot{\varepsilon}_2 / (\dot{\varepsilon}_1 - \dot{\varepsilon}_3) \quad (5)$$

where σ and ε are the effective flow stress and effective strain rate respectively, σ_m is the average stress, $\sigma_m{}^0$ is the average stress, while hydrostatic press $P_h = 0$ amd ξ is the coefficient of strain rate.

Considering the effects of the grain growth and cavitation growth, a new constitutive equation for superplasticity is derived and described as follows:

$$\begin{cases} \sigma = A_2(1-f)(\dfrac{\dot{\varepsilon}}{1+p^N})^{1/N} \\ p = \{1 - F_{gb}[1 - \dfrac{A_1 KT}{A_2 w D_{gb}}(\dfrac{d}{b})^3(\dot{\varepsilon})^{1-\frac{1}{N}}]\}^{-1} \\ d = d_0 + \{4\gamma\Omega / \delta[D_{gb0}\exp(-Q/RT)/KT]t\}^{1/2} \end{cases} \quad (6)$$

It should be noted that this model takes into account not only the grain-boundary sliding and dislocation creep, but also the effects of temperature, grain size and cavity growth on superplasticity. Thus it can predict the superplastic forming process accurately.

2.2. Results and discussions

The materials used to illustrate superplastic deformation here are Zn-Al alloy and LY12CZ alloy. A finite element simulation program has been developed to predict the cavitation growth and calculate the effect of hydrostatic pressure on cavitation growth for superplastic materials. Forming limits of superplastic materials are related to their cavitational behaviour. According to Zhou and Lian [8], the average limit thickness strain is defined as the thickness strain at the pole is five times the average thickness strain along the meridian. The relationship of the limit thickness strain with the relative ratio (r/r_o) for Zn-Al alloy superplastic bulging process was computed and Figure 1 shows the relationship between the average limit thickness strain and the strain rate sensitivity (*m* value). It was found that the average limit thickness strain is greatly enhanced by a larger *m* value. The existence of cavities in the forming specimen reduces the effective section, which is equivalent to an enhancement of stress under the same pressure distribution. From Fig. 1, it is also shown that the limit strain increases with an increased *m* value when β is small, and the limit strain decreases rapidly with a larger β value, which shows no relationship with the *m* value. This means that the limit strain is dependent on the cavity growth, which is reasonable for superplastic deformation failure.

Figure 2 shows the effects of strain on the cavity growth for LY12CZ alloys with various strain rates. It is found that the cavities grow with the increase of strain. The FE results are consistent with the experimental data [9].

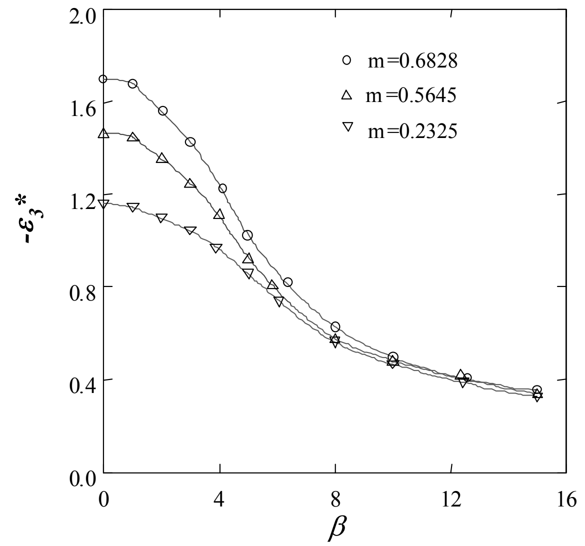

Fig. 1. Calculated limit thickness strain versus cavity grain rate β with various m values

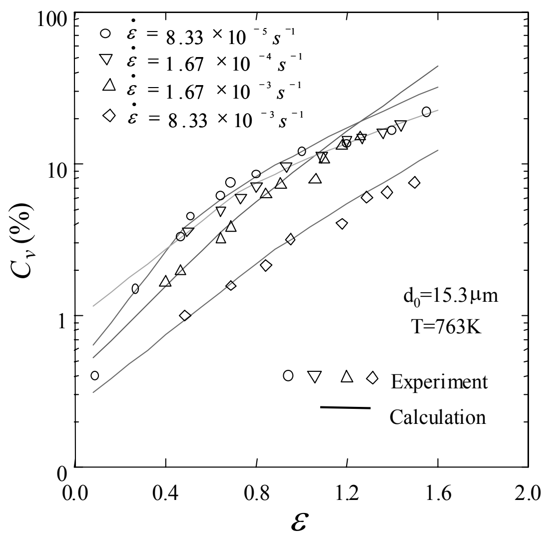

Fig. 2 The cavity growth of LY12CZ alloy for an unaxial tensile test

If cavity growth is not considered, the relationship between strain rate sensitivity (*m* value) and elongation rate δ can be described by [10] :

$$\delta = (\frac{m}{f_o})^m - 1 \tag{7}$$

Figure 3 shows the comparison of fracture elongation rate for LY12CZ alloy between the predicted and the experimental results for the uniaxial tensile test. With the higher strain rate sensitivity, the theoretical predictions given by Eq. (7) are almost consistentwith that of the finite element method (FEM) as well as

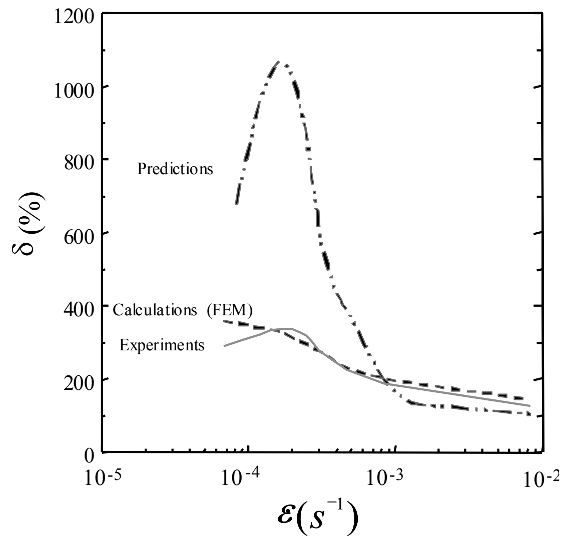

Fig. 3 Comparison of fracture elongation among calculations, the theoretical predictions and the experiment tests

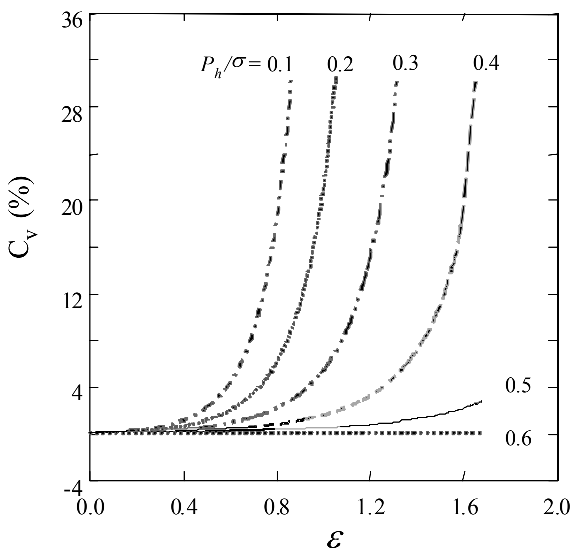

Fig. 4. The effect of imposed hydrostatic pressure on cavity growth during superplastic bulging process

the experimental data. It is found that cavity growth has little influence on the fracture, and the development of necking leads to final fracture for lower *m* values. With low strain rate sensitivity (*m* value), the deviation between the theoretical calculation and FE analysis is relatively large. However, the FE results and the experimental data are almost identical to each other. It is considered that the reason for the final fracture in this case is the cavity growth.

Experimental results show that the imposed hydrostatic pressure has a great effect on the cavity growth of superplastic deformation [11, 12]. Figure 4 is the calculated effect of imposed hydrostatic pressure on the cavity growth for the free superplastic bulging process of Zn-Al alloy. It is is shown that when the imposed hydrostatic pressure (P_h / σ) is small, the cavity grows rapidly. This leads to instability and fracture of the material. With the increase of the imposed hydrostatic pressure, the cavity growth is restrained generally. When the imposed hydrostatic pressure $P_h / \sigma \geq 0.6$, the cavity growth is restrained completely. It is observed from this figure that the FE prediction and experiment [13] are in good agreement.

During superplastic deformation, the cavitation damage increases with the increase in strain. With the high strain rate sensitivity, the development of necking leads to the final fracture. With the small strain rate sensitivity, the reason for the final fracture is cavitation growth. The imposed hydrostatic pressure can control the cavitation growth during superplastic deformation, which provides an effective means of improving the quality of superplastic forming products.

3. Grain growth during superplastic deformation

In this work, a new microstructual model for superplasticity, which is used to study the evolution of grain size and further reveal the microstructural mechanisms of superplastic deformation. This model is applied to conventional superplastic materials (Zn-Al alloy, LY12CZ alloy, and 7475Al alloy) to investigate the influences of initial grain size, grain growth, test temperature, and strain rate sensitivity on the mechanical properties of materials during superplastic deformation. The proposed model accurately predicts the relationship between stress and the strain rate, and the influence of grain growth on flow stress. Hence, it can be applied to optimize superplastic forming processes. Moreover, a rigid viscoplastic finite element method (FEM) program is developed to simulate the superplastic bulging processes and compare it to experimental data. The influence of the variation of the strain rate sensitivity (*m* value) on the limit strain of the superplastic bulging process is numerically analyzed in detail.

3.1. Grain growth model

A finer grain size is always desirable for superplastic deformation becasue it can lead to lower flow stress, higher strain rate sensitivity, and larger tensile elongation. Grain boundary sliding and dislocation creep contribute appreciably to total deformation at low strain rates, which require relatively low stresses to drive them. Conversely, at high strain rates, they occur too slowly to contribute appreciably to deformation. In this case, deformation occurs mainly due to dislocation creep. Deformation by dislocation motion requires a substantially higher flow stress than that by grain boundary sliding and dislocation creep. At low strain rates, deformation by grain boundary sliding and dislocation creep produces high strain rate sensitivity in materials. If the grain size is large, then the transition to grain boundary sliding and dislocation creep, with the increase of strain rate sensitivity, does not occur at reasonable strain rates, and superplasticity cannot be observed.

Experiments on grain growth in various metals and alloys have indicated that straining impedes it in the process of plastic deformation [14-16]. However, in the process of superplastic deformation, the strain enhances grain growth by grain boundary sliding. The activation energy at high-test temperatures enhances the instability of the grain boundary in superplastic materials. The difference in the dislocation energy between two sides of the grain boundary means that the grain boundary slides towards the dislocation area. The large grains become much larger, and the small grains become much smaller. As a result, the large grains consume the smaller grains due to the directional sliding of dislocation. Grain growth is not only the result of the annealing time at the test temperature; but is also enhanced by deformation. Due to its importance, grain growth has become an interesting topic in materials science and engineering. Beck et al [14] suggested an empirical expression for grain growth, which is given by

$$d = C_1 t^p, \tag{8}$$

where d is the grain size, C_1 is a constant, t is time, and p is the time exponent.

Later, Burke and Turnbull [15] deduced the following law for grain growth:

$$d^2 - d_0^2 = C_2 \exp\left(-\frac{Qt}{RT}\right) \tag{9}$$

where d_0 is the initial grain size, Q is the activation energy, C_2 is a constant, R is a gas constant, and T is temperature in degrees Kelvin.

Usually, the grain growth in metals can be expressed by,

$$d^2 - d_0^2 = kt^{n_1} \tag{10}$$

where k and n_1 are constants and n_1 is in the interval from 0.5 to 1.0.

Metallography analysis [16] has shown that grain boundary migration is related to atomic mobility, which is indicated by

$$M = D_{gb0} \exp\left(-\frac{Q}{RT}\right) = \frac{D_{gb}}{RT} \tag{11}$$

where D_{gb0} is the pre-exponential factor. The driving force can be derived and given as follows:

$$F = \left(\frac{\Omega}{\delta}\frac{\partial \gamma}{\partial d} + \frac{\partial U_{gb}}{\partial d}\right) \tag{12}$$

where Ω is the atomic volume and γ is the grain boundary surface energy. It should be noted that the value of $\partial U_{gb} / \partial d$ is far smaller than that of $\partial \gamma / \partial d$. Thus, the contribution of $\partial U_{gb} / \partial d$ can be neglected [16]. Assuming n_1=1 and $\dot{d} = MF$ in equation (10), the grain growth can be rewritten as:

$$d^2 - d_0^2 = \frac{4\gamma\Omega D_{gb0}}{\delta KT} \exp\left(\frac{-Qt}{RT}\right) \tag{13}$$

Equation (13) is a simplified model that describes the grain growth in superplastic deformation.

3.2. Constitutive equations

The typical characterization of superplastic deformation can be illustrated by two curves. One is a S-shaped curve that described the relationship between flow stress (lg σ) and strain rate (lg $\dot{\varepsilon}$). The other is a peak-shaped curve describing the relationship between strain rate sensitivity (*m* value) and strain rate (lg $\dot{\varepsilon}$). The two curves can be divided into three regions, marked I, II, and III. Many experiments have shown that the curves are influenced by temperature *T*, initial grain size d_0, and strain rate sensitivity $\dot{\varepsilon}$.

Some models of superplasticity describe a grain boundary sliding (GBS) process that is associated with accommodation processes, such as the diffusion-accommodation model given by Ashby and Verrall [17], the dislocation pile up accommodation model presented by Ball and Hutchinson [18] and Mukherjee [19], and the composite model that considers grain-boundary sliding and dislocation creep proposed by Baudelet and Lian [6].

Based on the composite model, the average applied stress is defined as:

$$(f_a + f_b)\sigma(\dot{\varepsilon}) = f_a\sigma_a(\dot{\varepsilon}) + f_b\sigma_b(\dot{\varepsilon}) \qquad (14)$$

where $\sigma_a(\dot{\varepsilon})$ is the stress for dislocation creep, $\sigma_b(\dot{\varepsilon})$ is the stress for gain boundary sliding, and f_a and f_b are the proportion of dislocation and grain boundary sliding, respectively.

Equation (14) can be rewritten as:

$$\sigma(\dot{\varepsilon}) = (1 - F_{gb})\sigma_a(\dot{\varepsilon}) + F_{gb}\sigma_b(\dot{\varepsilon}) = \frac{1}{f}\sigma_a(\dot{\varepsilon}) \qquad (15)$$

where $F_{gb} = \dfrac{f_b}{f_a + f_b}$ is the proportion of the stress contribution of grain boundary sliding.

The Ashby [3] model describes grain boundary sliding. The stress for grain boundary sliding is expressed by

$$\sigma_b = A_1 \frac{KT}{\delta D_{gb}} \left(\frac{d}{b}\right)^3 \dot{\varepsilon} \qquad (16)$$

where *d* is the grain size, δ is the grain boundary width, *b* is the Burgers vector, $D_{gb} = D_{gb0} * \exp(-Q_{gb}/RT)$, D_{gb0} is the grain boundary coefficient, and A_1 is an adjustable material-dependent constant.

The stress for dislocation creep can be expressed with the following empirical formulae:

$$\sigma_a = A_2^* \left[\frac{KT}{D_0} \exp\left(\frac{-Q}{RT}\right) \dot{\varepsilon}\right]^{\frac{1}{N}} \qquad (17)$$

$$\sigma_a = A_2 (\dot{\varepsilon})^{\frac{1}{N}} \qquad (18)$$

where D_0 is the pre-exponential factor and A_2 and A_2* are adjustable material dependent constants.

Substituting equations (16) and (18) into (15), a composite model for superplasticity can be obtained by

$$\sigma = A_2 \left(\frac{\dot{\varepsilon}}{1 + f^N}\right)^{\frac{1}{N}} \qquad (19)$$

where

$$f = \left\{1 - F_{gb}\left[1 - \frac{A_1 KT}{A_2 \delta D_{gb}} \left(\frac{d}{b}\right)^3 (\dot{\varepsilon})^{1-1/N}\right]\right\}^{-1} \qquad (20)$$

in which $\dot{\varepsilon}$ and σ are the applied strain rate and stress, and *N* is a stress-sensitivity exponent, which is about 4-5 for dislocation creep.

The grain growth model, as indicated in equation (13), is introduced into the composite constitutive equation for superplasticity, and a new constitutive equation considering the grain growth is developed as follows:

$$\bar{\sigma} = A_2 \left(\frac{\dot{\varepsilon}}{1 + f^N}\right)^{\frac{1}{N}} \qquad (21a)$$

$$f = \left\{1 - F_{gb}\left[1 - \frac{A_1 KT}{A_2 \delta D_{gb}} \left(\frac{d}{b}\right)^3 (\dot{\varepsilon})^{1-\frac{1}{N}}\right]\right\}^{-1} \qquad (21b)$$

$$d = d_0 + \frac{4\gamma\Omega}{\delta[D_{gb0}\exp(-Q/RT)/KT]t} \qquad (21c)$$

This model allows the behavior of superplastic materials to be determined as a function of strain rate, grain size, grain growth, and temperature. Moreover, it considers the grain-boundary sliding, dislocation creep, and grain growth effects. Using this model, the influences of temperature, strain rate and grain size on superplasticity can be predicted comprehensively.

3.3. Results and discussion

An analysis is carried out to investigate the influences of strain, strain rate, temperature, and initial grain size on the grain growth. Usually, a higher test temperature can accelerate atomic diffusion and in turn increase the sliding rate at the deformation region. Figure 5 shows the influence of the test temperature (*T*=498K, 473K, 448K) on the grain growth with the same strain rate ($\dot{\varepsilon} = 10^{-5} s^{-1}$) and initial grain size (d_0=1.2μm) for Zn-Al alloy. The experimental data of Campenni and Caceres [20] are also plotted. Less activation energy occurs at a low-test temperature, and the grain growth is reduced with the decrease of the test temperature. Figure 6 gives the grain size versus the strain with two different initial grain sizes (d_0=1.2μm, 4.4μm) for Zn-Al alloy ($\dot{\varepsilon} = 10^{-5} s^{-1}$, *T*=498K). Reducing the grain size can speed up the grain growth. These results agree well with the experimental data. Figures 7 show the influence of the strain on the grain size with various strain rates for Zn-Al alloy. Grain growth decreases with the increase in strain rate. The increased strain rate restricts grain boundary sliding, and further straining results in grain growth. Hence, superplastic deformation enhances grain growth.

The proposed model is applied to study the flow laws of superplastic materials. Figure 8 shows a comparision of the predicted and experimental flow stress versus strain rate for Zn-Al alloy at various temperatures (*T*=423K, 473K, 503K). The theoretical prediction is consistent with the experimental observation [21]. The calculated lg σ versus lg $\dot{\varepsilon}$ curve is S-shaped, and the flow stress decreases with the increase of temperature.

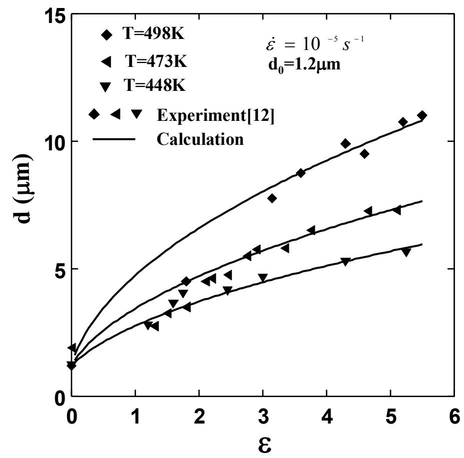

Fig. 5. Influence of test temperature on the grain size of Zn-Al alloy

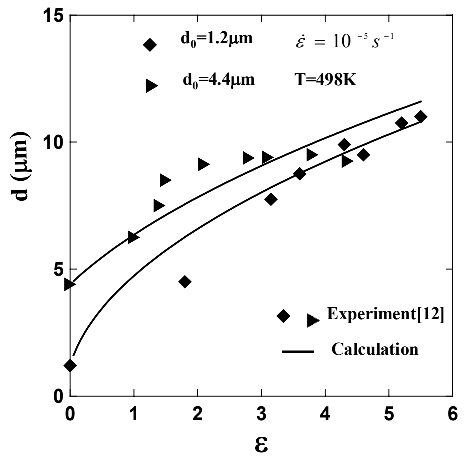

Fig. 6. Grain size versus strain for the various initial grain sizes of Zn-Al alloy

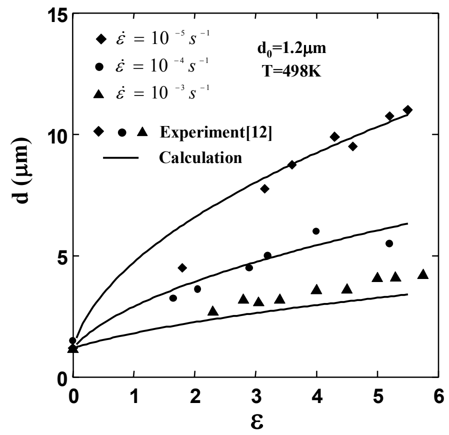

Fig. 7. Influence of strain rate on the grain size of Zn-Al alloy

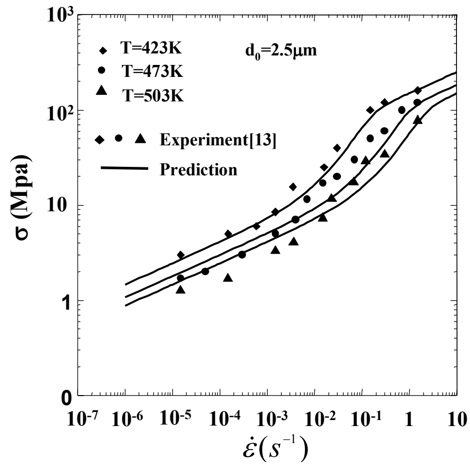

Fig. 8. Comparison of the predicted and experimental [13] flow stress versus strain rate for Zn-Al alloy

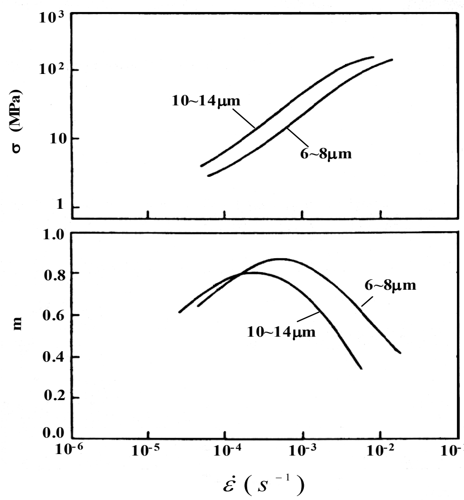

Fig. 9 The flow stress and strain rate sensitivity (*m* value) versus strain rate for 7475Al alloy [22]

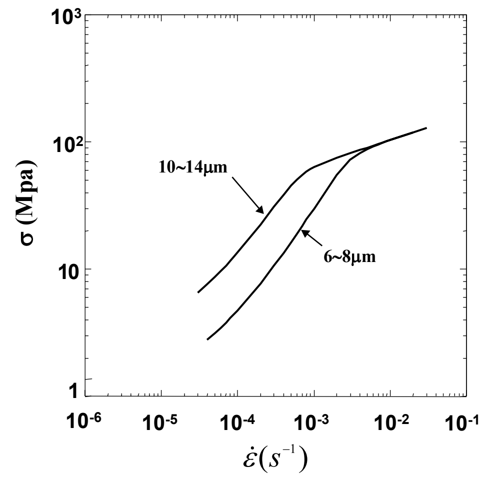

Fig. 10. The calculated flow stress versus strain rate curve for 7475Al alloy

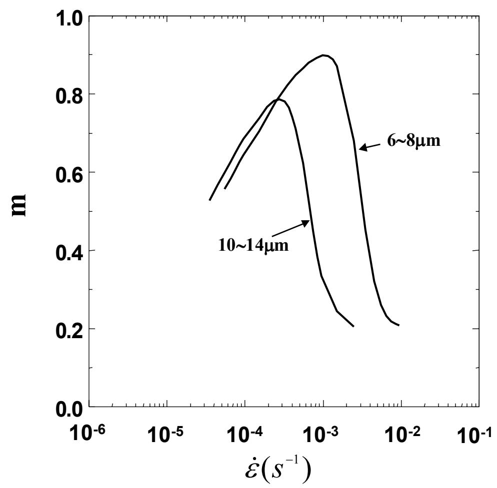

Fig. 11. The calculated strain rate sensitivity (*m* value) versus strain rate curve for 7475Al alloy

Figure 9 shows the experimental flow stress and strain rate sensitivity (*m* value) versus strain rate for 7475Al alloy (T=789K) [22], and the calculated $\sigma-\dot{\varepsilon}$ and $m-\dot{\varepsilon}$ curves are given in Figures 10 and 11. The three deformations regions I, II and III can be distinguished according to their dependences on temperature, strain rate, and grain size. The strain rate sensitivity (*m* value) in region II reaches the maximum value. The maximum strain rate sensitivity (m value) can be obtained at a critical temperature T_m, which is regarded as the best test temperature. It can be noted from the curves that m continuously varies throughout the three regions, with its maximum value occurring in region II. In regions I and III, m exhibits a low value. The superplasticity of 7475Al alloy is influenced by grain size. In region II, an increasing grain size increases the flow stress and reduces the maximum value of m as well as the strain rate at which that maximum can be observed. As a result, region II moves toward the direction of lower strain rate with the increase of grain size. The flow stress is a function of strain rate, strain rate sensitivity (*m* value), temperature and grain size. The comparision reveals that the theoretical prediction and experiment [22] are in good agreement.

All of the results indicate that the proposed model of superplasticity is accurate and reliable, and thus the derived constitutive equation for superplasticity can effectively describe the grain growth and flow law. It therefore becomes a “unifying bridge”, correlating microstructure to the macro-phenomenon of superplasticity.

4. Conclusions

A new microstructure model based on the microstructural mechanism of superplastic deformation has been proposed. This model has been successfully applied to analyze conventional superplastic materials. Using the proposed constitutive equation, the influence of material parameters on grain growth has been studied. The results indicate that a higher test temperature, higher strain, and lower strain rate can enhance grain growth for superplastic deformation. The deduced $\lg\sigma$–$\lg\dot{\varepsilon}$ curve is S-shaped. The flow law of superplasticity is related to temperature, initial grain size, grain growth and strain rate sensitivity. The flow stress decreases with the increase of the temperature and the decrease of the initial grain size. An increasing grain size increases the flow stress and reduces the maximum value of *m* as well as the strain rate, at which the maximum value of *m* is observed. The increasing grain size also causes region II to move toward the direction of high strain rate. The thickness distribution of free superplastic bulging is predicted by the model, and the calculated results are in good agreement with the experimental data. The limit thickness strain for the free superplastic bulging process is related to the final strain rate sensitivity *m* value, and it has no correlation with the initial m value and the final *m* value.

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