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Analysis of cavitation and its effects on superplastic deformation

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Analysis and modelling

ABSTRACT

Purpose: To study the effects of cavitation on the superplastic deformation using finite element method.
Design/methodology/approach: Using consitututive equations for superplastic deformation, and taking into account the effects of grain growth and cavitation growth, Zn-Al and LY12CZ alloys are used for simulations to show effects of m values, elongation-to-failure values, percentage cavities and effects of imposed hydrostatic pressure during superplastic forming processes.
Findings: During superplastic deformation, cavitation damage increases with the increase in strain. For high strain rate sensitivity, necking develops which leads to final fracture; whereas for low strain strain rate sensitivity, the final fracture is due to cavitation growth.
Research limitations/implications: 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.
Originality/value: A three dimensional viscoplastic finite element programe, taking into account of microstructural mechanisms, such as test temperature and cavity growth has been developed for superplastic deformation.
Keywords: Superplastic deformation; Cavitation; Finite Element Method

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.

$$f = f_0 \exp(\overline{\beta}, \varepsilon) \tag{1}$$

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

$$\overline{\beta} = \beta D(\sigma) \tag{2}$$

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

$$D(\sigma) = 0.558\sinh(X) + 0.008\xi\cosh(X) \tag{3}$$

where

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

and

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

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 $P_h = 0$ and 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:

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

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 Figure 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].

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

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

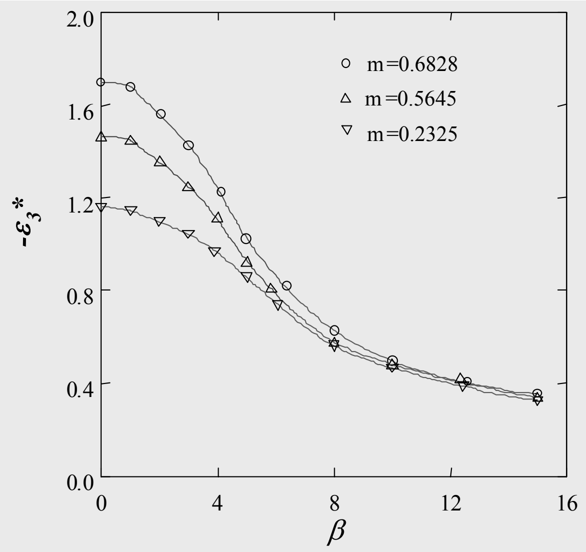

Fig. 1. Calculated limit thickness strain versus cavity grain rate β with various m values

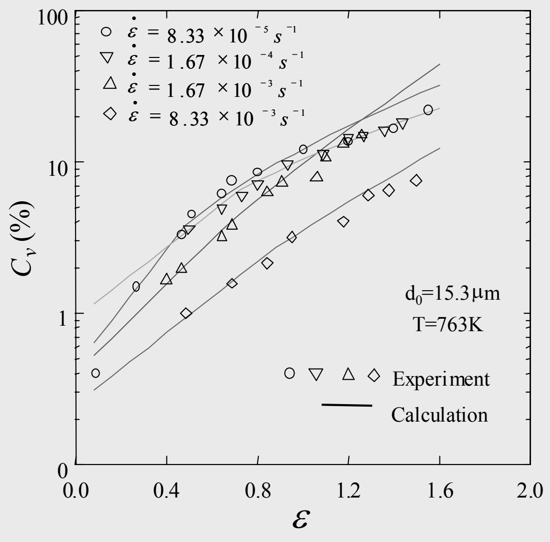

Fig. 2. The cavity growth of LY12CZ alloy for an unaxial tensile test

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 consistent with that of the finite element method (FEM) as well as 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.

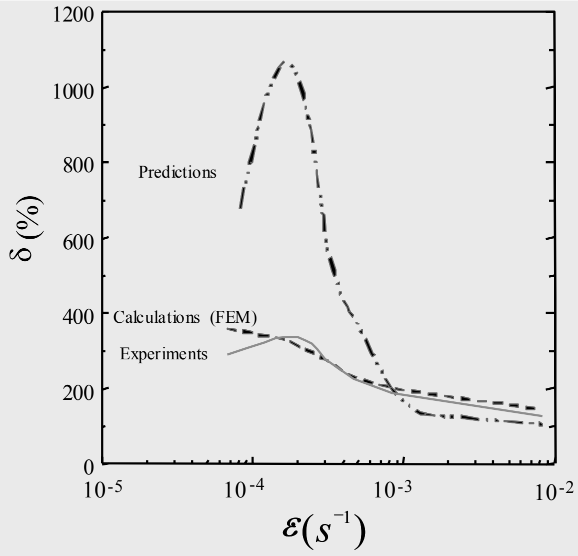

Fig. 3. Comparison of fracture elongation among calculations, the theoretical predictions and the experiment tests

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 experimental results [13] are in good agreement.

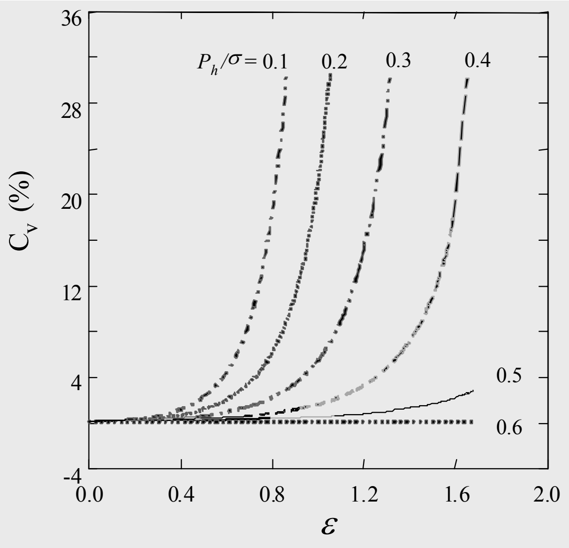

Fig. 4. The effect of imposed hydrostatic pressure on cavity growth during superplastic bulging process

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. Conclusions

A three-dimensional viscoplastic finite element program, taking into account of microstructural mechanisms, such as test temperature and cavity growth, has been developed for studying superplatic deformation. Cavity growth is considered an important damage or limiting factor for superplastic deformation, and increases with increase in strain. It is shown that with high strain rate sensitivity, the development of necking leads to the final fracture; and with low strain rate sensitivity, the cause for final fracture is cavity growth during superplastic deformation. Imposed hydrostatic pressure can control the cavity growth during superplastic deformation, which provides an effective means of extending the superplastic regime.

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