Forming Limit Diagram for a Superplastic 5083 Aluminum Alloy

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The superplastic blow forming limits for a 5083 aluminum alloy were investigated at a strain state from the plane strain to the balanced biaxial at a temperature of 773 K and a strain rate of about 1 x 10⁻³ s⁻¹. It was discovered that the equivalent strain at the forming limit was in a range of 1.3 ± 0.1 for every strain state and was consistent with that obtained by the uniaxial tensile tests. Namely, the forming limit for the blow forming could be estimated from the equivalent strain-to-fracture in the uniaxial tensile test. The cavity volume fraction and the cavity growth rate at the forming limit, however, increased by changing the strain state from uniaxial to balanced biaxial through a plane strain. The relationship between the forming limit and the cavity volume fraction is dependent upon the strain state.

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1. Introduction

Most research on the deformation characteristics of superplastic materials has been carried out using uniaxial tensile tests to evaluate the flow stress, strain rate sensitivity, elongation and cavity volume fraction at various temperatures and strain rates. The uniaxial tensile tests at high temperatures facilitated a comparison of the phenomena of creep and superplasticity and enabled the elucidation of the scientific characteristics of superplasticity. However, it is difficult to accurately estimate the capability of the superplastic blow forming from the results of the uniaxial tensile test. The superplastic blow forming is usually performed under the biaxial tensile conditions. Therefore, the deformation characteristics of the materials under the biaxial tension at high temperatures are required in order to compare them with those under the uniaxial tension. For instance, the prediction of the forming limit for the biaxial tension from the uniaxial tension is expected. There are many studies on the experimental and theoretical research regarding the cold press-forming limit for steels and aluminum alloys.¹⁻⁷ The theoretical and experimental results for the cold press-forming limit diagram showed that the minor strain at the plane strain state was lower than that at the biaxial strain state because the effect of the strain rate sensitivity on the plastic stability was not expected at room temperature. There are a few reports on the superplastic-forming limit.⁸⁻¹¹ Mahoney et al. carried out the superplastic deformation for the 7475 aluminum alloy at the uniaxial tension, the plane strain and the balanced biaxial strain state.³⁰ They showed that a forming limit diagram was developed to relate the damage due to cavitation during forming to a corresponding decrease in the mechanical properties and that a major strain at the plane strain was as large as that at the biaxial strain state. They also described that the strain state has no measurable influence on cavity growth rate during the superplastic forming. The result is somewhat surprising since the mean stress is known to influence cavitation in creep and superplasticity.⁹ In this study, a superplastic blow-forming machine was constructed for laboratory use in which the pressure-time path was precisely controlled by a personal computer. Using this equipment, the superplastic forming for a 5083 aluminum alloy was performed in a range of strain state from a plane strain to a balanced biaxial strain. The purpose of this study is to show the forming-limit diagram for a 5083 alloy and a relationship between the forming limit and cavitation.

2. Experimental Procedure

A superplastic 5083 aluminum alloy with an average grain size of 10 µm was used. The thickness of the sheet was 1 mm. The superplastic-blow-forming machine used in this study had the forming zone separated by an upper and a lower box. The former contained a pressure-panel and the latter contained a female die. The 5083 sheet was inserted between them and pressed. The superplastic forming was accomplished by applying gas pressure on one side of the aluminum sheet, causing it to form down into the die at a nearly constant strain rate. The dimensions of the lower box was a 250 mm cube. The uniformity of the temperature inside the boxes was achieved by controlling 6 cartridge heaters. A refractory ceramic with high machinability was used for the die material. The female dies had a rectangular hole of 4 x 10³ mm² area and 75 mm depth. Six dies with same area and varying ratios of short and long side lengths of the rectangular hole, D₂/D₁, were used in order to accomplish a different strain state for the superplastic forming. The ratios of D₂/D₁ were 63 mm/63 mm, 50/80, 44/90, 40/100, 35/125 and 27/150. The forming temperature was 773 K. The nitrogen-gas-pressure varied from 0.4 to 0.7 MPa. The gas pressure was increased to a predetermined value in the 120 s, and was maintained at a constant for various lengths of times. This pressure path was controlled by a personal computer. A suspension of boron nitride powder was sprayed on the sheet as a lubricant to prevent sticking. For the strain measurement, the scribbled circles with diameters of 10 mm were stamped on the sheet. The diameter of the circles was determined as large as the uniformly deforming zone in this study. After
forming, the consistency of the centers between a circle and the die was confirmed. The lengths of the major and minor axes of the scribbled circle were measured at the top of the rectangular cup to determine the actual strains. To measure the lengths of the major and minor axes a transparent adhesive-tape was attached on the sample to copy the circle. After stripping the tape, the lengths were measured with an accuracy of ±2%. For the sample including the crack, the lengths were measured at the circle neighboring the crack. A small square piece of about 10 mm × 10 mm was cut from the top using a sawing machine with a circular-blade of 0.5 mm thick and polished all surfaces with an abrasive paper of 1000 mesh for a sample of the density measurement. The cavity volume fraction, \( V \) was estimated as a percent of the density decrease caused during the deformation and given by the equation of (1).

\[
V = \left( \frac{\rho_1 - \rho_0}{\rho_0} \right) \times 100\%
\]  

where \( \rho_1 \) is the density of the deformed sample and \( \rho_0 \) is the density of the undeformed sample with the same thermal history. In addition, the cavities were observed using an optical microscope. The uniaxial tensile tests were also carried out at 773 K and at a strain rate of \( 1 \times 10^{-3} \text{s}^{-1} \) to compare the forming limit and cavitation.

3. Results and Discussion

3.1 Superplastic properties in the uniaxial tensile test

Figure 1 shows the true stress (a) and strain rate sensitivity (b) as a function of the true strain rate at a temperature of 773 K obtained by the repeated velocity jump test. The true stress varied from 3 MPa at a strain rate of \( 1 \times 10^{-4} \text{s}^{-1} \) to 35 MPa at \( 1 \times 10^{-2} \text{s}^{-1} \). The strain rate sensitivity, \( m \) value, greater than 0.3 was obtained in a strain-rate range of \( 5 \times 10^{-5} \) to \( 5 \times 10^{-2} \text{s}^{-1} \) and a maximum value of 0.55 was achieved at \( 1 \times 10^{-3} \). Figure 2 shows the true stress and true strain relationship. The strain hardening occurred up to a strain of 1.0 and fractured at a strain of 1.4.

3.2 Strain state in superplastic-blow forming

Figure 3 shows an example of a blow-formed cup after fracture. The ridge was curved along the long side of the rectangular cup. The fracture occurred at the top of the ridge and propagated along the ridge. Figure 4 shows a variation of the equivalent strain measured at the top as a function of the forming time for various gas pressures and die shapes. The von Mises equation of

\[
\varepsilon_{eq} = \left( \frac{2}{\sqrt{3}} (\varepsilon_1^2 + \varepsilon_1 \varepsilon_2 + \varepsilon_2^2) \right)^{1/2}
\]

was used for calculation of the equivalent strain, where \( \varepsilon_{eq} \) is the equivalent strain, \( \varepsilon_1 \) is the major strain and \( \varepsilon_2 \) is the minor strain. The equivalent strain increased at a strain rate of 0.001 to 0.002 s\(^{-1}\) in the early stage of formation and increased at a slightly higher rate of 0.003 to 0.005 s\(^{-1}\) in the late stage. The strain rate varied depending on the die ratio and gas pressure. The change in the strain rate during formation may be due to
an increase in the actual stress caused by a decrease in thickness under the constant pressure applied.

Figure 5 shows the typical relationship between the gas pressure and the average strain rate during the formation. The strain rate decreased with a decreasing die-aspect-ratio, \( D_2/D_1 \), for the same gas pressure. This figure shows that a strain rate in a range of 0.003 s\(^{-1}\) was obtained at a pressure of 0.4 MPa for the die-aspect-ratios of 63/63, 44/90, at 0.5 MPa for 40/100 and at 0.6 MPa for 27/150, respectively.

Figure 6 shows the relationship between the major strain, \( \varepsilon_1 \) and the minor strain, \( \varepsilon_2 \), at a strain rate of 0.003 s\(^{-1}\) for all die-aspect-ratios and the uniaxial tensile tests. The strain ratio of \( \varepsilon_2/\varepsilon_1 \) was constant up to the fracture for each die-aspect-ratio. The value of \( \varepsilon_2/\varepsilon_1 \) was 1.0 for the die-aspect-ratio of 63/63, 0.46 for 50/80, 0.4 for 44/90, 0.3 for 40/100, 0.22 for 35/125 and 0.08 for 27/150. The value of \( \varepsilon_2/\varepsilon_1 \) was slightly less than the die-aspect-ratio except the case of 63 \( \times \) 63. This may be due to the retardation of deformation by the friction between the alloy and the die surface. The minor strain of \( \varepsilon_2 \), which is parallel to the long side of the rectangular cup, is affected by the friction more than the major strain of \( \varepsilon_1 \) that is parallel to the short side of the cup. The forming limits showing the strains at fracture are depicted for all values of \( \beta \) in Fig. 7. All forming limits exist in the range of 1.3 ± 0.1 of equivalent strain. The superplastic-forming limit could be predicted from the equivalent strain at fracture obtained by simple tensile tests. Mahoney et al. also showed that the superplastic-forming limit for a 7475 aluminum alloy could be described by a constant equivalent strain line.\(^8\) However, it has been reported that for the sheet forming of aluminum alloys at room temperature, the forming limit is remarkably low at the plane strain as superimposed by a broken line in Fig. 7.\(^{10}\)

The characteristic differences in the forming limits is likely due to a difference in the effect of the strain rate sensitivity, \( m \) value, on the plastic stability. The strain rate sensitivity and the strain hardening are well known to inhibit the progress in the local necking during superplastic forming.\(^{11}\) Marciniak et al. and Ghosh analyzed the effect of the strain rate sensitivity, \( m \) value, on the forming limit curve.\(^5,10\) They showed that the limit strain at \( \beta = 0 \) increases with an increasing \( m \) value, because a significant diffusion of necking could be expected. Finally, the superplastic-forming limit might be dependent upon the probability of fracture caused by the cavity inter-linkage during superplastic forming.
3.3 Effect of strain state on cavitation

Figure 8 shows the relationship between the equivalent strain and the cavity volume fraction for several β values. The cavity volume fraction, V, is represented by the equation of $V = V_0 \exp(\eta \varepsilon_{eq})$ based on the plastic controlled cavity growth, where $\varepsilon_{eq}$ is the equivalent strain and $\eta$ is the cavity growth rate. Clearly the value of $\eta$ increases with an increasing $\beta$ value as shown in Table 1. The theoretical value of $\eta$ is given by the equation of (3),

$$\eta = 1.5(1 + 0932m - 0.432m^2)^{1/m}[\sigma_M/\sigma_E], \quad (3)$$

where $\sigma_M$ is the mean stress and $\sigma_E$ is an equivalent stress. The value of $\sigma_M/\sigma_E$ is given by

$$\sigma_M/\sigma_E = K_s / 3$$

where $K_s$ is a geometric constant of deformation; 1.5 for the uniaxial, 2.25 for the balanced biaxial and 2.07 for the plane strain at a 50% grain boundary sliding. Using these constants, the theoretical values of $\eta$ for $m = 0.5$ are calculated as shown in Table 1. The experimental value of $\eta$ increased with increasing values of $\beta$ as shown by the theory results.

Figure 8 shows that the cavity volume fraction at a strain of 1.4 increased from 1.5% to 6% with an increasing die-aspect-ratio, $D_2/D_1$, and a strain ratio, $\beta$. However, the forming limit lies in a limited extent of the equivalent strain regardless of a different strain state as mentioned in Fig. 7. It is important to consider why the forming limit is high regardless of the high cavity volume for a high $\beta$ value.

Figure 9 shows the cavities observed in the vicinity of the fractured surface for the cases of $\beta = 0.08$, 0.4 and 1.0. The cavities grow preferentially in a direction of the major strain. As the value of $\beta$ increases, the cavities begin to grow in the

![Fig. 8 Cavity volume fraction for various die-aspect-ratio as a function of the equivalent strain.](image)

![Fig. 9 Cavities observed in the samples fractured at strain states of (a) $\beta = 0.08$, (b) 0.4 and (c) 1.0.](image)

<table>
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<th>$\beta$</th>
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<td>2.23</td>
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<td>1.38</td>
<td>1.57</td>
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Table 1 Comparison between the experimental and theoretical $\eta$ values.
direction of the minor strain too. Therefore, the cavity volume fraction increases with an increasing $\beta$ value. However, the fracture probability may not always increase with an increasing cavity volume, because the fracture should occur due to the inter-linkage between cavities in a direction perpendicular to the major strain. The result concerning the relationship between the strain state and the cavity volume fraction is different from that of Mahoney et al.: they showed that the cavity growth is independent of the strain state.

4. Summary

This study has shown the following results:
(1) The superplastic-forming limit diagram has been examined using the 5083 Al alloy in several strain states from the plane strain to the balanced biaxial tension and compared to that of the uniaxial tension. The equivalent strain at the forming limit for all biaxial-strain-states investigated is close to that in the uniaxial tensile test.
(2) The cavity growth rate and the cavity volume fraction increase with an increasing strain ratio from $-0.5$ to $1.0$. However, the variation in the forming limits is very small regardless of such a difference in cavity development.

REFERENCES