Superplastic Characteristics of Ti-Alloy and Al-Alloy Sheets by Multi-Dome Forming Test

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The present study evaluates the superplastic material characteristics of Ti-alloy "Ti-4.5Al–3V–2Fe–2Mo", SP-700, and Al-alloy "A5083", which have been obtained by utilizing a multi-dome forming test. First, the flow stress vs. strain rate relationship was established for certain strain rate range, from a single circular sheet containing four different domes, sized 35, 30, 25, and 20 mm diameter, respectively. The multi-dome forming experiments were conducted under constant pressure at a superplastic temperature of 800°C for Ti-alloy and of 530°C for Al-alloy. The bulge forming of domes was also simulated by finite element method (FEM) to verify the experimentally-obtained material characteristics. Then the material characteristics obtained through multi-dome forming test were compared to those obtained by tensile strain rate tests. In contrast to the predictions of the tensile test, the multi-dome forming test's predicted time of deformation was generally in reasonable agreement with the results of the FEM simulation. There was no great difference, however, between the multi-dome forming test and the tensile testing with regard to the predicted final thickness distribution.

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1. Introduction

The superplastic forming process is presently accepted by several industries as a viable method to fabricate complex structural components.1) Superplastic materials are characterized by very large elongation and high strain rate sensitivity against a flow stress which is under deformation rates between $1 \times 10^{-5}$ to $1 \times 10^{-2}$ s$^{-1}$. The tensile test is currently the most common method used to obtain the superplastic characteristics of the materials. In this test, test pieces are elongated in one direction under a uniaxial stress system. The details of this method can be seen in references.2-4) In recent times, however, some studies reported on the dome forming method, which obtains its material characteristics under a biaxial stress system.5,6) The dome-forming method offers some advantages over the tensile testing method, such as shorter testing time, less equipment and easy clamping of test pieces during the testing. In addition, with small modifications, the same equipment used in the actual superplastic forming can also be employed to obtain material characteristics. Considering the importance of the simulation of superplastic forming with regard to the design of new superplastically formed parts, the need for an accurate determination of the material characteristics cannot be overemphasized.

The aim of this study is an evaluation of the superplastic characteristics obtained through the multi-dome forming on Ti-alloy and on Al-alloy sheet. The material characteristics obtained from the dome-forming were then compared with those obtained from tensile tests using a commercial FEM code with respect to the estimated bulge-time and final thickness distribution.

2. Experimental Procedure

2.1 Multi-dome forming test

The experiments of multi-dome forming test were performed by using two superplastic materials Ti-alloy Ti-4.5Al–3V–2Fe–2Mo, commercial name "SP700" and Al-alloy "A5083". The chemical compositions of the two materials are given in Tables 1(a) and (b) for Ti-alloy "SP700" and Al-alloy "A5083", respectively. The geometry of the blanks used as specimens was of a 120 mm diameter and an initial thickness of 0.72 mm for Ti-alloy "SP700" and of 1.5 mm for Al-alloy "A5083".

Figure 1 shows the illustration of experimental setup for multi-dome forming test. In the experiments each test piece was clamped between the blank holder and die holder. The electric furnace was used to heat the test piece to each superplastic temperature, 800°C for SP700 and to 530°C for A5083. The superplastic temperature was maintained within ±2°C by using a controller. After waiting five minutes to ensure a uniform temperature distribution throughout the sheet, constant Ar gas pressure was applied to deform the sheet to various heights within the mold, which has four holes of diameters 35, 30, 25, and 20 mm. The experiments were employed under the constant pressure-forming mode. The experimental conditions are shown in Table 2. Figure 2 shows

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Table 1 Chemical composition of materials used.

(a) Superplastic Ti-alloy "SP-700"

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<th></th>
<th>Fe</th>
<th>Mo</th>
<th>Al</th>
<th>V</th>
<th>Ti</th>
<th>Balance</th>
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<td>2.0</td>
<td>4.5</td>
<td>3.0</td>
<td>0.9</td>
<td>0.05</td>
<td>Balance</td>
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</table>

(b) Superplastic Al-alloy "A5083"

<table>
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<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
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<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
<td>0.4-1.0</td>
<td>4.0-4.9</td>
<td>0.05-0.25</td>
<td>0.25</td>
<td>0.15</td>
<td>Balance</td>
<td></td>
</tr>
</tbody>
</table>

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the photos of the metal mold with four holes and the test piece after the multi-dome forming test. Before the test, all surfaces of the sheet specimen and of the lower mold were coated with boron nitride to reduce the friction between the die and deformed part. After the forming test, a point micrometer with an accuracy of 0.001 mm was used to measure the thickness distribution of deformed test piece.

2.2 Tensile step strain rate test

A series of superplastic step strain rate tests were conducted to examine the relationship between the stresses and the strain rates. Figure 3 shows the specimen geometry of tensile test. Tensile test specimens were prepared from the same materials used in the multi-dome forming tests. The tests were performed at the superplastic temperature of 800°C for Ti-alloy and of 530°C for Al-alloy. All the specimens were coated by boron nitride to avoid the oxidation at high temperatures. A tensile test specimen was deformed at a constant crosshead velocity until a steady load is registered. An abrupt change of crosshead velocity was performed during the test until a new steady state is registered. 12 jump tests for Ti-alloy and 13 jump tests for Al-alloy were conducted to obtain the superplastic characteristics in the strain rate range from $5 \times 10^{-3}$ to $2 \times 10^{-5}$ s$^{-1}$. The $m$ value was calculated using the following equation:

$$m = \frac{\log(P_2/P_1)}{\log(V_2/V_1)}$$

where $P$ is the tension load and $V$ is the crosshead speed.

3. Analytical Equations for Superplastic Characteristics

A set of equations was formulated to evaluate the superplastic material characteristics of sheet metal, and to obtain the relationship between the stress and strain state. Figure 4 shows the illustration of a deformed sheet.

The following conditions were assumed to simplify the calculations:
1. The geometry of formed dome is equivalent to part of a sphere.
2. The blank material is isotropic and incompressible. The membrane theory is assumed.
3. The blank is rigidly clamped at the periphery.
4. The elastic strains are negligible compared with the extensive plastic deformation.
5. Grain growth, cavitations, and strain hardening are not considered in the calculations.

A constitutive equation, which satisfies assumption (5), was employed in this study:

$$\sigma = K \dot{\epsilon}^m$$

Where $\sigma$ is the flow stress, $K$ is the strength coefficient, $m$ is the strain rate sensitivity index of the material, and $\dot{\epsilon}$ is the strain rate.

The stresses at the apex of the dome can be calculated using the membrane theory, in which the thickness stress can be ignored ($\sigma_t = 0$). Meridional stress, $\sigma_m$, and the circumfer-
ential stress, \( \sigma_e \), are equal to each other at the dome apex and can be calculated by

\[
\sigma_e = \sigma_c = \sigma_m = \frac{P_R}{2r_f} = \frac{P}{4r_f f} \left( \frac{h^2 + R^2}{h} \right)
\]  

(3)

Where \( \sigma_e \) is the effective stress, \( P \) is the pressure, \( r \) is the radius of curvature, \( R \) is the radius of die, \( h \) is the bulging height, and \( t_f \) is the final thickness. Effective strain at the apex can be calculated by using the incompressibility condition as

\[
\varepsilon_m + \varepsilon_c + \varepsilon_t = 0
\]  

(4)

Where \( \varepsilon_m \) is the meridional strain, \( \varepsilon_c \) is the circumferential strain, and \( \varepsilon_t \) is thickness strain. Meridional strain and circumferential strain should be equal to each other, as well as to the stresses in the same directions, because of axi-symmetry at the dome apex. Thus, at the apex

\[
\varepsilon_m = \varepsilon_c, \quad \varepsilon_m = \varepsilon_c = -0.5\varepsilon_t
\]  

(5)

The effective strain \( \varepsilon_e \) at the apex is given as

\[
\varepsilon_e = \left[ \frac{2}{3} (\varepsilon_m^2 + \varepsilon_c^2 + \varepsilon_t^2) \right]^{1/2}
\]  

(6)

From eqs. (5) and (6), the effective strain \( \varepsilon_e \) at the apex can be calculated from the ratio between final thickness and initial thickness.

\[
\varepsilon_e = \left| t_f \right| = \ln \left( \frac{t_f}{t_i} \right)
\]  

(7)

Where \( t_f \) is the current (final) thickness at the apex, and \( t_i \) is the initial thickness.

The strain rate sensitivity index \( m \) can be obtained from the following equation

\[
m = \frac{d \log \sigma}{d \log \dot{\varepsilon}} = \frac{\log(\sigma_2/\sigma_1)}{\log(\dot{\varepsilon}_2/\dot{\varepsilon}_1)}
\]  

(8)

In the multi-dome test, the deformation time and the temperature are the same for any deformation process of domes. Thus, the strain ratio \( (e_2/e_1) \) can be used instead of the strain rate ratio \( (\dot{\varepsilon}_2/\dot{\varepsilon}_1) \) of two domes. In this case, the strain rate sensitivity index \( m \) can be obtained from the following equation,

\[
m = \frac{d \log \sigma}{d \log \dot{\varepsilon}} = \frac{\log(\sigma_2/\sigma_1)}{\log(\dot{\varepsilon}_2/\dot{\varepsilon}_1)} = \frac{\log(\sigma_{e_2}/\sigma_{e_1})}{\log(\varepsilon_{e_2}/\varepsilon_{e_1})}
\]  

(9)

In this study, the strain rate sensitivity index, \( m \), was obtained by using the strain ratio between every two domes (D1, D2, D3 and D4 respectively). For example, in the case of two domes D1 and D2, the average \( m \) between \( \varepsilon_{D1} \) and \( \varepsilon_{D2} \) can be obtained by

\[
m = \frac{\log(\sigma_{D1}/\sigma_{D2})}{\log(\varepsilon_{D1}/\varepsilon_{D2})}
\]  

(10)

4. FEM Simulation of Bulge Forming

To confirm the validity of the material characteristics, the multi-dome forming test was simulated using a commercially available FEM code MARC. The estimated bulge-time and final thickness distribution are the most important characteristics in the simulation of the superplastic deformation process. The same simulation was also carried out using tensile test results, in order to compare its results with the results of the present study.

In this FEM model, a finite element mesh was generated using 4-nodes axi-symmetric element. The total number of element was 400 in two layers. The finite element mesh, rigid die and boundary conditions are shown in Fig. 5. Nodes on the edge and centerline were fixed in the Y-direction. All nodes were free in the X-direction. Pressure was applied to the surface of the sheet in the X-direction as equally distributed loads. Friction was not taken into account, since the experiments were conducted using a boron nitride lubricant, which greatly reduced the friction between the die and the sheet. The material characteristics \( m \) and \( K \) obtained from the experiments were included in a sub-routine, which defines the relationship between stresses and strain rates to characterize the superplasticty of the materials.

5. Results and Discussion

5.1 Results of experiments

5.1.1 Flow stress-strain rate curve

Figure 6 shows the flow stress versus the strain rate relationship for the superplastic tensile step strain rate test and for the multi-dome forming test. (a) refers to SP-700 and (b) refers to A5083. In multi-dome forming test, flow stress-strain rate curve can be obtained by changing the forming pressure and the bulging time of the experiments. In this study, four experiments with different forming pressure and
bulging time were enough to obtain the curve with strain rate range between $4 \times 10^{-5} - 2 \times 10^{-3}$ s$^{-1}$. It can be seen from these figures that in both cases of SP-700 and A5083, the multi-dome forming test has low flow stress than tensile test. This may be due to the grain growth during superplastic deformation, because of long testing time of high temperature at the low strain rates. In the tensile test, such grain growth would increase the flow stress values. The difference between the curves decreases with increasing strain rate, since the testing time was reduced. The uniaxial stress system in tensile test and biaxial stress system in multi-dome forming, are thinkable to be another reasons for the difference between the two curves.

5.1.2 Strain rate-$m$ curve

Figure 7 shows the relationship between the strain rate and the strain rate sensitivity index, $m$, of Ti-alloy “SP-700” for tensile jump test and for the multi-dome forming test. The $m$ values were obtained by using the strain ratio eq. (9) between every two domes (D1, D2, D3 and D4 respectively). The $m$ value can be also obtained from the flow stress-strain rate curve by the differentiation. It is evident from the figure that the maximum $m$ value in multi-dome forming test is higher than in the tensile jump test and is shifted toward the high strain rate value.

5.1.3 Microstructure after deformation

Figure 8 shows the comparison microstructure of the Ti-alloy after the multi-dome and tensile tests. These figures show that there is a certain grain growth occurred in the tensile test specimen after the deformation, because the high temperatures and long testing times dictated by the low strain rates. At low strain rate, a tensile test specimen is deformed at a low crosshead speed and it takes long time until a steady load is registered. Whereas, there is no grain growth occurred in the multi-dome test specimen after the deformation compare to the original one due to shorter testing time than tensile jump test.

5.2 Results of FEM simulations

5.2.1 Estimated bulge-time

The bulge forming of domes was simulated by finite element method to verify the experimentally-obtained material characteristics from the multi-dome forming test and from tensile step strain rate test. The material characteristics $m$ and $K$, which obtained from the experiments of multi-dome forming test and of the tensile test, were included in a special sub-routine, which defines the relationship between stresses and strain rates to characterize the superplasticity of the materials. The material parameters used in the FEM simulation are shown in Table 3. In the multi-dome forming test, the $m$ value at every dome apex was obtained from the $m = \log$ & curve obtained from the multi-dome forming test at the strain rate, which was calculated at apex of every dome. In the case of tensile test, $m$ value was obtained from the $m = \log$ & curve at the same strain rate obtained by multi-dome forming test. The $K$ value was obtained from the equation (2) for every dome. The material characteristics, $m$ and $K$, were assumed to be constant in the FE simulation of every one dome.

Figures 9(a) and (b) show the FEM estimated bulging time for the multi-dome forming test and for the tensile test compared to the bulging time of the multi-dome forming experiments. (a) refers to experiment one (0.7 MPa) for Ti-alloy “SP-700” and (b) refers to experiment one (0.7 MPa) for Al-alloy “A5083”. It can be seen in these figures that there is a notable difference in the estimated bulging time of the dome forming simulation with $m$ and $K$ from the tensile test, as compared with the bulging time of the actual experiments, whereas the estimated bulging time of the dome forming simulation with $m$ and $K$ from the multi-dome forming test is in relative agreement with that of the experiments. The error in the estimated bulging time for the multi-dome forming for
Table 3  Superplastic material parameters used in the FEM simulation.

| Material | Dome No. | Multi-dome | | Tensile test | |
|----------|----------|------------|---------------|---------------|
|          | m        | K          | m             | K             |
| SP-700   | D1       | 0.567      | 765           | 0.515         | 1186          |
|          | D2       | 0.643      | 1272          | 0.559         | 1668          |
|          | D3       | 0.679      | 1646          | 0.590         | 2138          |
|          | D4       | 0.686      | 1732          | 0.613         | 2660          |
| A5083    | D1       | 0.540      | 187           | 0.499         | 193           |
|          | D2       | 0.580      | 273           | 0.585         | 385           |
|          | D3       | 0.620      | 380           | 0.621         | 527           |
|          | D4       | 0.622      | 381           | 0.627         | 578           |

both materials SP-700 and A5083 is less than 10%, whereas the error in the estimated bulging time for the tensile test is more than 160% for SP-700 and is more than 85% for A5083 in all the experiments.

5.2.2 Estimated wall thickness distribution

Figures 10 and 11 show the estimated wall thickness distribution for the multi-dome forming test and for the tensile test, compared to the estimated wall thickness distribution of the multi-dome forming experiments. Figure 9 refers to SP-700 and Fig. 10 refers to A5083. In these figures, there is no great difference observed in the estimated wall thickness distribution between the multi-dome forming test and the tensile tests, but the estimated wall thickness distribution of the multi-dome forming results is in closer agreement with the actual experiments than are the results of estimated wall thickness distribution for the tensile tests.

Akkus reported that the strength coefficient, K, has strong influence on the estimation of the bulging time and the deformation rate. The thickness distribution and the bulge shape were not highly influenced by K value. The m was alone responsible to change the bulging shape and thickness distribution of the bulged part. The strain-rate sensitivity index, m, plays significant role in the FEM estimated final thickness distribution and in the FEM estimated bulging time, but the effect of m value on the estimation of bulging time is greater than its effect on the estimation of final thickness distribution. Therefore, the estimated bulging time is affected by the both factors m and K, while the thickness distribution is affected only by the m factor. For this reason the difference in the estimated bulging time between the multi-dome forming test and the tensile test is greater than the difference in the estimated final thickness distribution.

6. Conclusion

The superplastic characteristics of Ti-alloy “Ti–4.5Al–3V–2Fe–2Mo” and Al-alloy “A5083” have been evaluated by multi-dome forming test and the results were compared with the more commonly used tensile step strain rate test. As a result, multi-dome forming tests revealed lower superplastic flow stress than tensile step strain rate tests. From the microstructure, there is certain gain growth was observed in tensile test specimen after deformation. Whereas, there is no gain growth was occurred in the multi-dome test specimen compare to the original one. FEM simulation was per-
formed to examine the accuracy of the material characteristics obtained from multi-dome and tensile test. The results of FEM simulations revealed that material characteristics obtained from multi-dome forming test are more suitable to simulate the deformation process especially for the estimation of the forming time.
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REFERENCES