Estimation of Plateau Stress of Porous Aluminum Based on Mean Stress on Maximum-Porosity Cross Section

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1. Introduction

Porous aluminum is expected to be applied as a multifunctional material in various industrial fields because of its lightweight and high energy absorptivity.1,2 When a compressive load is applied to porous aluminum, the cell walls between the pores are subject to high compressive stress and deform locally, and substantial deformation proceeds layer by layer.3 Through the continuous formation of these deformed layers perpendicular to the direction of compressive loading, a plateau region with approximately constant compressive stress appears. The plateau stress is defined as the average value of compression stresses for a compressive strain of 0.2–0.3, and the energy absorption $E_V$ can be evaluated for a compressive strain of 0–0.5 by the following equation:

$$E_V = \int_{\varepsilon=0}^{\varepsilon=0.5} \sigma \, d\varepsilon,$$

where $\sigma$ is the compressive stress and $\varepsilon$ is the compressive strain.4 Therefore, plateau stress is closely related to the amount of energy absorption. That is, if the plateau stress of porous aluminum can be estimated by a simple process, we can evaluate the energy absorptivity comparatively easily.

In this study, we fabricated ADC12 porous aluminum by the FSP (friction stir processing) route precursor method5–7 from ADC12 aluminum alloy die castings containing a large amount of gases. Through the X-ray computed tomography (CT) observation of the fabricated ADC12 porous aluminum and a commercially available porous aluminum (ALPORAS, Shinko Wire Company Ltd.),8 the porosities on the cross section perpendicular to the direction of compression loading were evaluated. Moreover, compressive tests were carried out on the porous aluminum specimens to evaluate the plateau stresses. Considering that a locally deformed layer is formed in the plateau region and the porosity greatly affects the value of the plateau stress, we simply assume that when the mean true compressive stress on a maximum-porosity cross section perpendicular to the direction of compressive loading reaches the critical value, a locally deformed layer appears and the nominal compressive stress becomes equal to the plateau stress. Through the comparison of compressive test results with the estimated results obtained according to this assumption, it was shown that the plateau stress can be evaluated approximately when the proof stress is used as the critical value.

2. Experimental Procedure

2.1 Compression specimens of porous aluminum

In this study, two types of porous aluminum were used. One was porous aluminum fabricated using Al–Si–Cu aluminum alloy ADC12 (equivalent to A383.0 aluminum alloy) die castings and the other was a commercially available porous aluminum (ALPORAS). In the fabrication of ADC12 porous aluminum, two types of ADC12 plate with total amounts of contained gases of 93.7 cm$^3$/100 g Al and 195.2 cm$^3$/100 g Al were used. The amounts and types of gases in the two types of ADC12 plates are shown in Table 1. The fabrication process of ADC12 porous aluminum is described below.9,11

Figure 1 shows a schematic illustration of the process used to fabricate the foamable precursor by the FSP route. Two ADC12 plates, A and B, of 3 mm thickness and 70 mm width were laminated with stabilization agent powder (α-Al$_2$O$_3$, H$_2$, N$_2$, CH$_4$, CO, CO$_2$, C$_2$H$_4$, C$_2$H$_6$ Total)

Table 1 Amounts and types of gases in ADC12 aluminum alloy die castings (cm$^3$/100 g Al).

<table>
<thead>
<tr>
<th>Type 1</th>
<th>H$_2$</th>
<th>N$_2$</th>
<th>CH$_4$</th>
<th>CO</th>
<th>CO$_2$</th>
<th>C$_2$H$_4$</th>
<th>C$_2$H$_6$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.9</td>
<td>37.6</td>
<td>8.2</td>
<td>4.6</td>
<td>27.6</td>
<td>4.8</td>
<td>1.0</td>
<td>93.7</td>
</tr>
<tr>
<td>Type 2</td>
<td>84.5</td>
<td>1.9</td>
<td>26.0</td>
<td>23.1</td>
<td>44.5</td>
<td>13.5</td>
<td>1.8</td>
<td>195.2</td>
</tr>
</tbody>
</table>
1 µm) distributed between them (cf. Figure 1(a)). As shown in Figs. 1(b)–1(d), the probe of a rotating tool was inserted into plates A and B, and multipass FSP of 5 lines × 4 passes was applied to obtain a larger precursor and to mix the gases and powders thoroughly \(^{10,11}\) using an FSW machine (SHH204-720, Hitachi Setsubi Engineering Co., Ltd.). Moreover, as shown in Fig. 1(e), after the plate joined by FSP was turned over, \(\alpha\)-Al\(_2\)O\(_3\) powder was placed on the reverse side of the FSP surface and one more ADC12 plate (C) was stacked on the joined plate. Then, as shown in Figs. 1(f) and 1(g), the same FSP procedures as those in Figs. 1(c) and 1(d) were carried out to obtain a thick precursor, and the foamable precursors were cut from the stirred region. On the cross sections of the precursors, few cavities or gas pores were observed by visual inspection. The foamable precursors were heated in a preheated electric furnace. The holding temperature and holding time during the heating process were fixed at 948 K and 12–13 min, respectively. Three precursors made from ADC12 plates with a gas content of 93.7 cm\(^3\)/100 gAl and five precursors made from ADC12 plates with a gas content of 195.2 cm\(^3\)/100 gAl were foamed. The foamed samples were cut by electro-discharge machining to obtain three compression specimens with dimensions of 15 mm × 15 mm × 15 mm for ADC12 plates with a gas content of 93.7 cm\(^3\)/100 gAl and five compression specimens with dimensions of 20 mm × 20 mm × 20 mm for ADC12 plates with a gas content of 195.2 cm\(^3\)/100 gAl. The compression specimens of ALPORAS were cut from a large ALPORAS block by electro-discharge machining, and 11 specimens with dimensions of 25 mm × 25 mm × 25 mm were fabricated. As examples of the compressive specimens, Figs. 2(a) and 2(b) show an ADC12 specimen with a gas content of 195.2 cm\(^3\)/100 gAl and an ALPORAS specimen, respectively. The cracklike pores cannot be seen in the specimens and the pore structures were comparatively good.

The porosity \(p (\%)\) of each compression specimen was calculated by the following equation:

\[
p = \frac{\rho_f - \rho_i}{\rho_i} \times 100,
\]

where \(\rho_f\) is the density of the porous aluminum and \(\rho_i\) is the density of the foamable precursor before heating. \(\rho_f\) was calculated by measuring the mass and the dimensions of the porous aluminum. \(\rho_i\) for ADC12 was evaluated by Archimedes’ principle, and the density of pure aluminum \(^{12}\) was used as the value of \(\rho_i\) for ALPORAS.

### 2.2 Compressive tests

The compressive test for each compression specimen was carried out at room temperature using an Instron type testing machine with a load capacity of 98 kN. The relative velocity between the cross head and the screw rod was set at 1 mm/min. The deformation state of the test specimen under compressive loading was observed by video imaging from a single direction. The plateau stress was evaluated using the relationship between the compressive stress and compressive strain obtained as the test result.

### 2.3 X-ray CT observations

Each compression specimen was scanned by a microfocus X-ray CT system (SMX-225CT, Shimadzu Corporation). In this system, the X-ray source was tungsten and cone-type CT was employed. The X-ray tube voltage and current used in the inspection were 80 kV and 30 µA, respectively. The resolution of the two-dimensional cross-sectional X-ray CT image was 512 × 512 pixels, and the lengths per pixel for the ADC12 and ALPORAS specimens were approximately 58 µm and 76 µm, respectively. Due to the resolution of X-ray CT image, pores with diameters below approximately 58 µm for ADC12 specimens and 76 µm for ALPORAS specimens cannot be observed. \(^{13}\) Ohgaki et al. pointed out that there are a huge number of micropores with a mean diameter of 3.6 µm in the cell walls. \(^{14}\) Therefore, it is considered that many of these micropores could not be detected by the X-ray CT system used in this study.

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**Fig. 1** Schematic illustration of fabrication process of foamable precursor for ADC12 porous aluminum by FSP route.

**Fig. 2** Compressive specimens: (a) ADC12 (gas content: 195.2 cm\(^3\)/100 gAl) and (b) ALPORAS.
Fig. 3 Compressive state of ALPORAS specimen with $p = 89.8\%$: (a) initial pore structure, (b) mean true compressive stress distribution on cross section and (c) pore structure at compressive strain of $\varepsilon = 12\%$.

In this study, a threshold was set for all the two-dimensional cross-sectional X-ray CT images, so that the cell walls could be clearly observed. From the obtained binarized images, the porosities on the cross section were evaluated by distinguishing the aluminum and the pores using image-processing software (WinROOF, Mitani Corporation). Moreover, the equivalent diameter $d$ was evaluated by the following equation:

$$ d = 2\left(\frac{A}{\pi}\right)^{\frac{1}{2}}, \quad (3) $$

where $A$ is the area of each pore. In the evaluations, pores with area less than 1.0 mm$^2$ were excluded owing to the resolution of the X-ray CT images. From the average values of $d$ for all pores in each specimen, the average equivalent diameter $d_m$ was calculated. As a result of these threshold setting procedures, it is considered that the values of $d$ and $d_m$ (i.e., the areas of pores) are slightly underestimated.

### 3. Estimation of Plateau Stress

The porosities $p$ evaluated by eq. (1) for the ADC12 specimens were 67–71% for the ADC12 plates with a gas content of 195.2 cm$^3$/100 gAl and 49–50% for the ADC12 plates with a gas content of 93.7 cm$^3$/100 gAl. Those of the ALPORAS specimens were 88–90%. The average equivalent diameters $d_m$ of the ADC12 specimens were 0.93–1.08 mm and those of ALPORAS specimens were 2.2–2.7 mm. As shown in Fig. 2, the pore structures are comparatively good, then we consider that the errors due to the variations of the pore structures are not so large on the estimation of the plateau stress. As examples of the deformation states of the compressive test specimens, Fig. 3 shows those of an ALPORAS specimen with porosity $p = 89.8\%$. Figures 3(a) and 3(c) show the initial pore structure and the deformation state at a compressive strain $\varepsilon$ of 12%, respectively. Figure 3(b) shows the distribution in the height direction of the mean true compressive stress $\sigma_l$ on each cross section (perpendicular to the direction of compressive loading) evaluated by the following equation:

$$ \sigma_l = \frac{\sigma_0}{(1 - p_l)}, \quad (4) $$

where $\sigma_0$ is the nominal compressive stress applied to the specimen and $p_l$ is the porosity on each cross section perpendicular to the direction of compressive loading. In Fig. 3(b), $\sigma_l$ is normalized by $\sigma_0$; thus, the distribution of $\sigma_l/\sigma_0$ corresponds to that of $1/(1 - p_l)$. From Figs. 3(a)–3(c), it is found that the deformation in the plateau region of porous aluminum occurs in a layer (cf. the gray shaded layer) including the maximum value $\sigma_{l\text{max}}$ and the porosity on each cross section $p_l$ most greatly affects the value of the plateau stress.

From the above results, using the maximum value $\sigma_{l\text{max}}$ of $\sigma_l$ as the typical parameter for the deformed layer, we simply assume the following.

(1) When the mean true compressive stress on a maximum-porosity cross section perpendicular to the direction of compressive loading $\sigma_{l\text{max}}$ reaches the critical value $\sigma_{cr}$, a locally deformed layer and plateau stress appear.

(2) The nominal compressive stress when local deformation occurs is equal to the plateau stress $\sigma_{pl}$.

From these assumptions, the plateau stress $\sigma_{pl}$ can be estimated by the following equation:

$$ \sigma_{pl} = \sigma_{l\text{max}}(1 - p_{l\text{max}}) = \sigma_{cr}(1 - p_{l\text{max}}), \quad (5) $$

where $p_{l\text{max}}$ is the maximum porosity on the cross section perpendicular to the direction of compressive loading.

As an example of the relationship between the distance $x$ from the top of a specimen, as shown in Fig. 2(b), normalized by the height $h$ of the specimen, and the local porosity $p_l$ on the $x$-section evaluated from X-ray CT images, Fig. 4 shows the result for the ALPORAS specimen with porosity $p = 89.8\%$. From these figures, $p_{l\text{max}}$ can be obtained for each ADC12 and ALPORAS specimen. However, as shown in Fig. 4, the porosity evaluated using the X-ray CT images was generally lower than the porosity over the entire specimen evaluated by eq. (2). This is mainly due to the resolution of the X-ray CT images, in which micropores are almost undetectable and the areas of pores are slightly underestimated, as mentioned in section 2.3. Thus, $p_l$ was modified by using the following equation, so that the porosity over the entire specimen evaluated using the X-ray CT images coincided with that evaluated by eq. (2):

$$ (p_l)_{\text{modified}} = p_l \cdot \frac{p}{\bar{p}_l}, \quad (6) $$

where $p$ is the porosity over the entire specimen evaluated by eq. (2) and $\bar{p}_l$ is the porosity over the entire specimen evaluated using the X-ray CT images. The value of $(p_{l\text{max}})_{\text{modified}}$ was evaluated from the distribution of
We consider that the distributions of \( p_l \) modified and the value of \( p_{l_{\text{max}}} \) modified have little errors at least which greatly affect on the estimation result of the plateau stress. This value of \( p_{l_{\text{max}}} \) modified was used as the maximum value \( p_l \).

### 4. Estimation Results and Discussion

As the values of \( \sigma_{\text{cr}} \), the 0.2\% proof stress \( \sigma_p \), and flow stress \( \sigma_f \) were employed. The flow stress \( \sigma_f \) is defined by the following equation:\(^{16}\)

\[
\sigma_f = \frac{\sigma_p + \sigma_t}{2},
\]

where \( \sigma_t \) is tensile stress.\(^{12,15}\) These stresses were adopted for convenience as the parameters related to plastic collapse. Figures 5(a) and 5(b) show the relationships between the results estimated by eq. (5) (lines) and the experimental results for the plateau stresses of the ADC12 and ALPORAS specimens, respectively. In these figures, as references, the results (lines) corresponding to \( \pm 20\% \) error of the estimated results for \( \sigma_f \) are also shown (cf. the lines for 0.8\( \sigma_p \) and 1.2\( \sigma_p \) in Fig. 5). The variation of the experimental results was slightly large owing to the scattering of the pore structures in porous aluminum. However, it can be considered that the experimental results show a similar tendency, i.e., \( \sigma_{p_l} \) decreases with increasing \( p_{l_{\text{max}}} \) to the estimated results (lines) and mostly exist in the range of \( \pm 20\% \) of the estimated result for \( \sigma_p \). The estimated results for \( \sigma_f \) closely corresponded to the maximum value in the experimental results. Obviously, further study on this method of estimating the plateau stress is necessary to improve the estimation accuracy by considering the effects of the pore structures which were not discussed in this study. Also, further improvement of the fabrication method to control the pore structures to reduce the variation in the plateau stresses of porous aluminum with almost the same porosity is necessary. However, by simply assuming the appearance of plateau stress as mentioned above, the plateau stress \( \sigma_{p_l} \) of porous aluminum can be approximately estimated from the mean true compressive stress on a maximum-porosity cross section perpendicular to the direction of compressive loading \( \sigma_{l_{\text{max}}} \) when \( \sigma_p \) is used as the critical value.

### 5. Conclusions

In this study, considering the continuous occurrence of a locally deformed layer in the plateau region of porous aluminum, the following simple assumption was proposed. When the mean true compressive stress on a maximum-porosity cross section perpendicular to the direction of compressive loading reaches the critical value, a locally deformed layer appears and the nominal compressive stress becomes equal to the plateau stress. This assumption was applied to the experimental results for ADC12 porous aluminum and ALPORAS, and it was shown that the plateau stress \( \sigma_{p_l} \) can be approximately estimated from the mean true compressive stress on a maximum-porosity cross section when the proof stress is used as the critical value.

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