Foaming and Filling-in Behavior of Porous Aluminum in Hollow Components

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Porous aluminum (aluminum foam) was fabricated by a powder processing route. TiH$_2$ powder was blended with Al powder as a blowing agent. The blended powder was then consolidated to make a precursor. When the precursor was heated, the TiH$_2$ powder started to decompose and hydrogen gas expanded in molten aluminum. Physical properties of the porous aluminum strongly depend on both porosity and pore morphology. In this research, pore morphology was characterized by an image analyzing software. Manufacturing temperature and heating time affected the pore morphology significantly. The manufacturing temperature should be in an adequate range. When the manufacturing temperature was low, the precursor did not expand sufficiently. The life-time of the pores became shorter when the temperature was too high. Although the pores at the initial stage of the blowing process were small (<0.5 mm) and relatively spherical, the pores become larger and irregular as the heating time became longer. A molding technique of porous aluminum in hollow parts becomes indispensable when porous aluminum is applied to automobile components. The precursor was heated in a hollow pipe and the specimen was cut in both vertical and horizontal sections to investigate the filling-in behavior of the precursor. In the beginning of the expansion, the precursor expanded in a radial direction of the pipe. After the cross section of the pipe was filled, then the precursor expanded along the longitudinal axis. Heating profile was one of the most important factors which determines the possibility of filling-in behavior and the porosity of porous aluminum. Another important factor turned out to be an aspect ratio of the precursor. [doi:10.2320/matertrans.47.2178]

1. Introduction

Reductions of the vehicle weight and CO$_2$ in emission gas are strongly required since the concern to the environmental issue increases. Moreover, both the rigidity of the body and improvement in the impact energy absorption are also required simultaneously. Porous metals are regarded as materials which can strike a balance between low density and high rigidity at the same time. Among many porous metals, porous aluminum shows high porosity and low density. Since the porous aluminum has the unique structure containing many closed pores inside, it shows some interesting features as shown below.

- Lightweight (specific gravity: <1.0)
- High rigidity compared with the same material of the same weight
- High energy absorption
- Low thermal conductivity
- High damping capacity

One of the techniques of manufacturing the porous aluminum is a precursor method which uses a foaming agent (titanium hydride: TiH$_2$). By this precursor method, the precursor is made after appropriate quantity of foaming agent is blended with aluminum powder. When the precursor is heated, the foaming agent decomposes and pores are formed in molten aluminum, which results in the fabrication of the porous aluminum. Physical and mechanical properties of porous aluminum are strongly influenced by pore morphology. When porous aluminum is applied to automobile components, a molding technique in hollow parts becomes indispensable. Pore morphology significantly influences mechanical properties of the integrated components (porous aluminum + hollow parts). Therefore, analysis of pore morphology and development of a controlling process are important. In this paper, foaming and filling-in behavior of the precursor was investigated aiming at making the integrated components, and controlling the pore morphology.

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Cu</th>
<th>Fe</th>
<th>Si</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Ni</th>
<th>Cr</th>
<th>Ti</th>
<th>Al</th>
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</thead>
<tbody>
<tr>
<td>Mass%</td>
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<td>0.08</td>
<td>6.86</td>
<td>TR</td>
<td>TR</td>
<td>TR</td>
<td>TR</td>
<td>TR</td>
<td>TR</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

TR $\leq$ 0.01%

2. Experimental Procedure

Al-7Si powder was used for making precursors and the chemical composition of the Al-7Si powder is shown in Table 1. Titanium hydrate powder (TiH$_2$, <45 µm) was used as a blowing agent. TiH$_2$ powder was blended with the Al-Si powder by 1 mass%. The blended powder was then consolidated to make a precursor either by hot compaction or by hot extrusion. The foaming behavior of the precursor alone was evaluated by the hot compacted precursor, and the filling-in behavior in the hollow tube was evaluated by the extruded precursor. The precursors were heated in an infrared furnace as shown in Fig. 1. The blowing behavior of the precursor was recorded by a camera and evaluated by a relative projected area ($A_p$) defined by the following equation.

$$\text{Relative Projected Area (A_p)} = \frac{\text{Projected Area of Precursor during Foaming}}{\text{Initial Projected Area of Precursor}}$$

The pore morphology was observed by an optical microscope and pore size (diameter of equivalent-area circle) and circularity were evaluated by an image analyzing software. Circularity was calculated by the following equation.

$$\text{Circularity} = 4\pi \times \frac{\text{Pore Area}}{\text{Peripheral Length}^2}$$

The circularity was calculated to be 1.0 when the pore morphology was completely spherical, whereas it was close to 0.0 when the pore morphology was irregular. Porosity was measured by an Archimedes method.
3. Result

3.1 Blowing behavior of Al-7Si/TiH\textsubscript{2} precursor

Figure 2 shows the relative projected area of the powder compacted Al-7Si/TiH\textsubscript{2} precursor as a function of heating time to identify the blowing behavior of the precursor. The manufacturing temperature was 883 K. The precursor started to expand at around 860 K (melting point of eutectic Al-Si alloy) and the maximum expansion was achieved during the holding period at 883 K. Figure 3 shows the relative projected area of the precursor heated at different temperatures. The expansion started at 860 K with every specimen. Once the projected area reached the maximum peak, the specimen manufactured at 903 K shrunk rapidly. Even though the maximum projected area of the specimen manufactured at 883 K was lower, the maximum expansion was sustained for a longer period of time (about 300 s). The same tendency was observed when the manufacturing temperature was 863 K. These results indicate that the high holding temperature resulted in high but unstable expansion. Figure 4 shows relative projected area of Al-7Si/TiH\textsubscript{2} precursor during heating process (manufacturing temperature: 883 K) and scatter diagram between circularity and diameter of the specimens cooled at (a) the beginning and (b) the end of the maximum expansion.
during heating process (manufacturing temperature: 883 K) and scatter diagram between circularity and diameter of every observed pores for the specimens cooled at (a) the beginning and (b) the end of the stable peak expansion. By comparing Figs. 4(a) and (b), it is understood that the pore size was relatively small (<3 mm) and the morphology was more spherical (circularity > 0.4) at the beginning of the peak expansion in comparison with the end of the peak expansion. The pores were continuously growing and incorporating each other in the precursor even though the expansion of the precursor (relative projected area) observed from the external view was constant. This suggests that the heating time is an important factor and should be short enough to create fine and homogeneous pore morphology.

3.2 Foaming behavior of precursors of different sizes

During the blowing process, pores are born, grow and finally disappear by sedimentation of molten aluminum (drainage). The life-span of the pore is strongly affected by the size of precursor because the drainage is dominated by the movement of pores caused by gravity. Therefore the size of the precursor is an important factor which determines the stability of pores. Figure 5 shows the porosity of the aluminum foam fabricated from two different-sized precursors (Precursors S and L) The shape and size of the precursors S and L are illustrated in Fig. 5. By using the large precursor, a decrease in porosity after peak expansion was restrained. However, the pore size increased during the holding time as shown in Fig. 6. Hence, when the size of the precursor is large enough to maintain the stability of pores, the size of the pores were affected by the heating time.

3.3 Filling-in behavior of precursor in hollow pipe

To investigate the blowing and filling-in behavior of the precursor in a hollow pipe, a steel pipe and an extruded precursor was inserted in a furnace (furnace temperature: 973 K) as illustrated in Fig. 11(b). The diameter and the length of the precursor before expansion was 12 and 100 mm, respectively, and a thermocouple was embedded in the precursor to monitor the precursor temperature. Figure 7 shows the cross-section of the specimen cooled at various precursor temperatures ranging from 883 K to 943 K, which shows a blowing and filling-in behavior of the extruded precursor. It was apparent that the precursor expanded in the radial direction first (Fig. 7(a)). After the radial cross section of the hollow tube was fully filled by the porous aluminum, then the precursor started to expand in the longitudinal axial direction (Figs. 7(b) and (c)). However, after the maximum expansion, the precursor started to shrink and the drainage was observed (Figs. 7(d) and (e)). It is apparent that the interface between porous aluminum and steel pipe was debonded as the aluminum foam started to shrink.

3.4 Filling in behavior of different shape precursors

Since the precursor could expand in the longitudinal direction, the aspect ratio of the precursor was one of the most important parameters affecting the pore structures.
Figure 8 shows the cross sections of the foam filled pipe made from precursors with two different aspect ratios. Homogeneous pore morphology was achieved with the relatively higher aspect-ratio precursor. With a low-aspect-ratio precursor, the radial direction tended to be filled quickly and the precursor needed to expand longer in the longitudinal axial direction and, therefore, the drainage was clearly observed at both ends of the specimen. However, by using high-aspect-ratio precursor, the precursor did not expand in a longitudinal direction, and the severe drainage was not observed at both ends.

3.5 Filling in behavior of multiple precursors

To make a large porous component, preparation of a large scale precursor is indispensable. However, it is technically more difficult to make a larger scale precursor than to make a smaller one by a powder processing technique. In order to avoid preparing the large precursor, two precursors were located side by side in a hollow pipe. Figure 9 shows the layout of the two precursors and cross sections of the aluminum foam cooled at various temperatures in between 853 and 953 K to observe the blowing behavior of multiple precursors in a single hollow pipe. At 853 K, expansion of the two precursors was observed but a boundary between them were still visible. As temperature of the precursor increased and the liquid phase appeared (873 K), the boundary started to disappear which indicates that the two precursors were united in one porous body. After the precursors were united, the blowing behavior of the specimen was quite similar to that of the single precursor. Figure 10 shows the porosity of porous aluminum at various points along the longitudinal direction. Similar to the blowing behavior of single precursor, high porosity was achieved at the center part and the drainage was observed at both ends of the precursor. To evaluate the radial filling-in rate, the projected area observed along the longitudinal axis was recorded. The specimen after cooling was cut along the longitudinal axis to evaluate the axial expansion rate. Radial filling-in rate and axial expansion rate of the precursors were calculated from the following equations.
Radial Filling-in Rate
\[ = \left( \frac{\text{Projected Area of Precursor}}{\text{Cross Sectional Area of Pipe}} \right) \times 100 \]

Axial Expansion Rate
\[ = \left( \frac{\text{Elongation of Precursor}}{\text{Initial Length of Precursor}} \right) \times 100 \]

Figure 11 shows the radial filling-in rate and axial expansion rate as a function of heating time. Similar to the blowing behavior of a single precursor shown in Fig. 7, the pipe was filled along the radial direction first. After the radial section was filled, the precursor expanded along the axial direction. Therefore, the aspect ratio of the precursor should be appropriate in order to achieve a homogeneous distribution of pores and to avoid the drainage at the end part.

4. Conclusions

Porous aluminum and its integrated components (porous aluminum + hollow pipe) were made by a precursor method. The foaming and filling-in behavior was investigated and the results shown below were obtained.

(1) Heating temperature (manufacturing temperature) is an important parameter for the foaming behavior. High manufacturing temperature brings the high but unstable (short-time) expansion. To improve the pore stability during manufacturing process, the temperature should be in an appropriate range.

(2) By using the large scale precursor, the life-span of the pores became longer and the size tended to be larger.

(3) In the beginning of the expansion, the extruded precursor expanded in a radial direction. After the radial pipe section was filled, the precursor expanded along the longitudinal axis.

(4) Even though the precursor expanded along the longitudinal direction, the aspect ratio of the precursor should be high to achieve the homogeneous pore distribution and to avoid the drainage.

(5) During the expansion, multiple precursors were united in one foam and no boundary between the precursors were visible at temperatures above 873 K. The blowing behavior of the united foam was quite similar to the single precursor.

REFERENCES