Producing Technology of Aluminum Foam from Machined Chip Waste

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The present study focuses on the investigation of the possibility of producing aluminum foam from low cost machined chip waste. To produce highly porous aluminum, manufacturing process of precursor, the effect of TiH<sub>2</sub> content and the effect of ceramic particle addition were examined. In the study of precursor manufacturing processes, precursors fabricated by extrusion process did not expand sufficiently and the pore morphology was very irregular. In contrast, precursors fabricated by compressive torsion processing satisfactorily expanded and the pore morphology was uniform. There was an adequate range of TiH<sub>2</sub> addition. The increase of TiH<sub>2</sub> content more than 3 mass% was not an effective way to produce highly porous aluminum foam. Addition of fine Al<sub>2</sub>O<sub>3</sub> particle resulted in a significant increase in foam expansion.

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1. Introduction

Aluminum foam is known to have many interesting physical and mechanical properties such as high energy absorption and high stiffness with very low specific weight. These potentials make porous materials attractive to a wide range of industries, including automotive and construction fields. Aluminum foam can be manufactured in either the liquid or solid state. In solid state processing, metal powder containing a foaming agent like TiH<sub>2</sub> is consolidated by hot pressing, extrusion or other compacting methods. Then the foamy precursor is heated above its melting point, the foaming agent decomposes, and releases gas, resulting in expansion of the semi-liquid viscous compact and a foam structure containing a large number of closed-pores. This manufacturing technique has the advantage of the possibility for producing near-net-shape components of aluminum foams. However, in order to put the aluminum foams in a practical use, producing cost and material reliabilities are still important key issues. For the cost reduction, it is effective to replace relatively expensive aluminum powders with cheap raw materials.

The aim of the present work is to investigate the possibility of producing aluminum foams from low cost machined chip waste via solid-state consolidation process. To produce highly porous aluminum foam, it is necessary to achieve both firm consolidation of the precursor and homogeneous dispersion of a foaming agent in the precursor. When using machined chips instead of aluminum powder, it is quite difficult to blend small TiH<sub>2</sub> powder with machined chips by a conventional method because of a big difference in size and shape of these materials. Furthermore, it is difficult to make firm consolidation precursor from machined chips due to their irregular shape, large size (longer than 10 mm in length), and surface contamination with oxides. Aiming at solving these difficulties, we researched an extrusion process and a compressive torsion process for producing well foamyable precursor from machined chips. The effects of foaming agent content and the addition of fine ceramic particles on the foaming of the precursor were also studied in the present work.

2. Experimental Procedure

2.1 Materials

Al-Mg-Si (A6063) alloy machined chip wastes used in this experiment are shown in Fig. 1. Titanium hydride powder (TiH<sub>2</sub> < 45 μm) was used as a foaming agent. Machined chips were cleaned with an acetone solution by ultrasonic cleaning. The machined chips and the TiH<sub>2</sub> powder were mixed using an organic adhesive.

To study the effect of TiH<sub>2</sub> content, TiH<sub>2</sub> powder content was changed from 0.5 to 3.0 mass%. To study the effect of addition of ceramic particles, fine Al<sub>2</sub>O<sub>3</sub> powder (2–3 μm) was added to the chip/TiH<sub>2</sub> mixture by 3 to 5 vol%.

Aiming at comparing the foaming behavior of machined chip precursor with conventional powder route precursor, Al-Mg-Si (A6061) alloy powder (<135 μm) was selected and mixed with 0.5 mass% TiH<sub>2</sub> powder.

2.2 Precursor consolidation

The chip/TiH<sub>2</sub> mixture was consolidated by hot extrusion and compressive torsion processes to produce foamyable precursors. The hot extrusion was carried out at 723 K by extrusion ratio of 16 and 31 after cold compaction (100 MPa). By the extrusion, rectangular rod precursors with cross-section of 8 mm × 10 mm and 4 mm × 10 mm were pro-
duced. The powder mixture was also consolidated by the hot extrusion to the rectangular rod (cross-section; $8 \times 10$ mm).

Figure 2 shows an appearance of the compressive torsion processing. Upper and lower dies can rotate in the reverse direction to give a torsional load with a vertical compressive load. The specimen is subjected simultaneously to compressive and torsional loading between upper and lower dies in a container. Top faces of upper and lower dies are rugged within 1 mm depth so that the torsional loading can be sufficiently given to the specimen. To use torsional loading, very large share deformation was delivered to the machined chips effectively in a short period of time. The chip/TiH$_2$ mixture was consolidated by the compressive torsion processing (temperature; 723 K, compression; 100 MPa, rotation repetition; 0–30) to cylindrical precursor ($4 \times 40 \times 10$ mm). For foaming experiment, the cylindrical precursors were cut off to $8 \times 25$ mm specimens from a center part and a peripheral part.

The consolidation condition and distribution of TiH$_2$ particles of the precursors produced by both processes were observed by an optical microscopy. For observing the consolidation condition, the specimens were chemically etched by Kellers etchant.

2.3 Foaming

Consolidated precursors were heated in an infrared furnace (holding temperature 973 K) and they were taken out from the furnace when the maximum expansion occurred. Porosity of the foamed specimen was measured by an Archimedes method, and the pore morphology was observed and evaluated.

3. Results

3.1 Precursor manufacturing methods

3.1.1 Hot extruded precursor

Figure 3 shows the cross section of the specimens foamed from the precursors manufactured by the extrusion process from machined chips and powder alloy. As for foamed aluminum made from the powder alloy, the size and shape of the pores were uniform and its porosity was very high (porosity; 76%). In contrast, as for foamed aluminum made from the machined chips, the size and shape of the pores were very irregular and its porosity was very low (porosity 46%; ratio 16, porosity 60%; ratio 31).

Figure 4 shows the optical micrographs of the cross section of the chips precursor (without TiH$_2$) consolidated by the hot extrusion process. Many chip boundaries were observed along the extrusion direction, showing each chip could not be well-consolidated by the hot extrusion. This result indicates that the gases released from the TiH$_2$ could not be entrapped fully in the specimen, and, therefore, the porosity became very low.

Figure 5 shows the optical micrographs indicating distribution of the TiH$_2$ particles in extruded precursors. As for extruded precursors from powder mixture, TiH$_2$ particles were dispersed homogeneously and no agglomeration of TiH$_2$ was observed. In contrast, as for extruded precursors from chip mixture, TiH$_2$ particles were aligned and agglomerated along the extrusion direction. It was difficult to achieve homogeneous dispersion of a foaming agent in the extrusion processes. As a result, pore coalescence occurred easily during the foaming process of these precursors, which made pore size larger and pore shape more irregular. To
realize high porosity and uniform pore distribution, it is important to achieve both firmer consolidation of a precursor and more homogeneous dispersion of a foaming agent.

### 3.1.2 Compressive torsion processed precursor

Figure 6 shows the relative density of the precursors manufactured by compressive torsion processing under various rotation repetitions. When the rotation repetition was 5, the relative density was 0.98. By increasing the rotation repetition, relative density rose and fully compacted precursor (relative density: 1.0) could be realized with the rotation repetition more than 10.

From geometrical reason of torsional loading, the shear deformation is varied along radial direction in the cylindrical specimen. The consolidation of chips, therefore, would be depending on the radial position in the processed specimen. Figure 7 shows the optical micrographs of the vertical cross sections of the chips precursors (without TiH$_2$) consolidated by compressive torsion processing with different rotation repetitions. When the rotation was 5, many chip boundaries were observed in a center part of the specimen, though firm consolidation with well-bonded chips was fabricated in a peripheral part. In contrast when the rotation repetition was 30, TiH$_2$ could be distributed homogeneously and no agglomeration of TiH$_2$ particle was observed even in the center part of the specimen. This indicates that the compressive torsion processing is effective to disperse TiH$_2$ particle homogeneously like the precursor produced from powder mixture due to the large plastic flow.

Figure 8 shows the optical micrographs of the compressive torsion processed precursor with TiH$_2$ addition, showing the distribution of TiH$_2$ particles. When the rotation repetition was 5, some agglomerations of TiH$_2$ powder was observed in a center part of the specimens. In contrast, no agglomeration of TiH$_2$ powder was observed in a peripheral part. When the rotation repetition was 30, TiH$_2$ could be distributed homogeneously and no agglomeration of TiH$_2$ particle was observed even in the center part of the specimen. This indicates that the compressive torsion processing is effective to disperse TiH$_2$ particle homogeneously like the precursor produced from powder mixture due to the large plastic flow.

Figure 9 shows the cross section of the specimens foamed from the compressive torsion processed precursors with different rotation repetitions. Specimens foamed from the center part of the precursor with the rotation repetition of 5 did not expand fully and its porosity became very low and irregular-shaped pores were observed. In contrast, specimens foamed from the peripheral part of the precursor expanded fully and its porosity increased and pore morphology became uniform. As for the rotation repetition of 30, porosity increased even in a center part of the specimens. Figure 10 shows the effect of the rotation repetition on porosity. The porosity of the specimen foamed from the precursor without
torsional loading (rotation repetition; 0) was 28%. In regard to the lower rotation repetition, porosity was different between the center part and the peripheral part, but this difference was improved by increasing the rotation repetition. By increasing rotation repetition, firm consolidated precursor was fabricated and TiH\(_2\) were dispersed homogeneously over the whole precursor, so the difference of porosity was improved. From these results, the compressive torsional processing can be concluded very useful to produce a foamable precursor from machined chip waste from a viewpoint of both firm consolidation of a precursor and homogeneous dispersion of TiH\(_2\).

### 3.2 Effect of TiH\(_2\) content

In this section, the effect of TiH\(_2\) content was investigated to increase the porosity. Precursor was fabricated by the compressive torsion processing followed by a hot extrusion to make a long rods precursor. Figure 11 shows the cross section of the specimens with different TiH\(_2\) content. Figure 12 shows the effect of TiH\(_2\) content on the porosity and the mean pore size. When TiH\(_2\) content was in between 0 mass% and 2.0 mass%, the porosity was increased with an increase in TiH\(_2\) content. But by increasing the TiH\(_2\) content to 3.0 mass%, pore coalescence occurred easily during the foaming process. So the mean pore size became larger, which could promote the severe drainage of molten aluminum. This result indicates that an increase of TiH\(_2\) content more than 3 mass% was not an effective way to produce highly porous aluminum.

### 3.3 Effect of ceramic particle addition

In this section, fine Al\(_2\)O\(_3\) particle (2–3 µm) was added at a level of 3–5 vol% to improve the foam stability and the porosity. The external view of the precursor during the foaming process was recorded by a camera and the foaming behavior was evaluated by a relative projected area (\(A_p\)) defined by the following equation.\(^8\)
Relative Projected Area \( (A_p) = \frac{\text{Projected Area}}{\text{Initial Projected Area}} \)

Figure 13 shows the relative projected area as a function of the holding time for the machined chip precursors with and without \( \text{Al}_2\text{O}_3 \) particles. The holding temperature was fixed to 973 K. The addition of \( \text{Al}_2\text{O}_3 \) particles resulted in a significant increase of the level of the maximum expansion.

Figure 14 shows the cross sections of porous aluminum foamed from machined chip precursors containing \( \text{Al}_2\text{O}_3 \) particle (a: 0 vol%, b: 3 vol%, c: 5 vol%). Figure 15 shows the effect of \( \text{Al}_2\text{O}_3 \) particle addition on the porosity and the mean pore size of the foamed aluminums. The both specimens with \( \text{Al}_2\text{O}_3 \) particle addition expanded higher than the one without \( \text{Al}_2\text{O}_3 \) addition. SEM images of pores in the foamed specimens with and without \( \text{Al}_2\text{O}_3 \) particles, as shown Fig. 16, revealed that the addition of \( \text{Al}_2\text{O}_3 \) particles reduces the minimum cell wall thickness in comparison with the specimen without \( \text{Al}_2\text{O}_3 \) particles. Most of \( \text{Al}_2\text{O}_3 \) particles attached to the gas/liquid interface (surface of cell walls) and modified its curvature. Some of \( \text{Al}_2\text{O}_3 \) particles were incorporated into the cell wall and inhibited the melt flow caused by an increase in the bulk viscosity.

It is effective to restrict the emission of the gas from the surface of the specimen for reducing the cell coarsening and the drainage. In the case of using aluminum powder for a precursor, fine oxide films of the powder plays an important role for the stabilization of cell structure. When machined chips were used instead of aluminum powder, it is conceivable that this stabilization mechanism cannot work fully. So the addition of the fine ceramic particle is very effective to make high porosity of porous aluminum foamed from machined chips.
4. Conclusions

The possibility of producing porous aluminum from low cost machined chip waste was studied. To produce porous aluminum with high porosity and uniform pores, the effects of precursor manufacturing process, TiH$_2$ content and Al$_2$O$_3$ particle addition were examined. The following results were obtained from this research.

1. The precursor manufactured by the extrusion process could not expand fully and its pore morphology tended to be irregular.
2. The precursor manufactured by the compressive torsion processing expanded largely and its pore morphology was uniform.
3. There was an adequate range in TiH$_2$ content for an effective foaming. The overdosage of TiH$_2$ was not an effective way to produce highly porous aluminum.
4. Addition of fine Al$_2$O$_3$ particle resulted in a significant increase in foam expansion. Porosity and pore morphology of specimens with Al$_2$O$_3$ addition were almost the same level of the foam made from aluminum powder precursor.

REFERENCES