Effects of Thermo-Mechanical Treatment on the Tensile and Compressive Properties of a Glass-Balloon-Dispersed Aluminum Alloy Composite

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A repeated thermomechanical treatment (RTMT) was adopted to control the microstructure of a glass-balloon-dispersed aluminum alloy (AC3A) composite. The RTMT, which involves the repetition of a multi-step process and followed by heat treatment, was applied to a cast plate of the composite. The composite was successfully worked into a rod or sheet by either swaging or flat rolling. The porous glass balloons were deformed or cracked so that the composite could be worked easily. The swaged material exhibited higher tensile strength, Young’s modulus, and elongation as compared to the cast material. The composite materials also exhibited excellent energy absorption properties.

Keywords: recycle, porous, lightweight, energy absorption, thermomechanical treatment

1. Introduction

Aluminum and its alloys are probably the most widely used matrix materials for metal matrix composites (MMCs).1) Although reinforcements in the form of continuous and discontinuous fibers have already been investigated in detail,2) discontinuous reinforcements such as those of dispersoids have also become more popular. Subsequent working of such dispersoid-reinforced MMCs can enhance their mechanical properties.3) Aluminum alloy/glass composites cast with glass particles of sizes in the range of several tens of micrometers have been fabricated and have exhibited superior mechanical properties with regard to strength and wear resistance.4,5)

Recently, various porous metals have been fabricated and their specific properties such as ultra-lightweight and low strength have been considered with more attention.6) Further, porous ceramics (e.g., Al2O3, ZrO2, TiO2, SiC, TiC, ZrC, etc.) have been used to develop ceramic matrix composites by various processing routes such as the melt stirring process and pressure infiltration technique.7–12)

Therefore, the dispersion of porous particles in a metal matrix is one of the methods employed to control the size and distribution of the cell structure in the composite. In fact, new recyclable materials composed of recycled aluminum and glass balloons have been developed13) and fabricated for building panels.14) However, in order to take the maximum advantage of their specific properties such as ultra lightweight and good electromagnetic shielding for mechanical or electronic parts, a workability that can deform them into any form is required. Since the balloon is a brittle second-phase particle, it is necessary to include either a thermomechanical treatment to plasticize the composite or perform near-net-shape casting. Umezawa et al.15) have developed a repeated thermomechanical treatment (RTMT) to refine the microstructure of Al-Si cast materials; the materials successfully obtained good plasticity by this treatment. In this study, the RTMT is adopted to control the microstructure of the glass-balloon-dispersed aluminum alloy (AC3A) matrix composite in order to achieve a satisfactory stress-strain relationship and ductility for the composite.

2. Experimental Procedure

2.1 Test material

The test material (AC) was a 10-mm-thick cast plate (Alclelite™, Naigai-Technos(14)), which consisted of a recycled glass balloon and aluminum alloy AC3A. The major compositions of the glass balloon were 68 SiO2, 6.3 Al2O3, 0.6 Fe2O3, 0.6 MgO, 9.5 CaO, 11.7 Na2O, and 1.3 K2O in mass%. The major properties of the AC and AC3A are listed in Table 1. Figure 1 shows the microstructure of the AC material and glass balloon. The porous glass balloon with a diameter of approximately 1 mm is dispersed in the AC3A matrix. The balloon contains numerous closed bubbles. The specific gravities of the glass balloon and AC3A are 1.58 × 10−3 and 2.7 g/cm3, respectively. The specific gravity of the AC material, which was measured with a rectangular bar of dimensions 9.57 × 9.47 × 32 mm, was obtained as 1.5 g/cm3. The volume fraction of the glass balloon was estimated to be approximately half in the AC. The material annealed at 793 K for 1.8 ks was designated as AN.

2.2 Repeated thermomechanical treatment

In order to avoid fracture, the AN samples were worked in multiple steps with intermediate annealing at 793 K for 1.8 ks by using the RTMT process.15) The samples were machined either as round bars (10 mm in diameter × 150 mm in length) for swaging or as plates (10 mm in thickness × 20 mm in width × 200 mm in length) for flat-rolling. After the samples were worked by either swaging or flat-rolling in multiple steps at room temperature, they were formed into a rod (CS) or sheet (CR). The reduction in section area per working step was approximately 10%, and the working-annealing cycle was repeated for a total section area reduction of approximately 90%. For the resulting RTMT materials in the final state, a multiple-step process involving either swaging or flat-
rolling was performed at a different value of total section area reduction. The working strains were defined as $\eta = \ln A_0/A$, where $\eta$ denotes the working strain; $A_0$, the initial section area of the sample; and $A$, the section area of the worked sample. The specific gravities of the worked CR and the selected CS samples ($\eta = 0.46$ and 1.38) were measured and their microstructures were observed. In the final step, the samples with or without annealing were indicated as -H or -A, respectively.

### 2.3 Tensile test and compressive test

A tensile test was performed for the AC, AN, and CS ($\eta = 1.38$) materials. Smooth-type specimens with a gauge diameter of 3.5 mm and length of 30 mm were used for the AC and AN materials. For the CS, the specimens were obtained from rods parallel to the longitudinal direction, and the gauge geometry was mechanically polished to obtain a diameter of 2.4 mm. The elongation was monitored by a clip gauge with the knife-edges set onto the tensile specimen. Its gauge length was 25 mm. A compressive test was also performed for the AC, AN, and CS ($\eta = 0.46$) materials. The cylindrical specimens were machined from rods parallel to the longitudinal direction. For the AC and AN materials, the diameter and height of the specimens were 9 mm. For the CS material, the diameter and height of the specimens were 6 mm. In the compressive test, the diameter at the center of the specimen was measured by using a micrometer. In both the tests, a crosshead speed of 0.5 mm/min was selected in a motor-driven testing machine at 293 K (in air) under displacement control.

#### Table 1 Mechanical and thermal properties of the test material (AC) and AC3A.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength, $\sigma_T$/MPa</th>
<th>Compressive strength, $\sigma_C$/MPa</th>
<th>Bending strength, $\sigma_B$/MPa</th>
<th>Bending elastic modulus, $G$/MPa</th>
<th>Thermal conductivity, $\kappa$/W m$^{-1}$K$^{-1}$</th>
<th>Thermal expansion coefficient, $\alpha$/10$^{-6}$K$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>15.7</td>
<td>49</td>
<td>41.2</td>
<td>144</td>
<td>54.4</td>
<td>16.5</td>
</tr>
<tr>
<td>AC3A</td>
<td>170</td>
<td>170</td>
<td>196</td>
<td>686</td>
<td>217.7</td>
<td>23.6</td>
</tr>
</tbody>
</table>

![Fig. 1](a) Microstructure of the (a) AC material dispersed glass balloons in the AC3A matrix and (b) whole view of a glass balloon.

![Fig. 2](b) Variation in the specific gravity of the test material during swaging or rolling.

![Fig. 3](c) Schematic illustration of compressive stress–strain curve in a porous material.

![Fig. 4](d) Schematic illustration of compressive stress–strain curve in a porous material.
2.4 Finite element analysis

Interactive algorithms used for computing the averaged response of non-linear composites have been applied to microscopically analyze the tensile deformation in the elastic regime. For the AC, spherical glass balloons were installed into the aluminum matrix as a closed-cell foam. Pores were distributed in the balloon. For the CS, ellipsoidal (rod-like) pores were installed into the matrix since the balloon was collapsed into pieces and could be plastically deformed within the matrix.

2.5 Energy absorption

Figure 2 schematically illustrates the compressive stress–strain curve of the porous material. The curve generally

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Fig. 4 Microstructure of the CS materials in the longitudinal section (a) and (c) and transverse section (b) and (d): (a),(b) $\eta = 0.46$ and (c),(d) $\eta = 1.38$.

Fig. 5 Microstructure of the CR materials with working strain (a),(b) $\eta = 0.41$ and (c),(d) $\eta = 1.38$.
shows a very low increase in stress (plateau regime); this is followed by an acceleration in the stress (densification). The energy absorbed per unit volume up to a strain at the transition point from the plateau to the accelerated level, $\varepsilon_1$, is defined as

$$ W = \int_{0}^{\varepsilon_1} \sigma d\varepsilon $$

The absorbed energy is schematically shown by the hatched area in Fig. 2. The energy absorption efficiency, $E$, is also evaluated as

$$ E = \frac{\int_{0}^{\varepsilon_1} \sigma d\varepsilon}{\sigma_0 \cdot \varepsilon_1} $$

Where, $\sigma_0$ is the stress at strain $\varepsilon_1$.

3. Results and Discussion

3.1 Microstructural modification by RTMT

The specific gravity of the materials increases from 1.5 to 2.3 g/cm$^3$ with the working strain up to $\eta = 2.6$ (Fig. 3). This indicates that the relative density of the materials increases. In the case of rolling, a linear relationship is obtained between the working strain and specific gravity. However, the CS material exhibits a higher value of specific gravity for a lower working strain. Although the data plots for the CS material are limited, the glass balloons in the CS after swaging may be divided and aligned along the working direction with a lower working strain due to a type of hydrostatic stress effect.

Then microstructures of the composites after swaging or rolling was observed and compared, as shown in Figs. 4 and 5. Rod-like voids in the CS (Figs. 4(c) and (d)) or pancake-like voids in the CR (Figs. 5(c) and (d)) are observed at higher working strains. The porous balloons may be cracked and dropped from the sample surface. Comparing the microstructure in the transverse section of the CS and CR materials that were worked at lower working strains, it is observed that the radius of the voids in the CS (Fig. 4(b)) is lower than that in the CR (Fig. 5(b)). This observation agrees with the higher value of specific gravity at lower working strains.

3.2 Tensile properties

Figure 6 shows the tensile stress-strain curves and Table 2 summarizes the tensile properties. The swaged materials (CS-H and CS-A) exhibit higher values of Young’s modulus as compared to the cast materials (AC and AN). This may be related to the increase in specific gravity due to deformation of the balloons. The tensile strength of the CS materials is approximately thrice that of the cast materials. The RTMT not only increases the specific gravity but also the uniform elongation. The CS materials exhibit necking instability; however, the cast materials are fractured before approaching it. Hence, a microstructural modification by the RTMT could result in the avoidance of early fracture due to tension, which is characteristic of the cast materials. The load drops that appear in the curves of the swaged materials and the early fracture in the cast materials may result from the instantaneous separation between the balloons and the matrix. In fact dimple in the matrix traced the interface with dropped glass-balloon or brittle fractured glass-balloon mostly covers the fracture surface of the AC, as shown in Fig. 7(a). The manner in which these fracture occurred were not detected in the CS. The annealing at 793 K for 1.8 ks results in higher uniform elongation in both the AC and CS materials. In particular, the
annealed CS material (CS-A) showed an excellent elongation up to a strain of approximately 20%. This manner is typical of materials that undergo the RTMT.15) Although delamination is detected in the tensile fracture in the CS materials, as shown in Fig. 7(b), the RTMT may allow greater flexibility in the working of the composite.

The area fraction of the matrix in the transverse section of the CS is higher than that of the AC, and the matrix in the CS continuously exists along the tensile direction in the form of a fiber. Therefore, the CS may exhibit the tensile performance of the aluminum matrix rather than the AC; such behavior results from the reduction in the stress concentration, which induces fracture of the matrix.

A simple stress analysis was applied to the materials in order to discuss the fracture manner and stress-strain relationship mentioned in above. Figure 8 shows an analysis map for the principal stress distribution under a microstrain in the elastic regime where the applied stress is 1 MPa in tension along the y axis. The area in white color shows the pores in the glass balloon. Arrows in (a) indicate a compressive stress concentration part. Arrows in (b) indicate a tensile stress concentration part.

Table 2 Tensile properties of the CS materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>0.2% proof stress, σ0.2/MPa</th>
<th>Tensile strength, σB/MPa</th>
<th>Elongation, El/%</th>
<th>Young’s modulus, μ/GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>15</td>
<td>15</td>
<td>1.4</td>
<td>2.2</td>
</tr>
<tr>
<td>AN</td>
<td>14</td>
<td>17</td>
<td>2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>CS-H</td>
<td>35</td>
<td>49</td>
<td>2.7</td>
<td>5.2</td>
</tr>
<tr>
<td>CS-A</td>
<td>27</td>
<td>54</td>
<td>19</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Fig. 8 Principal stresses in the AC material: (a) σxx and (b) σyy. Applied tensile stress is 1 MPa and its direction is parallel to the y-axis. The area in white color shows the pores in the glass balloon. Arrows in (a) indicate a compressive stress concentration part. Arrows in (b) indicate a tensile stress concentration part.

Fig. 9 Principal stresses in the CS-A material: (a) σxx and (b) σyy. Applied tensile stress is 1 MPa and its direction is parallel to the y-axis. The elongated pores are indicated in white color. Arrows in both (a) and (b) indicate a tensile stress concentration part.
tension and may lead to fracture. The stress concentration of the $\sigma_{yy}$ is estimated about three times of the applied stress. On the contrary, the compressive stress around the equator on the neighboring balloon occurs in Fig. 8(b). The maximum magnitude of the $\sigma_{yy}$ in compression is almost the same in tension. These stress concentration phenomena agrees with the fracture surface shown in Fig. 7(a). The brittle fractured glass-balloon may result from the concentrated tensile stress, and the glass-balloon concentrated compressive stress may be separated from the matrix. Even though the interface strength between the glass-balloon and the matrix is very low, it reveals that the stress concentration around the equator on the glass-balloon may predominantly affect the tensile fracture behavior.

In the case of the CS material, the stress concentration mostly appears near at both the top and bottom parts of the elongated pore, as shown in Fig. 9. The influence of tensile stress concentration at the ellipsoidal closed-cell foam due to fracture may be lower than that at the spherical foam, although the maximum magnitude of tensile stress concentration in the CS is higher than that in the AC. The tensile stress of $\sigma_{yy}$ between elongated pores occurs. It may give an origin of delamination of the composite.

### 3.3 Compressive properties

The plateau regime after linear elasticity appears in all the compressive stress-strain curves, as shown in Fig. 10. The arrows in Fig. 10 show the strain of the transition point from the plateau to the accelerated stress, $\varepsilon_1$, for the present evaluation. The higher the strain range of the plateau, the larger is the magnitude of energy absorption. When the material is compressed, the glass balloon within the AC3A matrix is compressed. The working during the plateau range may result in the plastic deformation of the matrix and fracture of the glass balloon. However, the balloon is brittle and collapses easily. It may then be harmonized with plastic deformation of the matrix. In fact, the energy absorption efficiency, $E$, of the AC and AN is approximately 0.8–0.9, as listed in Table 3; these values are excellent as they are similar to those of an open-cell foam material (nearly $E = 1$).

There is a possibility to use this composite material instead of cell foam materials. The CS materials show lower inclination of linear elasticity and higher yield stress as compared to the AC and AN materials. Since the CS materials exhibited higher Young’s modulus and relative density, the linear elasticity may involve the effect of bending of the closed-cell. The glass-balloons were broken into pieces and could be easily deformed so that the matrix containing elongated pores might result in the lower modulus. The absorbed energy, $W$, of the CS material is considerably higher than that of the cast material, although the energy absorption efficiency is lower. This may be related to the lower inclination of linear elasticity of the CS.

### 4. Conclusions

A RTMT was adopted to control the microstructure of a porous glass-balloon-dispersed aluminum alloy composite. The mechanical properties and the microstructure of the composite were characterized. The major results are concluded as follows:

1. The composite, which was subjected to the RTMT along with the working by either swaging or flat rolling, was successfully formed into a rod or sheet. The deformation and cracking of the glass balloons depend on the conditions of the thermomechanical treatment.

2. Microstructural modification by the RTMT avoided early fracture due to tension, which was detected in the cast material, and resulted in good ductility for the CS material.

3. The swaged material exhibited higher tensile strength and Young’s modulus as compared to the cast material. A stress concentration around the glass balloons was confirmed. The stress may lead to fracture.

4. The composite materials also exhibited excellent energy absorption properties. The swaged material showed lower inclination of linear elasticity and higher yielding stress as compared to the cast material.

### Acknowledgement

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