MECHANICAL PROPERTIES OF LIGHTWEIGHT COMPOSITES REINFORCED WITH MICRO GLASS BALLOONS

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SUMMARY
The mechanical properties of polymer composites with micro glass balloons are investigated in temperature conditions. A homogenization theory with multi-scale analytical method has been applied for evaluation of the mechanical properties of composites. Numerical calculations were performed by using a model of micro porous body and compared with experimental results.

Keywords: Composite Materials, Porous body, Mechanical Behavior, Lightweight, FEM Analysis.

INTRODUCTION
In recent years, we are in the global warming crisis which might be caused by greenhouse gases (CO₂). The amount of CO₂ emission from means of transportation shows an increase of 18.1% from 1990 to 2005 [1]. The auto industry is working on to use polymer materials and/or fiber reinforced plastics (FRP) for structural components in order to reduce their weight. Especially, European car manufacturers, for example Volkswagen and Daimler Chrysler (Mercedes-Benz division) take a positive attitude to use FRP. However, the problem of safety criterion prevents to using FRP [2]. Therefore, it is important to develop novel materials with lightweight and evaluate their mechanical behaviors in order to ensure the reliability.

In this study, mechanical behavior of composite material system with lightweight is investigated in temperature condition. From the experimental results, the effects of material properties and configurations on the mechanical properties of the composite will be discussed from the viewpoint of micromechanical study. Using an analytical model of micro porous materials, a homogenization theory with multi-scale analytical method has been applied in order to evaluate the mechanical behavior of the composite material system.
LIGHTWEIGHT COMPOSITES

We developed a lightweight composite material. The matrix resin of the composite is epoxy resin, and its dispersion for reinforcement is micro glassy spherical shells of “Sirasu Balloon” (Figure 1). That is, the micro porous composite material is micro glass balloon reinforced epoxy resin (“Sirasu Balloon”/Epoxy) composites [3].

Composition of Lightweight Composites

The epoxy resin used was Ciba-Geigy GY-250. The resin is unplasticized diglycidyl ether of bisphenol A (DGEBA) with a mean molecular weight of about 380 and an epoxide equivalent of 180 - 190g/eq. According to technical data for mechanical properties of the matrix resin, bending strength $\sigma_b$ is 147MPa, tensile strength $\sigma_t$ is 62MPa, glass transition temperature $\tan \delta$ (dry); 428K, fracture toughness $G_{IC}$; 0.15kJ/m$^2$ and water absorption ratio is 0.16%. The phthalic anhydride hardener HN-5500 of Hitachi Chemical Co., Ltd. and the accelerator #2E4MZ of Shikoku Chemical Co. were also used for mixture.

The “Sirasu Balloon” Maarlite 713D of Marunaka-Hakudo Co. was used for reinforcements. “Sirasu Balloon” has micro glassy spherical shell body which manufactured from volcanic ash by heating rapidly at about 1300K. Therefore, it has superior heat resistance, strong impact resistance, and high thermal insulation, for this reason, it could be applied to exterior wall and so on. From the reference of Maarlite 713D, the bulk density is 0.2 ± 0.025g/cm$^2$, the average diameter is 40-50 μm, float ratio 40-50wt%, Ph 6.0-7.0 [4].

The “Sirasu Balloon” / Epoxy composites was fabricated in batches by mixing 100g of GY250 with 85g of HN-5500 and 1g of #2E4MZ, and then adding the 200ml of Maarlite 713D. Degas process for the mixture is sometimes done by holding it in a vacuum chamber before curing in order to prevent the entrapment of air bubbles. However, the degas process were NOT taken in this case. The specimens were kept in a furnace at 423K for 1hour during cure.

(a) Spherical Balloon, (b) Broken Balloon, and (C) Deformed Balloon

Figure 1  SEM Photograph of Sirasu Balloon.
Experiments

For the experiments, the “Sirasu Balloon” / Epoxy composites was machined into the precise shape of specimens (length 190mm and diameter 25mm for rigid type; same geometry with thickness 2.5mm for hollow type, Figure 2). The density of specimen is 0.6 for rigid type, and the apparent density is 0.3 for hollow one. Bending tests, tension tests and impact tests were performed by using the rigid and hollow cylindrical specimens under the conditions of 50%RH at 298K. Figure 3 shows the photograph of bending tests and tension tests. The cross head speed (C.H.S.) of bending test and tensile test was kept at 1.0mm/min. The load and strain were recorded by personal computer throughout the tests. After the test we observed the damage propagation in the micro porous composites specimen by using an optical microscope and a scanning electron microscope (SEM).

(a) rigid cylindrical rod and (b) hollow cylindrical rod

Figure 2 Geometry of porous composites specimen.

(a) bending test        (b) tension test

Figure 3 Tests of composites specimens.
EXPERIMENTAL RESULT AND CONSIDERATION

Experimental Results of The Composites

From experimental results for porous composite specimens of rigid and hollow, Figure 4 (a) shows the load $P$ - Displacement $\delta$ curves of bending test and Figure 4 (b) that of tension test. In the case of bending test in Figure 4 (a), $P - \delta$ curve of hollow specimen indicates non-linear behavior at loading stage from displacement 2mm to maximum. On the other hand, $P - \delta$ curve of rigid specimen indicates linear behavior from earlier stage of loading to the maximum. Any load drop could not be observed. In the case of tension test, the $P - \delta$ curves for porous composite specimen both of rigid type and hollow type indicate linear behaviors from earlier stage of displacement to the maximum. The macroscopic fracture pattern for specimens of impact test was different from that of bending and tension tests. Impact test specimens broke into many small pieces while specimens of bending and tension tests break into two pieces. The precise results are not shown in this study for the sake of brevity.

From the experimental result, mechanical behavior and properties of micro porous composite were examined. For rigid cylindrical specimens at 298K and 50%RH, Young’s modulus is 2.3GPa, tensile strength 9.1MPa, Poisson’s ratio 0.3, bending modulus 1.5GPa and bending strength is 20.0MPa. For hollow cylindrical specimens, Young’s modulus is 2.2GPa, tensile strength 9.5MPa, Poisson’s ratio 0.3, bending modulus 1.5GPa and bending strength is 21.0MPa. Table 1 shows mechanical properties of porous composites.

<table>
<thead>
<tr>
<th>Geometry of specimen</th>
<th>rigid rod</th>
<th>hollow rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.6</td>
<td>0.3※</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>9.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>2.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Specific tensile strength</td>
<td>15.2</td>
<td>31.7</td>
</tr>
<tr>
<td>Specific tensile modulus</td>
<td>3.8</td>
<td>7.3</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Bending strength</td>
<td>20.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Bending modulus</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Specific bending strength</td>
<td>33.3</td>
<td>70.0</td>
</tr>
<tr>
<td>Specific bending modulus</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Charpy impact value</td>
<td>-</td>
<td>1.45</td>
</tr>
</tbody>
</table>

*apparent value
SEM Observation

We observed a fracture surface of micro porous composite specimen by using a SEM in order to discuss the influence of the dispersion of “Sirasu Balloon” on the characteristics of the composites.

From Figure 5, a lot of “Sirasu Balloon” and many air cavities of different size were observed.

Figure 6 shows the result of stochastic analysis for diameter size distribution of balloon particles and air cavities in micro porous composite specimens. Some characteristic peaks were observed on the axis of diameter for balloon particles and air cavities. There obviously exists the peak of “Sirasu Balloon” at 20-30μm of diameter and it found to be highest peak of the diagram. In addition, the peak at about 2μm indicates the existence of micro cavities of air which might be produced from inside of “Sirasu Balloon”, and the peak at 200μm shows relatively large air bubbles which could be caught in molding process of the composites. The strength of the composites would be affected by the existence of large size air bubbles.

Figure 4 Load P - Displacement δ curve of composites (CHS=1.0mm/min).

Figure 5 SEM Photographs of developed composites.
THEORETICAL ANALYSIS OF THE COMPOSITES

A Model for FEM Analysis

From the Figure 5, the composite materials developed have complex structure which contains a lot of spherical shells of “Sirasu Balloon”, air bubbles of 1-3 μm diameter and some voids of about 100-200 μm. The structure of the composites could assume to be periodical for the analysis. We employed a dispersion model on the basis of the composites structure as shown Figure 7 to evaluate the elastic behavior. Observing the periodicity of the structure, a periodical unit cell of 2D can be chosen [5]. Figure 7(c) shows the unit cell model for FEM analysis, which consists of two quartered “Sirasu Balloon” aligned diagonally and the epoxy resin of remaining part between baloons. The white part of quarter circle is filled with the air in the “Sirasu Balloon”. FEM analysis was performed for tensile test at the temperature condition of 123K (-150°C), 298K (25°C) and 403K (130°C). The elastic properties used in the analysis are shown in Table 2.

![Diameter histogram for voids in micro porous composite specimens.](image)

Table 2 Elastic properties used in FEM analysis.

<table>
<thead>
<tr>
<th>Temperature K</th>
<th>E(resin) GPa</th>
<th>E(sb) GPa</th>
<th>ν(resin)</th>
<th>ν(sb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>5.4</td>
<td></td>
<td>94</td>
<td>0.35</td>
</tr>
<tr>
<td>298</td>
<td>3.0</td>
<td>1.9</td>
<td>0.17</td>
<td></td>
</tr>
</tbody>
</table>

We also employed the other type of dispersion model as shown Figure 8 in order to evaluate the thermal conductivity. Figure 8(b) shows the unit cell model for FEM analysis, which consists of one “Sirasu Balloon” aligned the center of square and the epoxy resin of outside of the balloon. FEM analysis was performed for thermal conductivity at the composites density of 0.9 ~ 0.3. The thermal properties used in the analysis are shown in Table 3.
Table 3  Thermal properties used in FEM analysis.

<table>
<thead>
<tr>
<th></th>
<th>Sirasu Balloon</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>1.27</td>
<td>0.2</td>
</tr>
<tr>
<td>Specific heat J/kgK</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>density kg/m³</td>
<td>2800</td>
<td>1180</td>
</tr>
</tbody>
</table>

(a) 3D model                  (b) 2D model of dispersion                  (c) Unit cell model
Figure 7  Finite element models for elastic behavior of developed composites.

(a) 2D model of dispersion                     (b) Unit cell model
Figure 8  Finite element models for thermal conductivity of developed composites.

Results of FEM Analysis

Some numerical calculations were performed by using a unit cell model of micro porous materials shown in Figure 7 and 8 with each property of materials. The “Sirasu Balloon” was assumed to take constant elastic property independent of temperature.

Figure 9 shows the analytical results of stress - strain curves for tension test in various temperature conditions. The experimental results of tension test at temperature of 298K are also shown in the same figure. The analytical results at 298K made a good agreement with experimental ones of the composite. It means that a unit cell model of micro porous materials is valid for evaluation of the mechanical behavior of the composite material system in temperature conditions.
The calculated thermal conductivity of developed composites is shown in Figure 10. By applying Maxwell’s theory to rigid spherical particle dispersion composites, the estimated thermal conductivity is also shown in the same figure. The thermal conductivity of the composites from the Maxwell’s theory is expressed as follows

\[
\frac{\lambda_E}{\lambda_C} = \frac{\frac{n\lambda_C + \lambda_D}{n\lambda_C + \lambda_D} - \frac{n\lambda_C - \lambda_D}{n\lambda_C + \lambda_D} V_D}{\frac{n\lambda_C + \lambda_D}{n\lambda_C + \lambda_D} + \frac{n\lambda_C - \lambda_D}{n\lambda_C + \lambda_D} V_D}
\]

(1)

where \(\lambda_E\) is the thermal conductivity of particle dispersion composites, \(\lambda_C\) is the thermal conductivity of matrix resin, and \(\lambda_D\) is the thermal conductivity of particle (Sirasu Balloon). \(V_D\) is the volume fraction of particle, and \(n = 2\) in this case that the particle shape is sphere.

Viewing Figure 10, the thermal conductivity of developed composites gradually decreases as the volume fraction of composites increases. The result of FEM analysis is different from estimated value of the Maxwell’s theory. It is found that the air which Sirasu Balloons and/or the composites contain affects on thermal conductivity and it is necessary to examine the property of the light weight composites in the severe temperature conditions.

The thermal conductivity of Sirasu Balloon is higher than that of epoxy resin. It will be possible that if the balloons gather and touch with each other, the thermal conductivity of the composites becomes higher. It would be required to employ a thermal percolation model to evaluate actual thermal conductivity using results of this unit cell model.
Figure 10  Variation of thermal conductivity of developed composites against $V_f$.

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References
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