This paper describes the output voltage characteristics of the metal-core piezoelectric ceramic fiber/aluminum composites fabricated by the Interphase Forming/Bonding (IF/B) method. Piezoelectric materials are generally used as electric and mechanical energy transducers. When their devices are developed for fulfilling their functions, complicated electrode systems and resin layers for adhesion of the materials and the electrodes are usually needed, where depression of response and reliability, and complication of structure are caused. Additionally, as the metal-core piezoelectric ceramic fiber is brittle and reactive with molten aluminum, general fabrication processes such as diffusion bonding and casting are hard to be applied to embed it into an aluminum matrix. Therefore the IF/B method was used for embedding it in an aluminum matrix without fracturing it. In this study, a thin patch type device developed by the modified IF/B method was evaluated by a vibration test and an impact test. As the result, it was found that the output voltage from the device is proportional to its strain and the square root of the impact energy. In addition, the output voltage varies with its strain direction. Especially, at the strain direction 50.6 degrees, sign of the output voltage changes. Taking the above mentioned characteristics into consideration, this composite was found to be useful for structural health monitoring systems.

Key words: Metal Matrix Composite, Smart Material, Piezoelectric Ceramic, Aluminum, Sensor

1. INTRODUCTION

In recent years, Structural Health Monitoring (SHM) technology has been studied extensively because of aging and damage of structures such as bridges and highways. Especially in Japan, health monitoring of the structures have been investigated for detection of damages caused by earthquakes.

The SHM is a technology for dynamic diagnosis of positions and extent of damages in structures, and scope of the damages is estimated by observing physical quantities such as acceleration and strain which can be measured by installed sensors. As these sensors, optical fibers and piezoelectric ceramics are used. In particular, acceleration sensors using piezoelectric ceramics are often used because of their high-sensitivity and high-responsivity, and they do not need special equipment. However, fragility of the piezoelectric sensors caused by brittleness of the piezoelectric ceramics [1-4] has become problem. In consequence, when a large load of disaster such as an earthquake is applied, it is predicted that the sensors are broken earlier than the structures. In order to solve such problems, piezoelectric composites that fibrous piezoelectric ceramics packaged with resin were developed, such as Active Fiber Composite (AFC) which was developed by A. A. Bent et al. [5-7] and Macro Fiber Composite (MFC) that developed by W. K. Wilkie et al. [8-11]. These piezoelectric composites are improved in reliability and mechanical strength compared to the conventional piezoelectric ceramics.

However, the matrixes of these piezoelectric composites are resins, so their reliability and mechanical strength are insufficient compared to structural materials such as steels and aluminum alloys. Therefore, in order to improve the reliability and strength, Asanuma et al. succeeded in embedding the metal-core piezoelectric fiber [12-15] into an aluminum matrix without damage by the Interphase Forming/Bonding (IF/B) method [16-20]. This method is a sophisticated Transient Liquid Phase (TLP) bonding method [21-23] developed to enable embedding fragile functional fibers at low temperature and low pressure in a short period of time by using eutectic reaction of insert material and matrix.

In this study, the output voltages of the metal-core piezoelectric fiber/aluminum composite fabricated by the IF/B method were characterized because they are basic properties for adapting this composite to SHM systems.

2. MATERIALS

The materials used in this study are summarized in Table I. The pure aluminum plates were used as matrix and backing plate, the pure copper foils were used as insert material for eutectic reaction and as electrode. The metal-core piezoelectric fiber that has platinum core was used as sensor and actuator, and its properties are shown in Table II.

3. EXPERIMENTAL

3.1 Fabrication of specimen

The aluminum plates of each thickness and the 0.01
Table I  The materials used in this study.

<table>
<thead>
<tr>
<th>Usage</th>
<th>Material</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td>Pure aluminum (A1050P-O)</td>
<td>Thickness: 0.2, 0.4 mm</td>
</tr>
<tr>
<td>Backing</td>
<td>Pure aluminum (A1050P-O)</td>
<td>Thickness: 1.2 mm</td>
</tr>
<tr>
<td>plate</td>
<td>Insert</td>
<td></td>
</tr>
<tr>
<td>Insert</td>
<td>Pure copper foil (C1220)</td>
<td>Thickness: 0.01 mm</td>
</tr>
<tr>
<td>Fiber</td>
<td>Metal-core piezoelectric fiber</td>
<td>Outer diameter: 0.2 mm</td>
</tr>
<tr>
<td>Electrode</td>
<td>Pure copper foil (C1220)</td>
<td>Core diameter: 0.05 mm (Manufactured by AIST)</td>
</tr>
</tbody>
</table>

Table II  Electric and mechanical properties of the metal-core piezoelectric fiber.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling factor</td>
<td>( k_p )</td>
<td>0.7~0.73</td>
</tr>
<tr>
<td>Piezo charge constants ( /pC \cdot N^{-1} )</td>
<td>( d_{33} )</td>
<td>510~550</td>
</tr>
<tr>
<td>Dielectric constants ( \varepsilon \cdot \varepsilon_0 )</td>
<td>( \varepsilon_{33} )</td>
<td>1500</td>
</tr>
<tr>
<td>Dissipation factor (%)</td>
<td>( \tan \delta )</td>
<td>1.5</td>
</tr>
<tr>
<td>Young's modulus / GPa</td>
<td>( E_y )</td>
<td>28~30</td>
</tr>
<tr>
<td>Curie point / °C</td>
<td>( T_c )</td>
<td>285</td>
</tr>
<tr>
<td>Density / g cm(^{-3})</td>
<td>( \rho )</td>
<td>7.7~7.85</td>
</tr>
</tbody>
</table>

mm thick copper foil were cut to 20 mm × 30 mm pieces, polished along their rolled directions with a 600 grit waterproof abrasive paper for removal of the oxide layer, and the 0.4 mm thick aluminum plate was bonded to the 1.2 mm thick aluminum plate. Then, a SUS304 stainless steel spring wire of 0.25 mm in diameter was pressed with a hydraulic press equipment for formation of a U-groove in the center of the bonded aluminum plates that was stacked with the copper foil. The metal-core piezoelectric fiber was arranged in its U-groove, then, the 0.2 mm thick aluminum plate was stacked to it (Fig. 1). Stacked aluminum plates and copper foil were hot-pressed under the conditions at the temperature of 873 K, at the pressure of 2.2 MPa and for the period of 2.4 ks and in a vacuum of 0.1 kPa. After hot pressing, the composites were cut into square shape test pieces of 20 mm × 20 mm, and removed from the backing plate. Electrodes were attached to the composites pieces to form patch type specimens as shown in Fig. 2. And the piezoelectric fiber was polarized by applying 300 V between aluminum matrix and platinum core for 1.8 ks.

3.2 Vibration test

Output voltage characteristic was evaluated by the vibration test equipment shown in Fig. 3. An aluminum plate on which the specimen was attached was oscillated by an electro magnet, and the output voltage generated from the specimen was measured by a lock-in amplifier.

The effect of strain of the specimen on the output voltage was investigated by varying amplitude of the vibration plate. Frequency of the vibration test was kept at resonance frequency \( f=19.7 \) Hz. Attached location of the specimen \( D \) was 50 or 125 mm and vibration amplitude \( A \) was changed from 0.2 mm to 1.0 mm that was increased by 0.2 mm at each attached location. The amplitude was measured by a laser displacement sensor at the position of 135 mm from the end of a vise and the strain of the specimen was measured by using a strain gauge.

And, the effect of strain direction on the output voltage was investigated by changing attached angle of the specimen. The test conditions were as follows. Resonance frequency \( f=19.7 \) Hz, attached location at 125 mm and vibration amplitude at 1.0 mm were kept constant. The direction of the strain was changed by
shifting the attached angle from 0 deg (fiber direction) to 90 deg (transverse direction) that was increased by 15 deg.

3.3 Impact test

Output voltage characteristics at high frequencies such as vibrations which caused by applying impact were evaluated by an impact test. It was carried out by using the test system shown in Fig. 4. The impacts were applied by dropping a steel ball (diameter: 9.5 mm, weight: 3.5 g) on a duralumin disk (A2017-T351, diameter: 500 mm, thickness: 10 mm) on which the specimen was bonded with cyan acrylate adhesive to the center and conducted to the disk by silver paste. The test conditions are drop height $h_i$ and drop location (distance: $d_i$, angle: $\theta_i$) and output voltage generated from specimen by the impact was measured with an oscilloscope.

First, the effect of the impact angle on the output voltage was investigated by changing the angle of the drop location $\theta_i$. The angle $\theta_i$ was changed from 0 deg to 90 deg that was increased by 15 deg at the drop height $h_i=200$ mm and the distance of the drop location $d_i=50$ mm.

Next, the effect of impact energy on the output voltage was investigated by changing the drop height $h_i$. It was changed from 40 mm to 200 mm that was increased by 20 mm at the drop location $\theta_i=0$ and 90 deg, $d_i=50$ mm.

4. RESULTS AND DISCUSSION

4.1 Vibration test

The effect of the strain on the output voltage is shown in Fig. 5. According to the figure, it is found that the output voltage increases in proportion to the strain. Furthermore, the output voltage is dependent on the strain, and not on the attached location. These characteristics can be explained by a simple model of a piezoelectric material shown in Fig. 6. The following equation can be derived from the model.

$$ V = \frac{dFh}{\varepsilon_p S} = gh\sigma = ghE_p \varepsilon $$

Where
- $d$: Piezoelectric charge constant
- $F$: Force
- $h$: Distance between electrodes
- $\varepsilon_p$: Dielectric constants
- $S$: Area of electrode
- $\sigma$: Stress
- $g$: Piezoelectric voltage constant
- $E_p$: Young’s modulus of piezoelectric material

From this equation, it is found that the output voltage is proportional to the strain, and the result obtained from the model is consistent with the experimental results.

In Fig. 7, the effect of the strain direction of the
piezoelectric fiber on the output voltage is shown. The output voltage is reduced by increasing the angle, and the output voltage changes to negative sign at the angle is between 45 deg and 60 deg. Thus, phase of the output voltage is shifted 180 deg by the strain direction change. Moreover, a simple model for calculating the effect of the strain direction of piezoelectric fiber on the output voltage is shown in Fig. 8. The displacement of the plate was fixed to keep the strain $\epsilon$ constant in longitudinal direction of the vibration plate, and the strain is decomposed into fiber direction strain $\epsilon_x$ and fiber transverse direction strain $\epsilon_y$. In this case, $\epsilon_x$ and $\epsilon_y$ are expressed by the following equations.

$$
\epsilon_x = \frac{1}{2}\epsilon(1-\cos2\alpha)
$$

(2)

$$
\epsilon_y = \frac{1}{2}\epsilon(1+\cos2\alpha)
$$

(3)

Since the proportionality of the strain and the output voltage from Equation 1, the conversion constant $D_i$ as a constant that converts the strain into the output voltage can be determined, then, $D_i$ is determined in the fiber direction, and $D_i$ is determined in the fiber transverse direction. Thus, the output voltage $V$ is expressed by the following equation.

$$
V = D_i\epsilon_x + D_y\epsilon_y
$$

(4)

Therefore, the output voltage $V$ is also expressed by the following equation from Equation 2, 3 and 4.

$$
V = D_i\epsilon\frac{1-\cos2\alpha}{2} + D_y\epsilon\frac{1+\cos2\alpha}{2}
$$

(5)

Where, it was found that the output voltage obtained from Equation 5 matches with the experimental values as shown in Fig. 7. It should be noted that, $D_i$ and $D_y$ have opposite signs to each other in this case. If the angle $\alpha = 50.6$ deg, $|D_i\epsilon_x|$ is equal to $|D_y\epsilon_y|$, the output voltage $V$ becomes zero by Equation 5. Thus, it is considered that the output voltage generated from the strain of the fiber transverse direction component and that of the fiber direction component are canceled out. $|D_i\epsilon_x|$ is less than or equal to $|D_y\epsilon_y|$ between 0 deg and 50.6 deg, so, the fiber direction strain is dominant. In this range of the angle, negative output voltage generated by the fiber transverse direction strain is increased with increasing the angle, and positive output voltage generated by the fiber direction strain is reduced. Therefore, it is considered that output voltage $V$ to decline. Further, $|D_i\epsilon_x|$ is greater than $|D_y\epsilon_y|$ between 50.6 deg and 90 deg, the output voltage generated from the fiber transverse direction strain component is dominant with increasing angle, then, it was considered that the output voltage $V$ is increased to minus direction and the phase of the output voltage is inverted. These results show that this composite has anisotropy of sensitivity. The output voltage due to the strain in the fiber direction is dependent on the piezoelectric constant $d_{33}$, although $d_{33}$ have different signs, the phase of the output voltage was shifted 180 deg.

In addition, piezoelectric voltage constant $g$ of the composite is calculated from these results. Obtained fiber direction constant $g_{max} = 1.19\times10^{5}$ V-mN and fiber transverse direction constant $g_{transverse} = -0.79\times10^{5}$ V-mN, which are lower than that of the conventional lead zirconate titanate (PZT). The reason for this is decrease of the piezoelectric constant by high compressive stresses.

4.2 Impact test

Fig. 9 shows the relationship between output voltage of the specimen and the angle of impact point. The output voltage is decreased with increasing the impact angle, and the sign of the value is inversed between 30 deg and 45 deg. Comparison of output voltage values actually measured and calculated by using the model to calculate the effect of the direction of the strain applied to the fiber described above are also shown in Fig. 9. It is considered that, the change in the voltage is also from the same reason as described above.

The effect of the square root of the impact energy $E_i$ on the peak of output voltage is shown in Fig. 10. The sign of the output voltage is inversed by changing angle of impact location from 0 deg to 90 deg. This inversion of sign is due to the anisotropy of the output voltage as described above. Moreover, the output voltage is
The relationship of the strain caused by giving the impact energy, and depends on the direction of the detection of strain direction.

Additionally, this composite has possibility of dynamic strain sensor.

5. CONCLUSIONS

The output voltage characteristics of the metal-core piezoelectric ceramic fiber/aluminum composite were evaluated, and the results obtained are as follows:

1) The output voltage generated from the composite is proportional to its strain, and it shows that the composite has capability of dynamic strain sensor

2) The output voltage depends on the strain direction, and its dependence can be calculated by the simple strain decomposition model. Additionally, this dependence shows that this composite has possibility of the detection of strain direction.

3) The output voltage is increased with the square root of the impact energy, and depends on the direction of impact.

4) From the above mentioned results, the composite device can be found to be useful for a dynamic strain sensor and an impact energy/location detection sensor for SHM systems.

REFERENCES


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