Fabrication and characterization of piezoelectric ceramic fiber/aluminum alloy composites

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Abstract: This paper describes the fabrication and characterization of a piezoelectric ceramic fiber/aluminum alloy composite using the Interphase Forming/Bonding (IF/B) method. A metal-core piezoelectric ceramic fiber is very fragile and reacts with molten aluminum; therefore, general fabrication processes such as diffusion bonding and casting are difficult to apply. In this study, hot pressing conditions were examined in order to embed a metal-core piezoelectric ceramic fiber, without mechanical damage and loss of piezoelectricity, in an aluminum alloy matrix instead of the pure aluminum matrix used in previous studies. As the results, the proper hot pressing conditions, that is, pressure and temperature of 2.2 MPa and 873 K, respectively, enable the removal of the coarse and fragile eutectic alloy phase from the composite. In addition, the output voltage characteristics of the piezoelectric ceramic fiber/aluminum composite were evaluated by impact testing. The results show that the output voltage generated from the composite is proportional to the square root of impact energy.

Keywords: Smart Material, Piezo-Element, Sensor, Aluminum Alloy, Composite Material

1. Introduction

Piezoelectric ceramics are widely used in sensors and actuator elements in the form of mechanical-electrical energy conversion materials. However, as far as mechanical properties and dependability are concerned, these commonly used materials have drawbacks such as brittleness and vulnerability to rupture [1, 2]. Because of this, when creating functional devices, there are many limitations such as the requirement of complicated electrode systems. In order to overcome these problems, Asanuma et al. embedded platinum-core piezoelectric ceramic fibers [3-6] in aluminum using the Interphase Forming/Bonding (IF/B) method [7] and fabricated a composite without causing mechanical or electrical damage to the piezoelectric fiber [8-12]. The formation of this composite has made it possible to greatly expand the strength and scope of application in a successful manner in comparison with conventional piezoelectric ceramics. To this end, applications for robust dynamic strain sensors or energy harvesting devices that can withstand severe environmental conditions, such as disasters, have been proposed. Although the strength and scope of application has been successfully extended over a wide range in comparison

with conventional piezoelectric ceramics, the matrix material is presently restricted to weaker pure aluminum. The strength of this composite is therefore not sufficient to withstand the high stresses encountered during a disaster. Furthermore, increasing the volume fraction of the piezoelectric ceramic fiber is essential for the improvement of properties such as increasing the output power or enabling measurement of strain distribution in energy harvesting devices. However, there is a difficulty inasmuch as the mechanical strength reduces with increase in the volume fraction. In order to overcome this difficulty and increase the mechanical strength, the matrix material in the present work was changed to super duralumin, which has a strength equivalent to steel, and the sensor properties were evaluated by impact testing.

2. Experimental

2.1. Materials

Lead zirconate titanate (PZT) fibers using ϕ 0.05 mm platinum wire in the core were used as the piezoelectric ceramic fiber (metal-core piezoelectric fiber, ϕ 0.2 mm, AIST). A 0.8 mm thick super duralumin plate (A2024P-T3) was used as the matrix material, and a 0.01 mm thick foil composed of

pure copper (purity $\geq 99.90\%$) was used as the inserting material.

2.2. Examination of Fabrication Conditions

A 0.8-mm-thick super duralumin plate and 0.01 mm thick copper foil were cut to a size of 15×30 mm and polished with waterproof abrasive paper to remove the oxide film. The copper foil was then placed on the super duralumin plate and a ϕ 0.25 mm SUS304 stainless steel wire was centered in the lengthwise direction and pressed in the middle by means of a pressing machine to form a U-groove. After placing a metal-core piezoelectric fiber of length 20 mm in the groove, a super duralumin plate of the same shape was placed on top and hot pressing was carried out. Fig. 1 shows the laminate configuration of the specimen. For understanding the effect of the composite material fabrication conditions on the internal interfacial structure, specimens were prepared by keeping the vacuum, $v = 0.1$ kPa, and holding time, $T_h = 2.4$ ks, constant, and varying the holding temperature, $T = 853$, 873, and 893 K, and pressure, $P_s = 1.1$, 2.2, and 4.4 MPa, during hot pressing. The composite material thus obtained was cut in the center of the direction of piezoelectric fiber and its structure was observed with a scanning electron microscope (SEM). The specimens obtained under the conditions giving the best structure were subjected to elemental analysis by the electron probe micro analyzer (EPMA) to check if there was any chemical reaction between the piezoelectric fiber and the matrix.
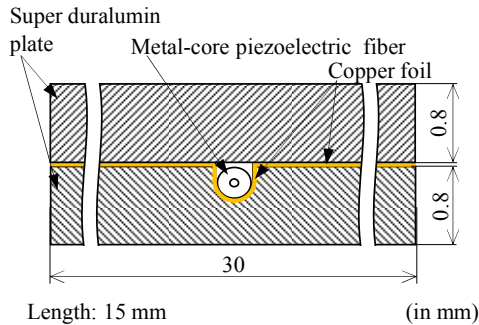

Figure 1. *Cross section of the materials prepared for hot pressing.*

2.3. Evaluation of Mechanical Properties

To examine the effect of the interfacial layer created in the IF/B method on the mechanical strength, tensile and tensile shear tests were carried out. For the tensile test, specimens of size 40×30 mm (length $\times$ width) were prepared from the super duralumin plate and copper foil, and for the tensile shear test, specimens of size 15×10 mm were prepared from the super duralumin plate and copper foil and processed into the shapes shown in Fig. 2.

The hot pressing conditions that yielded the best structures according to the results of the above tests were $T = 873$K and $P_s = 2.2$ MPa. Here, according to the hot pressing thermal history, the Guinier-Preston (GP) zone in super duralumin had vanished and the strength was presumed to have reduced, and

therefore, a heat-treated material was prepared by conducting heat treatment (heating at temperature 823 K, holding time 1 h followed by cooling in water and aging for 96 h at room temperature). Moreover, A2024 material having a thermal history equivalent to that of the hot-pressed material and A2024 material that was subjected to further heat treatment were prepared for comparison and the effect of the interfacial layer was studied by comparing the strength with that of the composite material. The composite material thus obtained and the materials for comparison were processed into the shapes shown in Fig. 2 and used for testing.
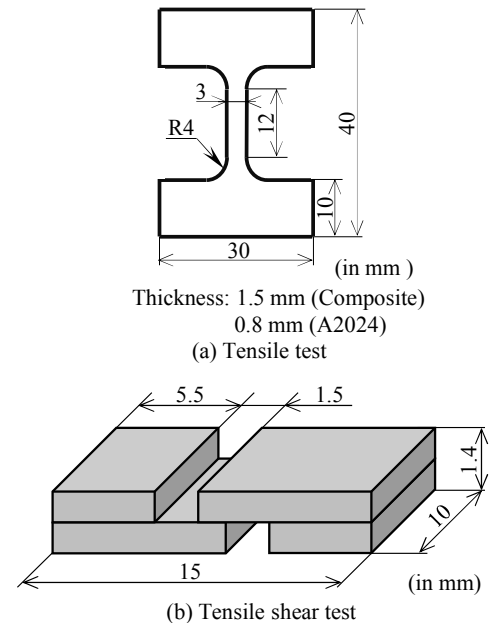

Figure 2. *Tensile and tensile shear test specimens.*

2.4. Evaluation of Sensor Properties

As shown in Fig. 3, specimens of size $7.5 \times 7.5 \times 1.45$ mm were prepared. The specimens were tested with the impact test system shown in Fig. 4. The test piece was fixed on a vise and impacted by a 3.5 g steel ball free falling from a height, hi, through a guide pipe. The output voltage from the metal-core piezoelectric fiber was measured by an oscilloscope. The impact was in two directions, namely, $0°$ and $90°$ as shown in (b) and (c) in the figure, and the impact position was the respective center of each surface. The falling height, h_i, was increased from 50 to 150 mm in 25 mm increments to examine the effect of impact energy on the output voltage.
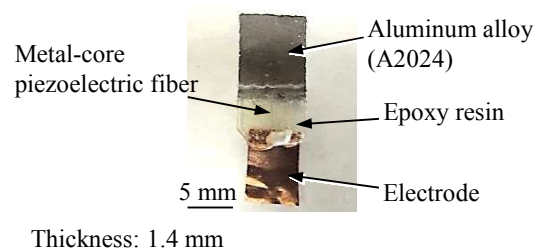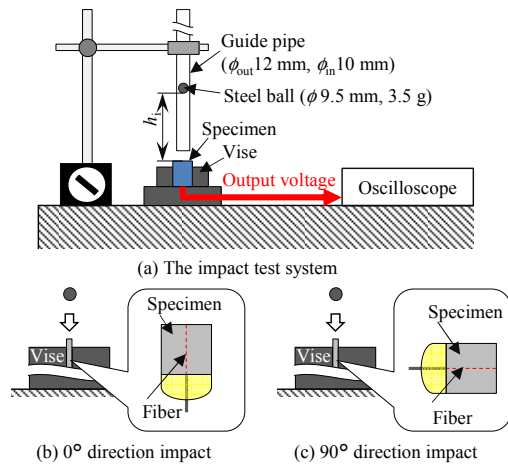

Figure 3. *Specimen for impact test.*

(a) The impact test system

(b) 0° direction impact   (c) 90° direction impact

Figure 4. Impact test system.

3. Results and Discussions

3.1. Examination of Fabrication Conditions

Fig. 5 shows images of the structure of the central portion of the specimen obtained with T = 873 K and T_h = 2.4 ks, and by varying P_s as 1.1, 2.2, and 4.4 MPa. From this, it can be seen that at P_s = 1.1 MPa, there remains a lot of residual Al-Cu eutectic alloy generated by the IF/B method around the piezoelectric fiber, and that the formation of voids also takes place. These phenomena may be attributed to insufficient deformation of the matrix on account of a lower hot-pressing pressure, resulting in a reduction in the discharge of the eutectic alloy and generation of voids. At P_s = 4.4 MPa, the amount of residual eutectic alloy is less, but the piezoelectric fiber was found to undergo rupture. In this case, as the hot-pressing pressure is high, plastic deformation of the matrix might be more, leading to increased discharge of the eutectic alloy, but excessive pressure acting on the piezoelectric fiber might have caused its rupture. In the case of P_s = 2.2 MPa, the amount of residual eutectic alloy is less and damage to the piezoelectric fiber is also not seen; therefore, P_s = 2.2 MPa can be considered to be the optimum pressure.

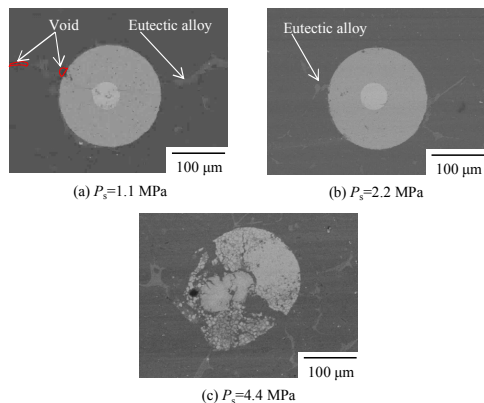(a) P_s=1.1 MPa   (b) P_s=2.2 MPa

(c) P_s=4.4 MPa

Figure 5. SEM images of cross sections of the metal-core piezoelectric fiber embedded in the duralumin matrix under each hot-press pressures at T = 873 K
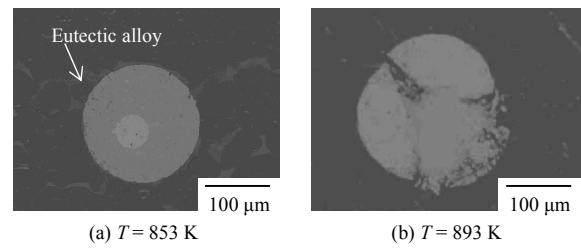

(a) T = 853 K   (b) T = 893 K

Figure 6. SEM images of cross sections of the metal-core piezoelectric fiber embedded in the duralumin matrix under each hot-press temperature at P_s = 2.2 MPa.

Fig. 6 shows images of the structure of the central portion of the specimens obtained at temperatures T = 853 and 893 K, while keeping P_s = 2.2 MPa and T_h = 2.4 ks (the image at T = 873 K is omitted because it is the same as Fig. 5 (b)). From this, it can be seen that at T = 853 K, the amount of residual eutectic alloy is large. This may be attributed to the low temperature, which caused insufficient softening of the matrix material, resulting in less plastic deformation and more residual eutectic alloy. It can be seen that at T = 893 K, the amount of residual eutectic alloy is insignificant, but the piezoelectric fiber was damaged. As the temperature is high, softening of the matrix material might have proceeded, resulting in an increase in plastic deformation, which may have caused excess pressure on the piezoelectric fiber, leading to its rupture. In case of T = 873 K, the amount of residual eutectic alloy is less and damage to the piezoelectric fiber could not be seen, therefore, T = 873 K seems to be optimum temperature.
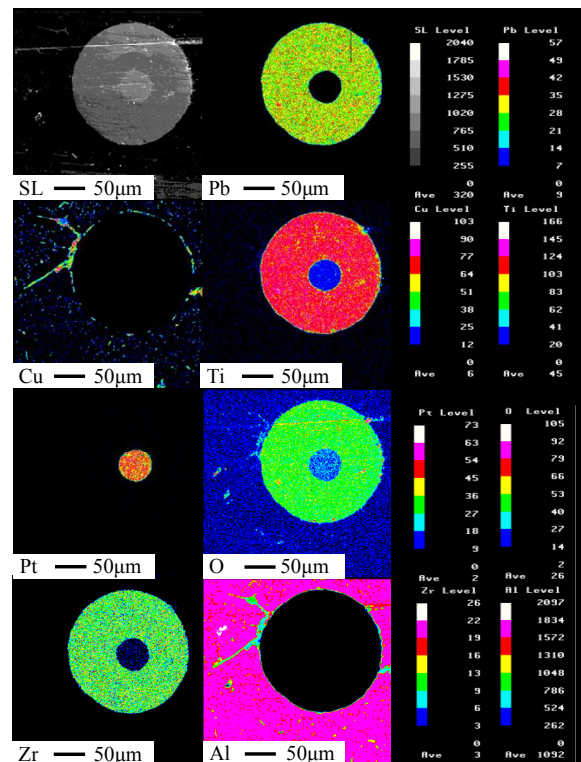

Figure 7. Result of EPMA analysis.

Fig. 7 shows EPMA of the specimens obtained under the optimum conditions mentioned above. As the residual

Al-Cu eutectic alloy formed in the IF/B method remains around the piezoelectric fiber, a large quantity of Cu was detected, but a diffusion reaction of the matrix with Pb, Zr, and Ti, the main components of PZT, could not be seen. A diffusion reaction of the Pt metal core and PZT was also not observed.

From the above, it is clear that piezoelectric fiber can be embedded into super duralumin without any mechanical and chemical damage, by using the IF/B method.

3.2. Evaluation of Mechanical Properties

Fig. 8 shows the tensile strength of each specimen. The tensile strength of the composite material just after hot pressing and that of the A2024 material are 180 MPa and 290 MPa, respectively, which are less than that of the starting material. This reduction in strength may be due to the disappearance of the GP zone according to the hot pressing thermal history. The difference between the tensile strengths of the composite material and A2024 material may a result of the solid solution buildup caused by an increase in copper concentration in the composite material matrix from the copper foil used in the IF/B method. Moreover, the strength of heat-treated composite and A2024 materials has increased to about 360 MPa and it is presumed to have recovered on account of the formation of GP zones. Furthermore, a comparison of the composite material and A2024 material shows that there is not much difference in the tensile strength. From this, it is understood that the interface generated in the IF/B method does not have much influence on the tensile strength after heat treatment.
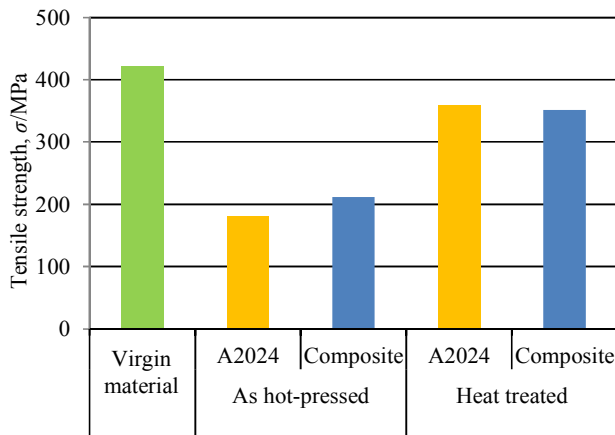

Figure 8. Result of tensile test.

Fig. 9 shows the tensile shear strength of each specimen. The tensile shear strength shows a trend similar to that for tensile strength and the difference in the tensile shear strength of various specimens can also be considered to have occurred by the same mechanism.
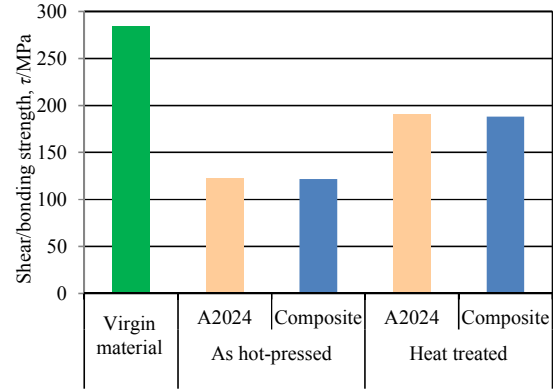

Figure 9. Result of tensile shear test.

3.3. Evaluation of Output Voltage

Fig. 10 shows the results of impact testing. From this figure, it can be seen that the output voltage increases almost proportionately with the square root of the impact energy. If a steel ball of mass m is allowed to fall from a height h_i with gravitational acceleration g, the impact energy, U_i, is given by

$$U_i = mgh_i \qquad (1)$$

and thus it is proportional to the falling height. Furthermore, if E_y is the stiffness of the material, the relationship between the elastic energy, U_e, and strain ε becomes

$$U_e = E_y \varepsilon^2 / 2 \qquad (2)$$

Here, the output voltage V from the simple model of the piezoelectric material is given by

$$V = G \varepsilon_p \qquad (3)$$

Here, G is the piezoelectric sensitivity and ε_p is the strain generated in the piezoelectric material. Since U_i and U_e, and ε and ε_p bear proportionality relationships, the output voltage from the piezoelectric material and strain bear proportionality with the square root of impact energy, Eq. (1), (2), (3) and the above experimental results are almost in agreement with this theoretical consideration.
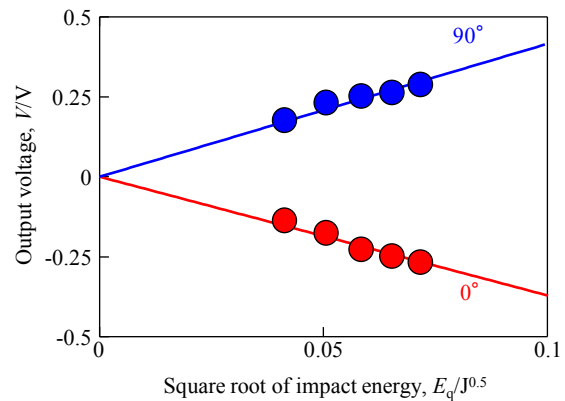

Figure 10. Result of impact test.

Furthermore, the output voltage has been found to change sign by changing the direction of impact from 0° to 90°. This may be because the deformation along the direction of fiber axis is predominant in case of 0° and depends on the piezoelectric constant d_{31}, whereas in case of the 90° direction, deformation in the circumferential direction of the fiber is predominant and depends on the constants d_{31} and d_{33}. In the case of general piezoelectric materials represented by PZT, d_{31} and d_{33} have opposite signs and the absolute value of d_{33} constant exceeds that of d_{31}. Because of this, in the 90° direction, d_{33} becomes predominant, which may cause the reversal of the waveform.

4. Conclusions

1) This composite can be fabricated by the IF/B method by embedding a metal-core piezoelectric fiber in super duralumin without mechanical damage. Furthermore, in the scope of the present experiments, under the hot pressing conditions of temperature = 873 K, pressure = 2.2 MPa, and holding time = 2.4 ks, the voids disappear and the residual eutectic alloy also almost vanishes.

2) From the results of tensile test, the interfacial layer generated during the interphase forming/bonding method does not have any influence on the tensile strength or bonding strength.

3) A metal-core piezoelectric fiber can be embedded by the interphase forming/bonding method in super duralumin without causing any degradation in the piezoelectric properties.

4) The output voltage of the composite material due to impact increases proportionately with the square root of the impact energy, and the output voltage changes sign according to the direction of deformation.

Acknowledgements

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