Proposal of an active composite with embedded sensor

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Abstract

Though advanced composites with embedded actuator materials such as shape memory alloys and piezo ceramics have been developed as active materials, another one by making use of thermal deformation of composites was proposed and an active laminate was prepared as an example by hot-pressing of aluminum plate as material of high coefficient of thermal expansion (CTE), uni-directional carbon fiber reinforced plastics (CFRP) prepreg as low CTE material and electric resistance heater, polymer adhesive film as insulator between them, and copper foils as electrodes. Actuation of this laminate is different from that of bimetal because CTE of the CFRP layer is strongly anisotropic due to directionality of its reinforcement fiber. As CTEs of the CFRP layer and the aluminum plate in the fiber direction are quite different from each other though they are close to each other in the transverse direction, smooth and uni-directional actuation becomes possible. In this study, its fundamental performances such as shape change and output force were observed and evaluated, and after establishment of its fabrication, an optical loss type sensor was formed in the active composite, by embedding multiply pre-notcheded optical fiber in the CFRP layer and breaking it at the pre-notches under bending, followed by lamination on aluminum plate with adhesive. As the sensing part can be formed inside the matrix without any complicated processes, a robust and low cost sensor is obtained. From the results, it becomes clear that: (1) curvature of the active composite linearly changes as a function of temperature between room temperature and its hot pressing temperature by electric resistance heating of the CFRP layer and cooling, (2) its output force against a fixed punch during heating from room temperature up to around glass transition temperature of the resin phase almost linearly increases with increasing temperature, (3) the multiply pre-notched, embedded and fractured optical fiber works as a sensitive sensor for monitoring the curvature of the active composite. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Smart material; Composite; Actuator; Sensor; Heater; Carbon fiber; Optical fiber; Thermal deformation

1. Introduction

Advanced structural materials with sensor and/or actuator functions have attracted worldwide interest because of their potential uses: damage detection, performance monitoring, noise reduction, vibration suppression, actuation, shape control, self-repair, and fabrication process monitoring [1]. Most of these new material systems have been developed by embedding sensor and/or actuator materials in host structural materials such as polymer matrix composites [2]. As these material systems consist of extremely dissimilar materials and functions, composite design to realize overall systematic integration through harmonic interface/interphase design becomes very important. In some cases, useful functions are observed in the host structural materials, which contribute to the enhancement of simplicity of the complicated materials systems [3]. For example, carbon fiber in carbon fiber reinforced plastics (CFRP) works as a sensor, near-zero coefficient of thermal expansion (CTE) material, heating element as well as reinforcement. These highly functional material systems regarded as ‘smart materials’ will be able to replace such complicated mechanical systems as flow control valves, hatches, doors, flaps, air brakes without using hinges, and actuators.

Though in the case of active materials development, shape memory alloys and piezo ceramics have been mainly used [4,5], Asanuma proposed another effective active material by making use of thermal deformation of fiber–metal laminates [6], which is normally suppressed by symmetrical lamination of materials [7]. This active laminate was more generalized and is shown in Fig. 1. The reinforcement fiber works as ‘bone’ and the matrix works as ‘muscle’. Both are controlled by stimulation and energy transmitted through the functional fibers regarded as ‘nerve’ and ‘blood vessel’. This material system could have a variety of functions such as health monitoring and self-repair.

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The purpose of this study is to develop a high-performance active composite with embedded sensor to demonstrate a part of the concept. An active composite can be realized by changing the designing concept from conventional rigid composites by symmetric lamination to active composites by asymmetric lamination of materials, and by heat generation. As shown in Fig. 2, an example can be prepared by lamination of metal plate as high CTE material and CFRP prepreg as low CTE material in situ electric heater with thin insulation layer. There are many parameters to govern its complicated actuations. The most simple and useful actuation of this active composite is uni-directional actuation as shown in Fig. 3. Mechanism of this actuation is different from that of bimetal, because CTE of the CFRP layer is strongly anisotropic due to directionality of its reinforcement fiber. As CTEs of the CFRP layer and the aluminum plate in the fiber direction are quite different from each other though they are close to each other in the transverse direction, smooth and uni-directional actuation is possible even when the material has large dimension in the width direction.

As a sensor for this active composite, a simple and effective optical loss type sensor was proposed by Asanuma as shown in Fig. 4. As the sensing part is formed inside the matrix without the necessity of alignment of the fibers’ optical axes, a tube for the alignment and an adhesive for fixing the fibers inside the tube, which enables the formation of a simple, compact, robust and low cost fiber optic sensor are not necessary. In comparison with conventional strain gages, it does not need insulator and leading wires, and its fibrous shape is also very convenient for its embedment in composites. Though this sensor might not be suitable for general strain measurements, it will be used for shape control of the active composite.

In this study, the uni-directional actuation type active composite optical loss type sensor was proposed by Asanuma as shown in Fig. 4. As the sensing part is formed inside the matrix without the necessity of alignment of the fibers’ optical axes, a tube for the alignment and an adhesive for fixing the fibers inside the tube, which enables the formation of a simple, compact, robust and low cost fiber optic sensor are not necessary. In comparison with conventional strain gages, it does not need insulator and leading wires, and its fibrous shape is also very convenient for its embedment in composites. Though this sensor might not be suitable for general strain measurements, it will be used for shape control of the active composite.

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composite was fabricated and its fundamental performances such as curvature change and generation of force were observed and evaluated in detail. After establishment of its fabrication, the newly proposed optical loss type sensor was attempted to be formed in the active composite for monitoring its curvature change.

2. Experimental

2.1. Fabrication of the active laminate

The materials used in this study are summarized in Table 1. The CFRP prepreg was used as low CTE material and heater. The aluminum plate was used as high CTE material. The epoxy adhesive film was used as an insulator between the CFRP prepreg and the aluminum plate. The copper foil was used to form electrodes for electric resistance heating of the CFRP layer. Quartz and single mode type optical fiber with core and clad of 10 and 125 μm diameter was used for the formation of sensor. Resin jacket of the optical fiber was partially removed with a jacket stripper and the exposed fiber was cleaned with ethanol for embedment in the active laminate.

The CFRP prepreg and the copper foil were cut into pieces. Bonding surface of the copper foil was roughened with water proof #600 abrasive paper and degreased with methyl ethyl ketone. These were piled up as shown in Fig. 5(a) to be consolidated by hot pressing under the conditions, that is, at the temperature of 453 K, under the pressure of 0.1 MPa and for the period of 7.2 ks. Then, the aluminum plate and the adhesive film were cut into pieces and the aluminum plate was roughened with water proof #320 abrasive paper and degreased with methyl ethyl ketone. These were piled up as shown in Fig. 5(b) with the previously consolidated CFRP prepreg and copper electrodes layer, and hot pressed at 448 K under 0.1 MPa and for 3.6 ks to obtain the active laminate shown in Fig. 5(c).

2.2. Measurement of curvature of the active laminate

Schematic diagram of the curvature measurement set-up is shown in Fig. 6. The active laminate specimen was put on the block having supporting edges of 50 mm span and heated by electric resistance heating of carbon fiber in the CFRP layer. The central point $P_1$ and the other two points near the supporting edges $P_2$ and $P_3$ on the specimen surface were selected for evaluation of the curvature. In general, the coordinates are given as $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$, $P_3(x_3, y_3, z_3)$, where $x_1 = 0$ mm, $y_2 = -20$ mm and $x_3 = 0$ mm in this experiment. $z_1$, $z_2$, and $z_3$ were measured with the laser displacement sensor attached to the $x$–$y$ stage. Average curvature of the specimen was calculated using these data under the assumption that those three points exist in the same circle. The curvature $r^{-1}$ is generally given in Eq. (1) which can be simplified using the above

| Material          | CTE, $\alpha$ (10^{-6} K) | Thickness, t (mm) | Type                        |
|-------------------|-----------------------------|-------------------|-----------------------------|
| Aluminum plate    | 23.6                        | 0.2               | A1050P-H24                  |
| CFRP prepreg      | 0.7                         | 0.12              | P3060B-12 (Fiber: Torayca T300 (V_f = 0.6), Resin: 453 K cure type epoxy resin (#3601)) produced by Toray Co., Ltd. |
| Epoxy adhesive film | 60                         | 0.25              | Redux 319 produced by Hexcel Composites Ltd. |
| Copper foil       | 16.5                        | 0.02              | C1100                       |

Table 1. The materials used in this study.
conditions

\[ r^{-1} = \frac{1}{\sqrt{(x - a)^2 + (z - b)^2}} \]  

(1)

where

\[ a = \frac{B(CD - AF) + C(AE - BD)}{2A(AE - BD)}, \quad b = \frac{AF - CD}{2(AE - BD)} \]

\[ A = x_1 - x_2, \quad B = z_1 - z_2, \]

\[ C = (x_1^2 - x_2^2) + (z_1^2 - z_2^2), \quad D = x_3 - x_1, \]

\[ E = z_3 - z_1, \quad F = (x_3^2 - x_1^2) + (z_3^2 - z_1^2) \]

2.3. Measurement of output force of the active laminate

In Fig. 7, schematic diagram of the output force measurement set-up is shown. The active laminate was put on the same block used for curvature measurement, and was fixed with the punch, which was heated and the force generated against the punch was measured with the load cell. Temperature of the specimen was measured with the thermocouple attached to the center of the CFRP layer.

2.4. Method to form a fiber optic loss type sensor in the active laminate

The process to form the optical loss type fiber optic sensor in the active laminate is shown in Figs. 8 and 9. First of all, pre-notches were made on optical fiber with an optical fiber cutter and it was placed in the laminate of CFRP prepreg and copper foils as shown in Fig. 8 (a). This pile was hot pressed under the conditions of 453 K, 0.1 MPa and 7.2 ks. Next, this consolidated layer was bent with the rod as shown in Fig. 8(b) to break the embedded optical fiber at every pre-notch under monitoring optical loss by using the LD light source of 0.67 μm wavelength and the power meter. Finally, this layer was laminated with other materials as shown in Fig. 9(a) and hot pressed at 448 K, under 0.1 MPa and for 3.6 ks to obtain an active composite with embedded optical loss type sensor shown in Fig. 9(b).
2.5. Monitoring of curvature of the active composite with the sensor

In Fig. 10, schematic diagram of the curvature and optical loss measurement set-up is shown. The laminate was put on the same block and its embedded optical fiber was connected to the LD light source of 0.67 μm wavelength and the power meter. Variation of the optical loss was monitored during curvature change of the active composite.

3. Results and discussion

3.1. General views and cross-sections of the active laminate

Shapes of the obtained active laminate are shown in Fig. 11(b) by electric resistance heating of the CFRP layer under the applied voltage of 3.6 V and current of 1.4 A/mm$^2$.

Cross-sections of the active laminate near the center and near the end including electrode are given in Fig. 12. The CFRP layer is bonded well with the aluminum layer having adhesive layer of about 45 μm thickness as shown in Fig. 12(a), and a part of the carbon fiber filaments are observed to be in contact with the copper electrode as
shown in Fig. 12(b). The contact between them proved to be good enough because its contacting resistance at room temperature was experimentally obtained as 0.005 Ω which is negligibly small compared with that of the CFRP layer 0.428 Ω because there was no excessive heating at the electrodes when the laminate was kept at the hot pressing temperature by electric resistance heating.

3.2. Generations of curvature change and output force of the active laminate as a function of temperature

Curvature change and generated force of the active laminate when it was heated by electrical resistant heating of carbon fiber from 313 K up to the hot pressing temperature 448 K are shown in Figs. 13 and 14, respectively.

According to Fig. 13, curvature of the active laminate linearly decreases with increasing temperature up to the hot pressing temperature. Though thermal cycles were applied to the active laminate up to 100 times, there was no hysteresis, and its curvature at 313 K and the temperature where the curvature becomes zero after each cycle were reproducible.

As shown in Fig. 14, output force of the active laminate generated against a fixed punch linearly increases with increasing temperature up to around the glass transition temperature of the resin phase 390 K, and tends to saturate and reduce above this temperature. The output force at higher temperature range was found to reduce during holding. So the maximum force generated at an elevated temperature, which does not reduce even during holding for 3.6 ks, was defined as the output force limit. It was examined by moving down the punch to increase output force and holding for 3.6 ks at 343 K, and the same process was repeated at three more elevated temperatures. The results are shown in Fig. 15. According to this figure, the temperature dependence of the output force limit can be expressed as a linear line in the experimental temperature range. This line shows the upper boundary of output force which does not reduce even during holding for 3.6 ks at each temperature. It becomes almost zero at around 385 K which corresponds with the glass transition temperature of the resin phase.

3.3. Optical fiber embedded active composite

An example of the pre-notch made on optical fiber with an optical fiber cutter is shown in Fig. 16. The length and the depth are about 50 and 5 μm, respectively. This pre-notch
obviously degraded the optical fiber and its fracture radius increased from 1.3 to 56 mm.

In Fig. 17, a cross-section of the active composite with embedded optical fiber is shown. According to this figure, the optical fiber is placed adjacent to the surface to be subjected to almost the largest tensile strain and bending in this composite.

In Fig. 18, the effect of fracture number \( m \) of embedded optical fiber on the relation between curvature and optical transmission loss of the active composite is shown. According to this figure, the optical loss as a function of curvature is clearly increased by the increase in number \( m \) from 1 to 10. So the multiple fracture of the embedded optical fiber at its prenotches is effective to form a sensitive sensor for curvature monitoring of the active composite. As shown in Fig. 19, the relation between curvature and optical transmission loss of the active composite with 10 optical fiber fractures \( (m = 10) \) is reproducible up to at least 100 thermal cycles. So, the proposed one is accepted as a sensor for shape control of the active composite.

In this active composite, there are different kinds and roles of interfaces, that is, the aluminum (muscle)/CFRP (bone) interface where adhesive and insulation interphase exists, the optical fiber (nerve)/CFRP interface as well as conventional interface such as the carbon fiber/epoxy matrix. According to the performances of the multifunctional composites obtained in this study, they are mutually working well in the complicated material system.

4. Conclusions

In order to demonstrate one useful example of active and sensitive structural materials, an active composite with embedded sensor was proposed by changing the designing concept from conventional rigid one by symmetric laminating to active one by asymmetric lamination and heat generation by itself, and by formation of a sensitive fiber optic sensor in it. In this study, a uni-directional actuation type active composite plate was fabricated and its fundamental performances such as curvature change and generation of force were observed and evaluated in detail. After establishment of its fabrication, the newly proposed sensor was tried to be formed in the active composite to monitor its curvature change. The important results obtained are as follows:

1. An active laminate can be prepared by hot-pressing of metal plate such as aluminum as high CTE material (as muscle), CFRP prepreg as low CTE material (as bone) and electric resistance heater (as blood vessel), polymer adhesive film as insulator between them, and copper foils as electrodes.
2. Curvature of the active laminate linearly changes with electric resistance heating of the CFRP layer and cooling.
between room temperature and its hot pressing temperature.
3. Output force generated by the active laminate against a fixed punch during heating from room temperature up to around glass transition temperature of the resin phase almost linearly increases with increasing temperature, and above this temperature range, it saturates and decreases.
4. Optical fiber, which was multiply pre-notched, embedded in the CFRP layer and then broken at the notches in it, works as a sensitive optical loss type sensor (as nerve) to monitor curvature change of the active composite.

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