Development of High Performance CFRP/Metal Active Laminates*

Hiroshi ASANUMA**, Osamu HAGA** and Masataka IMORI**

This paper describes development of high performance CFRP/metal active laminates mainly by investigating the kind and thickness of the metal. Various types of the laminates were made by hot-pressing of an aluminum, aluminum alloys, a stainless steel and a titanium for the metal layer as a high CTE material, a unidirectional CFRP prepreg as a low CTE/electric resistance heating material, a unidirectional KFRP prepreg as a low CTE/insulating material. The aluminum and its alloy type laminates have almost the same and the highest room temperature curvatures and they linearly change with increasing temperature up to their fabrication temperature. The curvature of the stainless steel type jumps from one to another around its fabrication temperature, whereas the titanium type causes a double curvature and its change becomes complicated. The output force of the stainless steel type attains the highest of the three under the same thickness. The aluminum type successfully increased its output force by increasing its thickness and using its alloys. The electric resistance of the CFRP layer can be used to monitor the temperature, that is, the curvature of the active laminate because the curvature is a function of temperature.

Key Words: Smart Material, Actuator, Multifunction, Laminate, Metal, Composite, Carbon Fiber

1. Introduction

Composite materials, hybrid materials and fiber-metal laminates[1] have been developed mainly because of their high mechanical properties such as specific strength, specific Young’s modulus and/or fatigue strength to replace such conventional materials as aluminum alloys for aerospace applications. Toward future, material functions will be of increasing importance to make those materials more reliable, smart and/or cost effective. They are able to acquire new functions by embedding functional materials, or they might already have useful functions in themselves.

In the case of developing active and smart structural materials, shape memory alloys and piezoelectric ceramics have been mainly used[2,3], but Asanuma proposed another effective active material by making use of thermal deformation of CFRP/metal laminates with electric resistance heating of the carbon fibers in the CFRP[4,5]. An example can be made by laminating a metal plate as a high CTE (coefficient of thermal expansion) material and CFRP prepreg as a low CTE material/in-situ electric heater with a thin insulating layer between them. The most simple and useful actuation of this laminate is unidirectional as shown in Fig. 1. The way of this actuation is different from that of bimetal, because CTE of the CFRP layer is strongly anisotropic due to directionality of its re-

* Received 28th May, 2005 (No. 05-4201)
** Department of Electronics and Mechanical Engineering, Chiba University, 1–33 Yayoicho, Inage-ku, Chiba-shi, Chiba 263–8522, Japan.
E-mail: asanuma@faculty.chiba-u.jp
Table 1  Materials used in this study

<table>
<thead>
<tr>
<th>Material</th>
<th>Function</th>
<th>Thickness, t/mm</th>
<th>CTE, α/10^−6K⁻¹</th>
<th>Young's Modulus, E/GPa</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure aluminum plate</td>
<td>High CTE</td>
<td>0.2, 0.4, 0.8</td>
<td>23.6</td>
<td>72</td>
<td>*1</td>
</tr>
<tr>
<td>2024 aluminum alloy plate</td>
<td></td>
<td>0.8, 1.6, 3.2</td>
<td>22.9</td>
<td>72.4</td>
<td>*2</td>
</tr>
<tr>
<td>7075 aluminum alloy plate</td>
<td></td>
<td>0.8, 1.6, 3.2</td>
<td>23.4</td>
<td>71</td>
<td>*3</td>
</tr>
<tr>
<td>Stainless steel plate</td>
<td></td>
<td>0.2</td>
<td>16</td>
<td>198</td>
<td>*4</td>
</tr>
<tr>
<td>Pure titanium plate</td>
<td></td>
<td>0.2</td>
<td>8.9</td>
<td>116</td>
<td>-</td>
</tr>
<tr>
<td>CFRP prepreg</td>
<td>Low CTE/heater</td>
<td>0.1</td>
<td>0.7</td>
<td>130</td>
<td>*5</td>
</tr>
<tr>
<td>KFRP prepreg</td>
<td>Low CTE/insulator</td>
<td>0.15</td>
<td>-1.5</td>
<td>77</td>
<td>*6</td>
</tr>
<tr>
<td>Pure copper foil</td>
<td>Terminal</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*1: A1050P-H24  
*2: A2024P-T3  
*3: A7075P-T6  
*4: SUS304  
*5: P3052S-10 (Vf=0.60) produced by Toray Co., Ltd.  
   (Fiber: Torayca T700S. Resin: 393K cure type epoxy resin #2500.)  
*6: PC0S-F-14 (Vf=0.56) produced by Toray Co., Ltd.  
   (Fiber: Kevler 49 type 968. Resin: 393K cure type epoxy resin #2500.)

inforcement 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 unidirectional actuation is caused.

In the previous study(6), a unidirectional actuation type CFRP/Al laminate was selected and its fabrication condition, performances of its electrodes and the CFRP layer as a heater, and actuator performances such as curvature change and force generation as a function of temperature were examined.

In this study, the effects of the kind of the metal layer and its thickness on the performances of the active laminates were mainly examined in order to enhance them. In addition, the condition of the heating temperature to enable their repeatable actuation and the possibility of using the carbon fiber as a temperature sensor were also examined.

2. Experimental

2.1 Fabrication of active laminates

The materials used in this study are summarized in Table 1. The metal or alloy plate was used as the high CTE material. The CFRP prepreg was used as the low CTE/heating material. The KFRP prepreg was used as the low CTE material and the insulator between the metal or alloy plate and the CFRP layer. The copper foil was used to form the electrodes for electric resistance heating of the CFRP layer. The metal or alloy plate, the CFRP prepreg, the KFRP prepreg and the copper foil were cut into pieces. Bonding surfaces of the metal or alloy plate and the copper foil were roughened with a #320 abrasive paper and degreased with methyl ethyl ketone. They were prepared as shown in Fig. 2 and consolidated by hot pressing under the conditions of 393 K, 0.1 MPa and 3.6 ks.

2.2 Evaluation of active laminates

A schematic diagram of the curvature measurement setup is shown in Fig. 3 (a). The active laminate was put on the block which has supporting edges of 50 mm span. The central point and the other two points on the central line near the supporting edges were selected for evaluation of the curvature. Those positions were measured with the laser displacement sensor attached on the x-y stage. Average curvature of the specimen was calculated using the data under the assumption that those exist on the same circle.
Electric resistance of the CFRP layer in the active laminate during actuation can be calculated by dividing the applied voltage by the current. Electric resistance of a CFRP layer without lamination, which is not subject to curvature change, was also examined as a reference to clarify effect of the curvature change on the electric resistance.

In Fig. 3 (b), a 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 fixed with the punch, which was heated and the force generated against the punch was measured with the load cell.

### 3. Modelling of Active Laminate

As modeled in the previous study\(^{(6)}\), the active laminate was assumed as a three layered beam and its curvature obtained by the temperature decrease \(\Delta T\) from the temperature where its curvature becomes zero (around the hot pressing temperature 393 K) was calculated. This curvature \(r^{-1}\) can be expressed as Eq. (1).

\[
\frac{1}{r} = \frac{2(E_1\alpha_1 t_1 + E_2\alpha_2 t_2 + E_3\alpha_3 t_3)\Delta T}{E_1(t_1+2a)+E_2(t_2+2(a+t_1))+E_3(t_3+2(a+t_1+t_2))}
\]

where

\(E_1, E_2, E_3\): Young’s modulus

\(\alpha_1, \alpha_2, \alpha_3\): CTE

\(t_1, t_2, t_3\): thickness of layer

\(a\): distance from the neutral axis to the surface of layer 1

\(\Delta T\): temperature decrease

### 4. Results and Discussion

#### 4.1 Effect of kind of metal layer

As the laminates were fabricated by hot pressing in a flat die, they bent during cooling due to large contraction of the metal plate compared with that of the FRP (CFRP/KFRP) layer.

The effect of the kind of the metal under constant thickness of 0.2 mm, that is, CTE and Young’s modulus of it, on the curvature of the laminate at 313 K was calculated by using the Eq. (1), and the result is given in Fig. 4, where the experimental results of the active laminates using aluminum, stainless steel and titanium are also shown.

According to this figure, CTE of higher value and Young’s modulus of higher than about 50 GPa are preferred for the metal layer, so aluminum is the best out of the three. It is clear that the experimented results coincide well with the theoretical values. In the case of titanium, the error becomes the largest, of which main reason is considered that it has a double curvature bending as shown in Fig. 5 due to the CTE mismatch existing not only in the fiber direction but also in the transverse direction. The shape of the laminate using stainless steel at this temperature has a single curvature bending as the aluminum type does as shown in the same figure.
4.2 Effect of temperature on curvature and output force of active laminates

In order to evaluate the performances of the active laminates, they were heated by electric resistance heating of the CFRP layers, and the results, that is, the effect of temperature on the curvatures and the output forces of the active laminates using the pure aluminum, the stainless steel and the pure titanium plates were obtained as shown in Fig. 6.

As shown in Fig. 6 (a), the curvature of the aluminum type laminate linearly decreases with increasing temperature up to around the hot pressing temperature 393 K and coincides with the theoretical value. In the cases of the other two, the values deviate from the theoretical values with increasing temperature, and the stainless steel type causes a sudden shape change at around 393 K.

As for the generated forces shown in Fig. 6 (b), the stainless steel type active laminate generates the highest and a little higher force than that of the aluminum type. From 313 K up to around 360 K, their forces increase linearly with increasing temperature, whereas the titanium type does not generate force due to its complicated shape change. Above this temperature range, all of them change their slopes and continue to increase, but the stainless steel type stops increasing at 393 K due to its sudden shape change which appears as its sudden curvature change shown in Fig. 6 (a).

4.3 Higher performance active laminates based on aluminum

In order to increase the output force of the aluminum type laminate, the thickness of the aluminum plate was increased from 0.2 to 0.4 and 0.8 mm, and its effect on the curvature and the output force were examined. In all of the cases, the curvatures linearly decrease with increasing temperature from 313 K up to 393 K where they all become zero. These experimented results coincide well with the theoretical values in this temperature range. They tend to deviate from the theoretical values above this temperature range. The curvature becomes smaller with increasing the thickness in this temperature range, but the generated force of the active laminate increases with increasing thickness at the sacrifice of the curvature. They increase linearly with increasing temperature up to around the glass transition temperature of the matrix resin 360 K, and then the slopes decrease up to around 420 K, and then saturate and decrease.

In order to improve the higher temperature performances, the aluminum alloy plates were used. The curvatures and the output forces of the laminates using the 0.8 mm thick pure aluminum and aluminum alloy plates were obtained as a function of heating temperature and are shown in Fig. 7. The aluminum alloy type laminates maintain their linear curvature decrease and output force increase up to higher than 410 K, whereas pure aluminum can do so only up to about 390 K. So it became clear that the performances at the higher temperature range can be improved by using the aluminum alloys instead of using pure aluminum.

Finally the thickness of the aluminum alloy plates was increased up to 1.6 and 3.2 mm to obtain much higher force at the sacrifice of the curvature. As shown in Fig. 8, it is clear that the output forces of the both aluminum alloy type active laminates increase up to as high as about 250 N.

4.4 Temperature limit for repeatable actuation

The pure aluminum and aluminum alloy type active laminates were heat cycled from 313 K up to a maximum
Fig. 7 The curvature $r^{-1}$ (a) and the output force $f$ (b) changes of the active laminates under the constant metal thickness $t_{\text{Metal}} = 0.8$ mm and width $w = 40$ mm using pure aluminum, A2024 alloy and A7075 alloy with increasing temperature $T$. The output force was measured under constant span of supporting edges $s = 50$ mm.

Fig. 8 Effect of the thickness $t_{\text{Metal}}$ of the aluminum alloy plates on the curvature $r^{-1}$ at $313$ K (a) and the maximum output force $f_{\text{max}}$ (b) of the active laminate under the constant specimen width $w = 40$ mm. The output force was measured under the constant span of the supporting edges $s = 50$ mm.

In Fig. 9, the curvature changes during the heating and cooling cycles up to 413, 433 and 453 K are shown. Up to 413 K, there are no hysteresis observed in all cases. But, up to 433 K, a slight hysteresis started to appear only in the case of pure aluminum type. The aluminum alloy types did not cause any hysteresis up to 453 K. According to these results, the aluminum alloy types are able to increase the limitation of service temperature.

As for the output force changes during the heating and cooling cycles up to 343, 358, 363 and 368 K, there are no hysteresis observed in all cases up to 358 K. But, up to 363 K, a slight hysteresis started to appear only in the case of pure aluminum. During the cycle to 368 K, all of the types caused hysteresis. According to these results, it also became clear that the aluminum alloys are able to increase the limitation of service temperature.

4.5 Electric resistance change of CFRP

The electric resistance of the CFRP layer in the active laminate using 0.2 mm thick pure aluminum plate was measured as a function of temperature during actuation, and that of the CFRP reference which is not subject to the curvature change was also measured as a reference, in order to investigate the effect of the curvature change on the electric resistance of the laminated CFRP. The results are shown in Fig. 10. According to the results, the electric resistance change of the laminated CFRP layer is proportional to its temperature change and is almost the same as...
Fig. 10 Electric resistances $R$ of the active laminate and the CFRP as reference as a function of temperature $T$.

That of the reference, that is, the curvature does not affect its electric resistance in this case. So, it can work as a temperature sensor and can be used to monitor the curvature because it is a function of temperature.

5. Conclusions

In order to develop high performance CFRP/metal active laminates, various types of the laminates were made by hot pressing of an aluminum, aluminum alloys, a stainless steel and a titanium with the other materials, and the following conclusions were obtained.

(1) The aluminum type and the aluminum alloy types have almost the same and the highest room temperature curvatures and they linearly change with increasing temperature up to their fabrication temperature, above which the alloy types still maintain their linearity.

(2) The curvature of the stainless steel type jumps from one to another around its fabrication temperature, whereas the titanium type causes a double curvature and its change becomes complicated.

(3) The output force of the stainless steel type attained the highest value of the three under the same thickness. In order to successfully increase the output force of the aluminum type, its alloys were used and their thicknesses were increased.

(4) The electric resistance change of the CFRP layer can be used for temperature sensing and monitoring of the curvature because it is a function of temperature.

References


