Fabrication of Nickel Based Active Composites*

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This paper describes fabrication of an active metal-matrix composite working at elevated temperatures. To realize this material, a SiC fiber reinforced nickel layer was laminated on a unreinforced nickel one with an aluminum insert. Fabrication condition of this material was examined and the most appropriate one, that is, hot-pressing temperature of 993 K, pressure of 27 MPa and time of 4.8 ks in a low vacuum of 1×10^2 Pa using a 0.1 mm thick insert was obtained in the experimental range. Curvature of the composite monotonously changes with increasing temperature up to and higher than 1 200 K. A cyclic heating was also performed on the composite by increasing the maximum temperature from 373 K up to 1 273 K in 100 K steps, and it was found that its curvature change has no hysteresis up to 673 K, and has hystereses but is reproducible at 773 K and 873 K, and is no longer reproducible when heated up to 973 K and above.

Key Words: Composite Material, Thermal Stress, Bending, Actuator, Active Material, Metal Matrix Composite, Fiber Reinforced Metal, Nickel, SiC Fiber

1. Introduction

Advanced composites with embedded active materials are attracting worldwide interest because of their potential applications. For example, they will be able to replace such complicated mechanical systems as flow control valves, hatches, doors, flaps, air brakes and others, without using hinges and actuators.

In the case of developing those active composites, shape memory alloys and piezoelectric ceramics have been mainly used^{(1),(2)}. Asanuma already proposed a different approach to develop active composites by making use of the thermal deformation of composites⁽³⁾. As the conventional composites have been designed to suppress the thermal deformation by symmetrical lamination⁽⁴⁾, high thermal stresses are

usually produced in them. A part of them can be released by deformation, which can be regarded as an actuation function. So, the active composites can be realized by changing the designing concept from the conventional rigid composites made by symmetric lamination to deformable composites by asymmetric one.

An example of the concept of the active composites is schematically shown in Fig. 1. The reinforcement fiber works as a "bone," the matrix works as a "muscle" and the functional fiber works as a "nerve" or a "blood vessel."

In this study, the concept of the thermal-deformation type active composites was applied to a fiber reinforced nickel to make a high temperature active composite, and its fundamental performances such as curvature change as a function of temperature and its reproducibility were investigated.

2. Experimental

2.1 Fabrication of the active composite

0.1 and 0.3 mm thick, 30 mm wide, 60 mm long and 99.7% purity nickel plates were used as the matrix,

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Fig. 1 A new FRM based active material

and SiC fiber of 0.14 mm diameter produced by Textron Systems (Type SCS-6) was used as the reinforcement. Pure aluminum foil or plate of 0.01, 0.018 or 0.1 mm thickness was used as an insert. These materials were prepared as shown in Fig. 2 and they were hot-pressed under various conditions, that is, temperatures of 983, 993, 1 003 and 1 013 K, pressures of 27 and 33 MPa and periods of 2.4, 3.6 and 4.8 ks, in a low vacuum of 1×10^{-2} Pa.

2.2 Evaluation of the active composite

The sample obtained under the best fabrication condition was heated from room temperature up to 1 273 K in an electric furnace and cooled down to room temperature, of which shape was recorded with a digital camera for calculation of its curvature. The same type of sample was also exposed to thermal cycles, where the maximum temperature was increased after the each cycle from 373 K up to 1 273 K in 100 K steps.

A schematic illustration of the active composite with the coordinates and the points for calculation of its curvature is shown in Fig. 3. The point near the center P_1 and the other two points at the edges of the specimen P_2 and P_3 were selected for evaluation of the curvature. The coordinates are given as $P_1(x_1, y_1)$, $P_2(x_2, y_2)$, $P_3(x_3, y_3)$, where P_1 is fixed at the origin, that is, $(x_1, y_1) = (0, 0)$ in this experiment. Average curvature of the active composite was calculated under the assumption that those three points exist on

Fig. 2 Cross sections of the materials prepared for hot-pressing

Fig. 3 A schematic illustration of the active composite with the points P_1 , P_2 , P_3 and coordinates to evaluate its average curvature

the same circle. The curvature r^{-1} can be given by Eq. (1).

$$r^{-1} = \frac{1}{\sqrt{(x-a)^2 + (y-b)^2}} \quad (1)$$

where

$$a = \frac{B(CD - AF) + C(AE - BD)}{2A(AE - BD)}$$

$$b = \frac{AF - CD}{2(AE - BD)}$$

$$A = x_2 - x_3$$

$$B = y_2 - y_3$$

$$C = (x_2^2 - x_3^2) + (y_2^2 - y_3^2)$$

$$D = x_1 - x_2$$

$$E = y_1 - y_2$$

$$F = (x_1^2 - x_2^2) + (y_1^2 - y_2^2)$$

3. Results and Discussion

3.1 Fabrication of the active composite

The nickel plates were successfully bonded only when the thickest aluminum plate (0.1 mm) was used. The most appropriate hot-pressing condition in the experimental range was found to be at the temperature of 993 K, under the pressure of 27 MPa and for the period of 4.8 ks, where the microstructure shown in Fig. 4 was obtained. Most of the reaction zones observed in the microstructures proved to consist of Ni_2Al_3 intermetallic phase due to XRD analysis and the results of the EPMA line analyses shown in the same figures.

Fig. 4 SEM images of cross sections of the active composite (a) with and (b) without a SiC fiber and the results of EPMA line analyses of nickel and aluminum along the lines (a) A-B and (b) C-D shown in the images

Fig. 5 The shape of the active composite at room temperature measured with a laser displacement sensor

In Fig. 5, shape of the composite at room temperature measured with a laser displacement sensor attached on a x-y stage is shown. It is apparently bent in the fiber direction due to the large CTE (coefficient of thermal expansion) mismatch between the SiC fiber reinforced nickel layer and the unreinforced nickel layer. It has also slight curvature in the transverse direction due to the small CTE mismatch between them. This problem can be solved by adding a reinforcement of smaller aspect ratio in the unreinforced layer to adjust the CTEs of them in the transverse direction.

3.2 Actuation of the active composite

A sample fabricated under the best hot-pressing condition was heated and its curvature as a function of temperature was obtained as shown in Fig. 6. The

Fig. 6 Effect of temperature on the curvature of the active composite during a heating and cooling cycle between room temperature and 1 273 K

figure shows that the curvature continues to increase up to and higher than 1 200 K and the shape drastically changes as shown in Fig. 7. These results mean that this material system has a possibility to work as a high temperature active material.

In Fig. 8, the effect of the maximum temperature of the heating and cooling cycles on the profile of curvature change of the active composite is shown when the maximum temperature was increased from 373 K up to 1 273 K in 100 K steps. According to this figure, the curvature change has no hysteresis up to 673 K, and has hysteresis but is reproducible at 773 K and 873 K, and is no more reproducible at 973 K and

above. The reason for the hysteresis at 773 K and 873 K is the cracking appeared in the intermetallic layer as shown in the SEM image of Fig. 9(b), and the reason for the deviation of the curvature at 973 K and above is the sliding between the fiber and the matrix.

Fig. 7 The shapes of the active composite at (a) room temperature and (b) 1273 K

Fig. 8 Effect of the maximum temperature of the heating and cooling cycles on the profile of curvature change of the active composite

as shown in Fig. 9(c) and (d).

4. Conclusions

(1) A SiC/Ni active composite was obtained by laminating a continuous SiC fiber reinforced nickel layer on a unreinforced nickel layer with an aluminum insert to reduce fabrication temperature, pressure and time.

(2) It was successfully obtained by hot-pressing at the temperature of 993 K, under the pressure of 27 MPa, for the period of 4.8 ks and in the low vacuum of 1×10^2 Pa using an insert of 0.1 mm thick aluminum, where Ni_2Al_3 intermetallic layer was formed near the bonded plane of the matrix nickel plates.

(3) Its curvature monotonously changes with

Fig. 9 SEM images of the active composite at room temperature after heating and cooling cycles up to the maximum temperature of (a) 673 K, (b) 773 K, (c) 973 K and (d) 1 273 K

increasing temperature up to 1 273 K and the shape drastically changes, which means that this material system has a possibility to work as a high temperature active material.

(4) A cyclic heating was performed on the composite by increasing the maximum temperature from 373 K up to 1 273 K in 100 K steps, and it was found that the curvature change has no hysteresis up to 673 K, and has hystereses but is reproducible at 773 K and 873 K, and is no more reproducible at 973 K and above.

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