Thermal Expansions and Mechanical Properties of Al/C and Al/(SiC+C) Composites Based on Wood Templates

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Wood is a natural material with a rational and aesthetic structure. Recently, we have succeeded in using wood as a template to produce Al/C and Al/(SiC+C) composites. Porous carbon was first pyrolyzed from the wood template. The final composites were then obtained by injecting aluminum alloy and silicone resin into the porous carbon. The microstructures, thermal expansions, and mechanical properties of these products were then analyzed. The results indicated that the structures of the composites are controlled by the natural structure of wood. Moreover, the composites exhibit a lower coefficient of thermal expansion than aluminum and are stronger than the porous carbon. [doi:10.2320/matertrans.47.2576]

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1. Introduction

Usually, the structures of metal matrix composites depend on the artificial fabrication processes. Through these processes, we can determine the diameter of fibers, shape and size of the granules, distribution of the components in composites, etc. However, the technique of fabricating materials with desired and delicate microstructures is still not simplified and easy. Wood, after hundreds of millions of years of evolution, possesses rational and graceful microstructures that cannot be obtained artificially. It can be considered as a natural composite material with a hierarchical architecture, where cellulose, hemicellulose, and lignin form cellular microstructures.^{1,2)} In wood structures, there exists large number of channels made up of cells. Through these channel-structures, water and mineral elements can be transported to every part of the tree. Moreover, it should be noted that a huge tree is capable of standing up in the wind on its thin trunk for hundreds of years. This is possible due to its high strength, modulus, and stiffness.³⁻⁵⁾ These outstanding mechanical properties of the tree can be attributed to its rational structures; this can give us illumination for manufacturing metal matrix composites.

When heated at high temperatures, the mixed biopolymers in wood are decomposed into carbon and gases. This gives rise to a porous carbon with the morphology derived from its wood template.⁶⁻¹⁰⁾ As an example, Figure 1 shows the microstructure of porous carbon obtained by carbonizing the wood of the lauan. The channel-structure of the wood was not damaged and was retained still in porous carbon perfectly. It was shown that this porous carbon has many favorable characteristics such as low coefficient of thermal expansion (CTE), stable coefficient of friction, good electromagnetic shielding properties, and high damping capacity. It can be used in several kinds of industrial fields to improve the performance of many new products.¹¹⁾ However, the me-

Fig. 1 Microstructure of porous carbon derived from the wood of lauan.

chanical properties of the C-preform are not as good as the properties mentioned above.²⁾ It is not applicable in the place where high loading is exerted. Therefore, the improvement of its mechanical properties is one of the attractive research subjects.

Aluminums alloys are used in internal combustion engines as in piston, cylinder blocks, and cylinder heads because of their high specific strength, good castability, and high wear resistance.¹²⁻¹⁵⁾ However, aluminum alloys have high CTE and they expand greatly in the friction heat, which gives serious influence on the stability of coefficient of friction. Therefore, the CTE of aluminum alloys has been recognized as one of the important thermomechanical properties, and many researches have been carried to reduce their CTE.^{16,17)}

In this study, an attempt has been made to manufacture an aluminum/carbon composite (Al/C) with a wood-like structure. Also, we manufactured the aluminum/(silicon carbide + carbon) composite (Al/(SiC+C)) by treating porous carbon with the silicone resin before injecting Al. The microstructures, thermal expansions, and mechanical properties of these products were analyzed.

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Fig. 2 Flow chart of the fabrication process.

2. Experimental

2.1 Sample preparation

The wood structure of lauan was used as a plant template. The wood was first pyrolyzed to produce porous carbon at 1400°C for 2 h in a vacuum. Then at a high temperature (730°C) and a high pressure (8.5 MPa), Al alloy (3.8 mass% Cu, 1.3 mass% Si, 0.5 mass% Mn, balance Al) was melt and injected into this porous carbon to manufacture Al/C composite.¹⁸⁾

To fabricate the Al/(SiC+C) composite, porous carbon was firstly changed to a mixed ceramic composed of silicon carbide and carbon (SiC+C). The SiC+C ceramic was produced by impregnating porous carbon with methyl organic silicone resin (solid content: 27.5–32.5%, solvent: isopropyl alcohol, structural formula:

curing the silicone resin at 80°C for 48 h, and sintering at 1400°C for 6 h in the vacuum condition. Then Al alloy was melt and injected into the SiC+C ceramic to manufacture Al/(SiC+C) composite. The processing scheme is summarized in Fig. 2.

2.2 Microstructure characterization

A scanning electron microscopy (SEM, S-520, Hitachi, Japan) was used to characterize the morphology. The phases of porous carbon and SiC+C ceramic were identified by a X-ray diffractometer (XRD, Cu-K α , Rigaku-D/maxA IIIX, Japan). The transmission electron microscopy (TEM, H-800,

Fig. 3 SEM image of the porous SiC+C ceramic derived from the wood of lauan.

Hitachi, Japan) was employed to examine the microstructure of the composite.

2.3 Thermal expansions and mechanical properties characterization

The CTE measurements were performed using a LK-02 high-speed quenching dilatometer (Adamel. Lhomargy, France). The sizes of the thermal expansion specimens were 2 × 2 × 12 mm³. During measurements, samples were cycled three times in the temperature range from 25 to 300°C. The heating/cooling rate was 10°C/min.

The mechanical property testing was performed using the material test system model (MTS 810, MTS, America). The rectangular three point bending specimens of 50 × 8 × 8 mm³ were cut from porous carbon, Al/C, and Al/(SiC+C). The span distance was 30 mm. Bending loading with a constant loading speed of 0.5 mm/min was applied and bending strength was measured. The compression test specimens of 10 × 8 × 8 mm³ were obtained from the three materials. The compression strength was measured with the loading speed of 0.5 mm/min.

3. Results and Discussion

3.1 Microstructure

Porous carbon could turn to porous SiC+C ceramic after it had reacted with the silicone resin at high temperature. Figure 3 shows the microstructure of the SiC+C ceramic. The SiC+C also retained the structure of the wood perfectly; this is similar to porous carbon in Fig. 1.

The XRD patterns (Fig. 4) reveal the difference between the SiC+C and porous carbon. The XRD pattern of porous carbon comprises only carbon peaks. On the other hand, in the XRD pattern of the materials subjected to the methyl organic silicone resin impregnation, curing, and sintering, the SiC peaks appear along with the carbon peak. First, the silicone resin in porous carbon was decomposed to a silicone compound (Si_xO_y) between 400–650°C, and the SiC was formed at temperatures exceeding 1400°C through the reaction between the carbon and silicone compound.¹⁹⁾ This

Fig. 4 XRD patterns of porous carbon and the SiC+C ceramic.

Fig. 6 SEM images of the Al fibers.

Fig. 5 SEM images of the composites [(a): Al/C; (b): Al/(SiC+C)].

indicates that it is a mixed material, *i.e.*, SiC+C, which is different from porous carbon.

After injecting Al alloy into the porous carbon and the SiC+C, the Al/C and Al/(SiC+C) composites were obtained. The structures of the composites were shown in Figs. 5(a) and (b). Compared with the porous materials in Figs. 1 and 3, the hollow channels in porous carbon were filled with Al alloy. It is noted that the composites retain perfectly porous carbon of its natural counterparts. The shape, the size, and the distribution of Al alloy are then controlled by the channel-structure of the wood. This is different from the traditional metal matrix composites with their structures obtained artificially.

Since there are plenty of channels in the templates, liquid Al alloy can flow into the channels at high temperature and the Al fibers were then formed after it solidifies. The shapes of fibers in the composite are shown in Fig. 6. The shape, the size, and the distribution of the fibers are as same as the channels. It is preferable that the diameter of every single fiber maintains uniformity along the length and continuity of fibers.

It is difficult to find out the difference between the two composites from the SEM images. However, the difference

could be revealed from their TEM images. Figures 7(a) and (b) show the TEM images of the interfaces in the Al/C and Al/(SiC+C) composites. It can be seen from Fig. 7(a) that Al alloy is combined with porous carbon without reaction product between them in the Al/C composite. On the other hand, in the Al/(SiC+C) composite in Fig. 7(b), there is an additional black layer between Al alloy and carbon; this is different from the microstructure of Al/C composite. This layer is just composed of SiC. This indicates that the silicone resin was firstly deposited on the inner surface of the channels and subsequently decomposed to silicone compound with increasing temperature. At the end, the reaction between the silicone compound and the carbon occurred in the channel wall to form SiC at 1400°C.¹⁹⁾

Table 1 gives a group data of these materials. The bulk density (geometrical density) was determined by measuring the weight and the volume of the cuboid specimens. The densities of the Al/C and Al/(SiC+C) are lower than that of Al alloy ($2.8 \times 10^3 \text{ kg/m}^3$). The volume percentage of Al alloy in Al/C can be calculated by the following law:

$$\rho_m + \rho_{Al}V_{Al} = \rho_C$$

Here, ρ_C , ρ_m , and ρ_{Al} represent the densities of the Al/C

Fig. 7 TEM images of the interfaces in the composites [(a): Al/C; (b): Al/(SiC+C)].

Table 1 Densities and content of some components in the materials.

	Porous carbon	Al/C composite	SiC+C	Al/(SiC+C) composite
Bulk density ($\times 10^3 \text{ kg/m}^3$)	0.22	2.67	0.27	2.71
Volume content of carbon (%)	—	12.5	8.2	8.2
Volume content of SiC (%)	—	0	4.5	4.5
Volume content of Al (%)	—	87.5	—	87.3

composite, porous carbon, and Al alloy, respectively. V_{Al} represents the volume percentage of Al alloy in the composites. It should be noticed that ρ_m is the bulk density of porous carbon; therefore, it need not multiplied by the volume percentage of the carbon. Similarly, the volume percentage of Al alloy in Al/(SiC+C) can also be calculated by the above law if ρ_C and ρ_m represent the densities of the Al/(SiC+C) composite and SiC+C, respectively. The calculated V_{Al} of Al/(SiC+C) is very close to that of Al/C, which is given in the last row of Table 1. Further, it is indicated that the porosities of SiC+C and porous carbon are almost identical; this indicates that the SiC formed only in the positions that were previously occupied by carbon, *i.e.*, the SiC replaced part of carbon. To determine the SiC content, it needs to be separated from the SiC+C ceramic during the process of burning off the residual carbon at 700°C for 4 h. Since the amount of SiC was maintained constant during the process, the content of SiC in the SiC+C ceramic can be calculated. Subsequently, the carbon content in the SiC+C ceramic can be determined.

3.2 Thermal expansions and mechanical properties

Figure 8 shows the CTE as a function of temperature for Al alloy, porous carbon, Al/C, and Al/(SiC+C). It can be seen that porous carbon has much lower CTE than Al alloy. Due to the function of porous carbon, the CTE of the Al/C composite was lower as compared to that of the Al alloy. It can also be seen that the CTE of the Al/(SiC+C) composite is a little lower than that of the Al/C composite; this is more obvious at high test temperatures. Usually, the CTE for SiC is around $5 \times 10^{-6} \text{ K}^{-1}$, being higher than that of the porous

Fig. 8 CTE as a function of temperature for Al alloy, porous carbon, Al/C, and Al/(SiC+C).

carbon. However, the replacement of porous carbon by SiC did not increase the CTE of Al/(SiC+C). This may be due to the high mechanical strength of SiC. SiC is stronger than porous carbon, as will be revealed by the results of mechanical property tests. The stronger component can prevent the expansion of Al fibers more efficiently.

Figures 9(a) and (b) show bending strength and compression strength of the porous carbon, Al/C, and Al/(SiC+C). Obviously, Al alloy can improve the strength of porous carbon remarkably. As shown in Fig. 9(a), bending strength of the Al/C composite is 462 MPa, which is far higher than

Fig. 9 Mechanical properties of the materials prepared in this study. [(a): Bending strength; (b): Compression strength]

that of porous carbon (10.3 MPa). Similarly, it can be seen from Fig. 9(b) that compression strength of the Al/C composite (729 MPa) is also far higher than that of porous carbon (33.4 MPa). Moreover, the SiC improved the strength of the composite further. The bending and compression strength of the Al/(SiC+C) composite has reached 484 MPa and 762 MPa, respectively.

It is supposed that the much more excellent bending and compression strength of the Al/C composite compared with porous carbon are related to the Al fibers preventing crack propagation. The brittle porous carbon in the composite was relatively weak compared to the Al fibers, so cracks initiated in the carbon and propagated into the whole section rapidly if there were no Al fibers. The Al fibers prevented the crack propagation efficiently so that the composite did not fracture immediately even when the cracks emerged.

The excellent bending strength of the Al/C composite may also be related partly to the compressive residual stress of porous carbon. Due to the big difference in CTE between porous carbon and Al alloy, it is supposed that as the sample was cooled following injecting metal, the compressive residual stress in the carbon and tension one in Al alloy will be introduced. Compressive stresses in the carbon are supposed to raise the fracture initiation stress effectively, and hence acts to hinder micro crack initiation.²⁰⁾

The fact that the mechanical properties of the Al/(SiC+C) composite are better than that of the Al/C composite is attributed to the reinforcing of the SiC. As stated above, the reaction between the silicone compound and the carbon took place to form the SiC+C ceramic. The hard SiC acts to raise the strength of the SiC+C in comparison with porous carbon. In addition, when Al alloy liquid was injected into the SiC+C ceramic, it could diffuse into SiC phase to form a thin SiC/Al composite, which could also improve the strength of the Al fibers.

On the earth exist more than three thousand kinds of wood. Different kinds of wood, however, may exhibit a wide range of the shape, size, and distribution of the channel-structure. For example, the channels in the softwood almost exhibit rectangle, but in the broad-leaved wood plenty of elliptical, triangular, hexagonal, and other polygonal channels are involved. The sizes of the channels in the softwood range usually between 0.5–10 μm , but in the broad-leaved wood between 0.5–200 μm . These characters of the channel-structure can influence thermal expansions and mechanical

properties of the composites based on wood. Also the ceramic phase in the composite is not confined to carbon and SiC. Other ceramic such as TiC and B₄C can also be obtained through the reaction between the carbon preform and the other compounds. Different ceramic phases have different effects on the properties of the composite. They are interesting subjects for research.

4. Conclusions

Wood is a natural material with rational and aesthetic structure. Based on its unique intrinsic structure, the Al/C and Al/(SiC+C) composites were produced by injecting Al alloy and methyl organic silicone resin into porous carbon derived from wood. Al alloy liquid could flow into the channels of the preform and form fibers after solidifying. The shape, the size and the distribution of the components in these composites are controlled by the natural structure of wood. The SiC layer could be obtained by the reaction between silicone resin and carbon preform.

The wood-template-based Al/C and Al/(SiC+C) composites have a lower CTE than Al alloy. Moreover, it is observed that their bending and compression strengths are also higher than those of porous carbon. The Al/(SiC+C) composite exhibited lower CTE and higher mechanical strength as compared to the Al/C composite. The present study suggests that this composite has an advantage; therefore, the method of producing wood-template-based composites could provide a new idea for composite design.

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REFERENCES

- 1) J. E. Mark and P. D. Calvert: *Mat. Sci. Eng. C* **1** (1994) 159–170.
- 2) P. Greil, T. Lifka and A. Kaindl: *J. Eur. Ceram. Soc.* **18** (1998) 1975–1983.
- 3) M. F. Ashby, K. E. Easterling, R. Harrysson and S. K. Maiti: *Proc. Roy. Soc. London A* **398** (1885) 261–280.
- 4) M. F. Ashby: *Acta Metall.* **37** (1989) 1273–1293.

- 5) M. F. Ashby: *Acta Metall.* **39** (1991) 1025–1039.
- 6) P. Ehrburger, J. Lahaye and E. Wozniak: *Carbon* **20** (1982) 433–439.
- 7) M. Patel, A. Karera and P. Prasanna: *J. Mater. Sci.* **22** (1987) 2457–2464.
- 8) B. H. Sun, T. X. Fan, D. Zhang and T. Okabe: *Carbon* **42** (2004) 177–182.
- 9) T. X. Fan, T. Hirose, T. Okabe and D. Zhang: *J. Porous Mater.* **8** (2001) 211–215.
- 10) W. M. Qiao, Y. Korai, I. Mochida, Y. Hori and T. Macda: *Carbon* **40** (2002) 351–358.
- 11) T. Okabe and K. Saito: *Advanced Materials '93*, V/A: Ecomaterials, Japan, 1994, 681.
- 12) M. A. Martinez, A. Martin and J. Llorca: *Scripta Metall. Mater.* **28** (1993) 207–212.
- 13) R. A. Somi, B. N. Pramila, K. S. Murthy and S. K. Biswas: *Wear* **171** (1994) 115–127.
- 14) P. R. Gibson, A. J. Clegg and A. Das: *Wear* **95** (1984) 193–198.
- 15) S. Das, S. V. Prasad and T. R. Ramachandran: *Wear* **133** (1989) 173–187.
- 16) K. C. Chan and J. Liang: *Composites Science and Technology* **61** (2001) 1265–1270.
- 17) L. D. Wang, W. D. Fei and C. K. Yao: *Materials Science and Engineering A* **336** (2002) 110–116.
- 18) T. C. Wang, T. X. Fan, D. Zhang and G. D. Zhang: *Carbon* **44** (2006) 900–906.
- 19) D. Zhang, B. H. Sun and T. X. Fan: *Science in China Series E-Engineering and Materials Science* **47** (2004) 470–478.
- 20) X. Q. Xie, D. Zhang, T. X. Fan, T. Sakata, H. Mori, T. Okabe and T. Hirose: *Mater Let.* **56** (2002) 102–107.