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LETTER

Fabrication, thermal expansions, and mechanical properties of carbon/aluminum composites based on wood templates

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Introduction

Usually, the shape, the size, and the distribution of the components in metal matrix composites depend on the artificial fabrication processes. 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 maintaining its position 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 assist us in the conception of structures in the manufacturing of 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, Fig. 1 shows the microstructure of porous carbon obtained by carbonizing the wood of lauan. The channel-structure of the wood was not damaged and was still retained 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 [11, 12]. It can be used in several kinds of industrial fields to improve the performance of many new products [13]. However, the mechanical 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.

Aluminum alloys exhibit high specific strength, good castability, and high wear resistance. These properties have led to their applications in all types of internal combustion engines as pistons, cylinder blocks, and cylinder heads [14–17]. For piston applications, low CTE of the materials is also of great importance. Therefore, CTE of aluminum alloys has been recognized as one of the important thermomechanical properties, and many researches have been carried to reduce its CTE.

In this study, an attempt has been made to fabricate the carbon/aluminum composite with a wood-like structure. It was obtained by injecting the molten aluminum alloy into porous carbon derived from wood. We hoped that porous carbon could reduce the CTE of Al alloy. Meanwhile, it was also expected that Al alloy could improve the mechanical strength of porous carbon.

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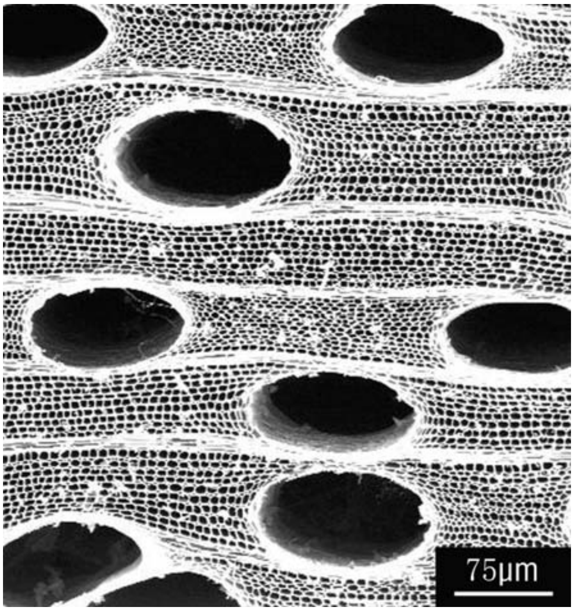

Fig. 1 Microstructure of porous carbon derived from the wood of lauan

Experimental procedure

Materials preparation

The wood structures of lauan, elm, and oak were used as plant templates to manufacture carbon/aluminum composites (C/Al). The wood was first pyrolyzed to produce porous carbon at 1400 °C for 2 h in a vacuum. Then at a high temperature (720 °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 C/Al composite. To inject Al alloy, porous carbon and solid Al alloy need to be put in an airtight furnace. The air in the furnace was drawn out. In the vacuum condition, the furnace was heated to 720 °C to melt Al alloy. After aluminum had melted, nitrogen was blown into the furnace rapidly to raise the atmospheric pressure in the furnace to 8.5 MPa. At this high pressure, the molten Al alloy could be injected into porous carbon. Finally, the C/Al composite was obtained as Al alloy solidified in porous carbon.

Microstructures and properties characterization

A scanning electron microscopy (SEM, S-520, Hitachi, Japan) was used to study the microstructures of C/Al composites. The bulk density (geometrical density) was determined by measuring the weight and the volume of the cuboid specimens.

The CTE measurements of porous carbon and C/Al composites were performed by a LK-02 high-speed quenching dilatometer. The sizes of the thermal expansion specimens were $2 \times 2 \times 12$ mm^3. The CTE of the axial direction was measured. During measurements, samples were cycled three times in the temperature range from 25 °C to 300 °C. The heating/cooling rate was 10 °C/min.

The bending strength and compression strength of porous carbon and C/Al composites were measured by MTS 810 test machine. The test-pieces for three-point bending tests were $50 \times 8 \times 8$ mm^3 and those for compression tests were $10 \times 8 \times 8$ mm^3. Bending load parallel to radius of wood and compression load parallel to axis were applied by speed of 0.5 mm/min. The span for three-point bending tests was 30 mm. Three specimens were tested to obtain an average value.

Results and discussion

Microstructures

After injecting Al alloy into porous carbon, the C/Al composites were obtained. Figure 2a shows the microstructure of the C/Al composite produced from lauan template. The composites produced from other two woods also possess the similar microstructures. Compared with porous carbon (Fig. 1), the hollow channels in porous carbon were filled with Al alloy. The composite is almost fully dense since there is no pore found in its microstructure. It is noted that the C/Al composites retain perfectly porous carbon of its natural counterparts. Moreover, 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 a high temperature and the fibers were then formed after it solidifies. The shapes of fibers in the composite are shown in Fig. 2b. 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.

Figure 3 shows the channel-distributions in lauan, elm, and oak. It can be seen that the channel-distribution changes with different wood templates. In lauan and elm, the thick channels have a uniform distribution on the wood section, and the thin channels also have a uniform distribution among these thick channels. However in oak, the distribution of the thick channels

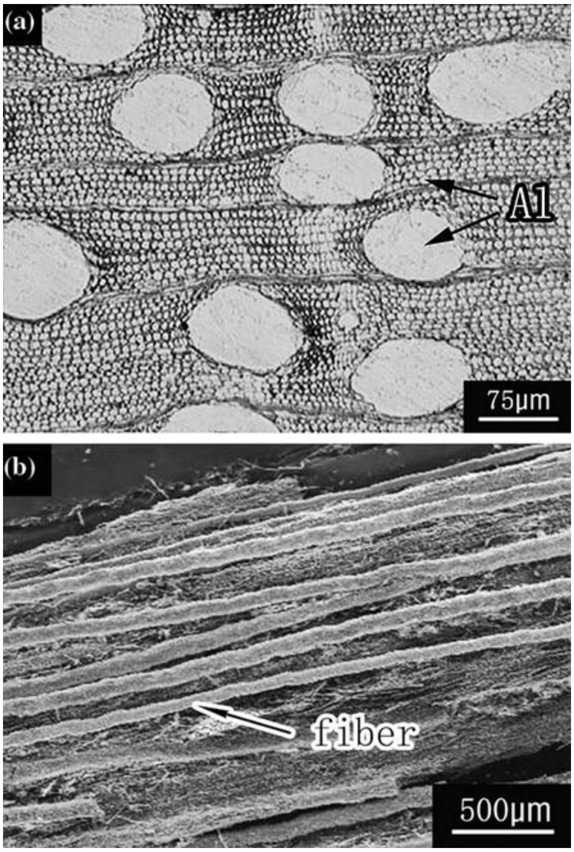

Fig. 2 SEM images of the C/Al composite (**a**), and the Al fibers (**b**)

is not uniform. They are rich in some zones and barren in other zones. The different channel-distributions in wood templates can lead to different distributions of the Al fibers in the C/Al composites.

Table 1 gives a group data of these materials. The densities of the composites are lower than that of Al alloy (2.8 g/cm^3). The volume percentage of Al alloy in the composites can be calculated by the following law [19]:

$$\rho_{\text{char}} + \rho_{\text{Al}} V_{\text{Al}} = \rho_{\text{C}}$$

Here, (ρ_c, ρ_{char}, and ρ_{Al} represent the densities of the C/Al 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_{char} is the bulk density of porous carbon; therefore, it need not multiplied by the volume percentage of the carbon.

Thermal expansion and mechanical properties

Figure 4 shows the CTE as a function of the temperature for Al alloy, porous carbon, and C/Al composites. It can be seen from Fig. 4a that porous carbon has a much lower CTE than Al alloy. It can be seen from Fig. 3b that the CTE of the C/Al composites is between Al alloy and porous carbon. Due to the function of porous carbon, the thermal expansion of the composites was lower as compared to Al alloy.

Figure 5 shows the bending and compression strengths of porous carbon and the C/Al composites. Obviously, the strengths of the composites are much higher than that of porous carbon.

It is supposed that the much more excellent strengths of the C/Al 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 strength of the C/Al composite may also be related partly to the compressive residual stress in the carbon. Due to the big difference in thermal expansion coefficients between porous carbon and Al alloy, it is supposed that as the sample was cooled following metal injection, the compressive residual stress in the carbon and tension one in Al alloy will be introduced. Compression stresses in the carbon are supposed to raise the fracture initiation stress effectively, and hence act to hinder microcrack initiation [16].

It can also be seen from Fig. 5 that the strengths of the C/Al composites changed with the wood templates. The C/Al composite based on lauan had a higher strength than that based on elm and oak. This is because the C/Al composite based on lauan had a higher Al content for preventing cracks propagation than the other two, as shown in Table 1. This indicates that the porosity of the wood template can influence the mechanical properties of the C/Al composites. Further, the strengths of the C/Al composite based on elm are higher than that based on oak, although the Al contents of the two C/Al composites are almost identical. This may be related to the different distributions of the Al fibers. The thick channels in elm have a uniform distribution while the thick channels in oak have not, as shown in Fig. 3. Hence, Al fibers in the C/Al composite based on elm also have a uniform distribution. Al fibers with uniform distribution can prevent crack propagation more efficiently. This indicates that the channel-distribution in wood templates can also influence the mechanical properties of the C/Al composites. Except for the porosity and distribution of

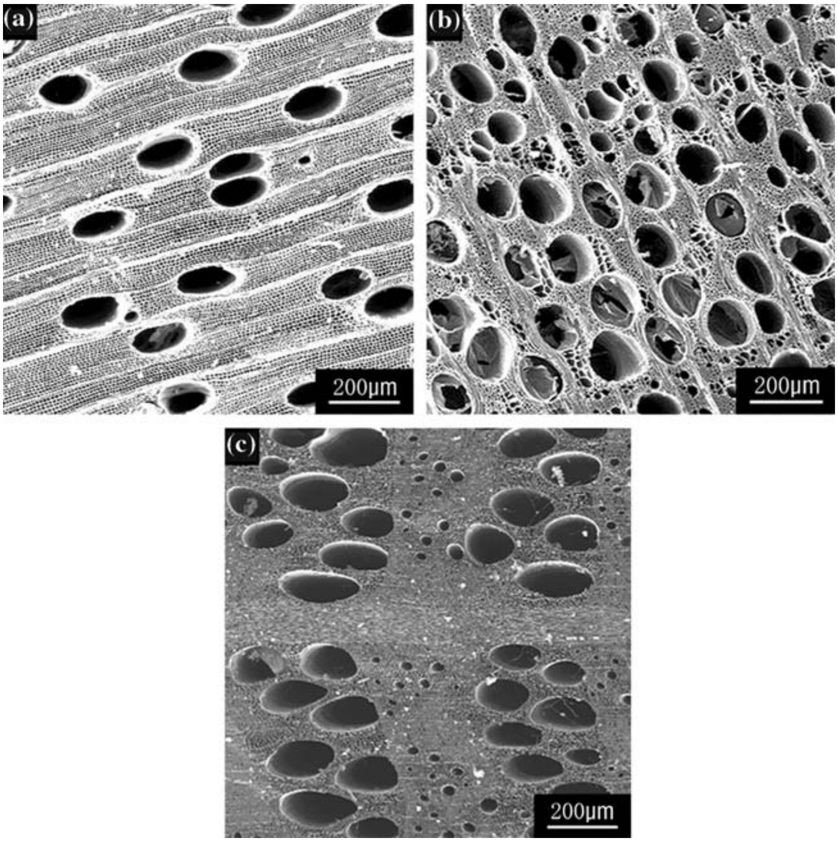

Fig. 3 SEM images of channel-distribution in wood (**a**. lauan, **b**. elm, **c**. oak)

Table 1 Characteristics of the wood, porous carbon, and C/Al composites

	Elm	Oak	Lauan
Bulk density (g/cm^3) of wood	0.61	0.60	0.38
Bulk density (g/cm^3) of porous carbon	0.46	0.41	0.22
Density (g/cm^3) of C/Al composite	2.47	2.38	2.67
Al-content (%) of C/Al composite	71.1	71.0	87.5

the channels, the roughness, camber, and shape of the channels may also influence the mechanical properties of the C/Al composites. This is a complex process that needs a greater selection of wood templates for analysis.

Conclusions

Wood is a natural material with rational microstructures, which can change into porous carbon through carbonization. Based on this unique intrinsic structure, the carbon/aluminum composites could be produced. It was obtained by injecting Al alloy into porous carbon derived from wood. Al alloy liquid could flow into the channels of porous carbon and form fibers after solidifying. The shape, the size, and the distribution of the structure in the composite are controlled by the natural structure of wood. The wood-template-based C/Al composites have a lower CTE than Al alloy. Moreover, it is observed that their bending and compression strengths are also higher than that of porous carbon. Since it is different from the traditional metal matrix composites with their structures obtained artificially, the method of producing the wood-template-based composites could provide a new idea for composite design.

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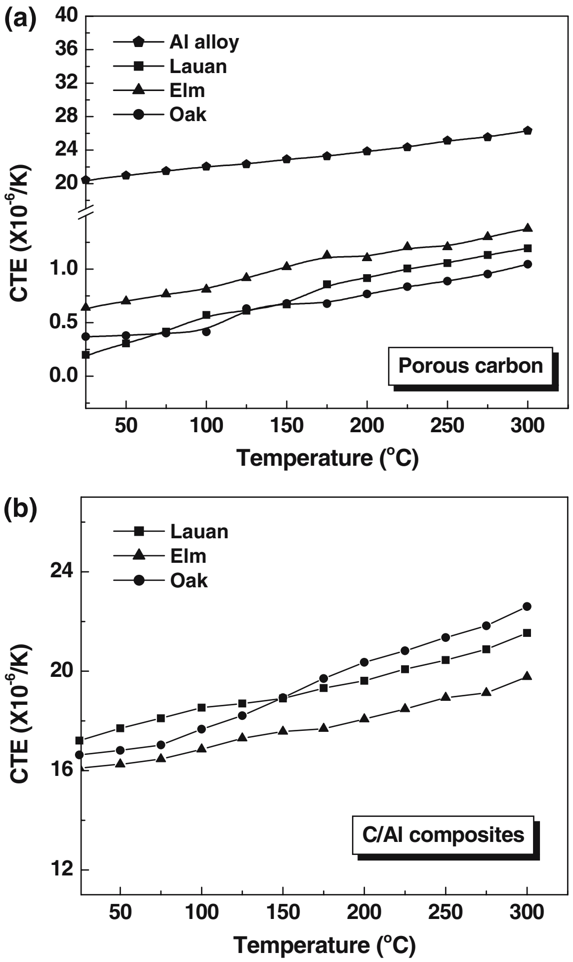

Fig. 4 CTE as a function of the temperature for (**a**) porous carbon and (**b**) composites

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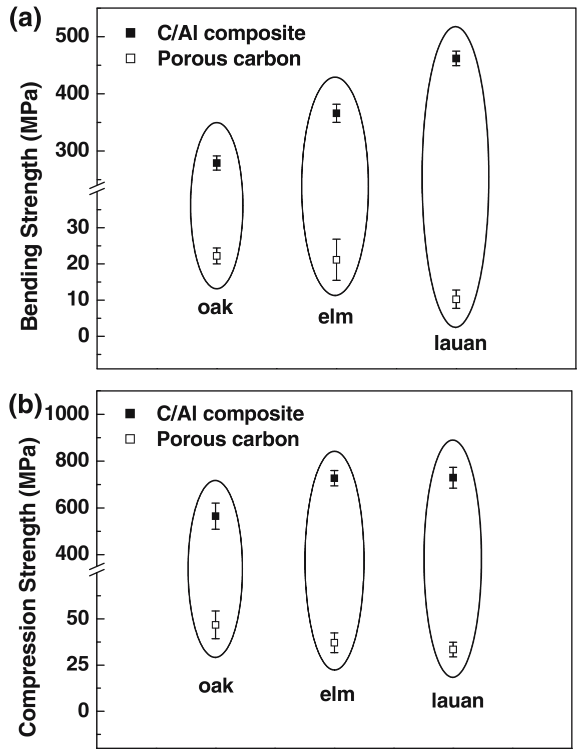

Fig. 5 Mechanical strength of porous carbon and the C/Al composites (**a**) Bending strength, and (**b**) compression strength)

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