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Thermal conductivity and mechanical properties of various cross-section types carbon fiber-reinforced composites

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In this work, to study the characteristics of carbon fiber-reinforced composites with different fiber cross-section types, such as round, C, and hollow-shape, the thermal conductivity and mechanical properties were investigated and compared. The thermal conductivity was measured by means of steady-state method to the parallel and perpendicular direction of reinforcing fibers. The mechanical properties were evaluated by a variety of test methods i.e., flexural, interlaminar shear strength, and impact strength. As a result, it was found that the thermal conductivity was greatly depended on the cross-section type of the reinforcing fibers, as well as, the reinforcing orientation. Especially, the anisotropy factor ($k_{///}/k_{\perp}$) and the thermal diffusivity factor ($\alpha_{///}/\alpha_{\perp}$) of C and hollow-type carbon fiber-reinforced composites showed about two times higher values than those of round-type one. Also, the mechanical results showed that C and hollow-type carbon fibers-reinforced composites had higher values than those of round-type one in all mechanical tested. These results were probably due to the basic properties of non-circular (C and hollow-type) carbon fiber which can improve interfacial binding forces and widen interfacial contact area between reinforcement and matrix, resulting in effectively transferring the applied stress.

1. Introduction

Carbon materials, such as carbon film, carbon fiber, carbon black, carbon-carbon composites, have been known to possess an excellent thermal conductivity [1]. Sometimes they require a high directional thermal conductivity to distribute heat transfer and to insulate rocket nozzles or nose cones [2].

One of the carbon materials is quasi-crystalline pyrolytic carbon that shows very high anisotropy factor about 1250 [3]. But it is difficult to use as thermal structural materials due to process problem. Among the carbon materials with easy preparation process, it is carbon fiber that has good thermal properties and can be made easily structural materials [4]. Especially, a graphitizable pitch-based carbon fiber also reveals very high anisotropic characteristics and is used as ablative materials of aerospace applications.

Generally, the round-type is used as a reinforcement fiber in fiber-reinforced composites. In structural mechanics, as the optimization of the stress distribution of materials, some design engineers proved that hollow or noncircular-type is better than round one in mechanical properties [5] and that they has applied in many structural materials, such as I-beam train road, construction support pipe/pile rod, etc. Especially, C-type carbon fiber has a curved area in the surface contacting with matrices that can improve interfacial bonding force. The phenomena result may solve a delamination, playing a great part in the mechanical properties of carbon fiber-reinforced composites.

From the mid of 1980's, the researches on noncircular carbon fibers have been proceeding as the moot focus on microstructure, optimization of preparation process, and mechanical properties of them [6, 7].

The thermal conductivity, as well as, the mechanical properties of the fiber-reinforced composites greatly depends on the micro-molecular orientation controlled by precursors and cross-sectional geometry or the cross-section structures of the reinforcements [8, 9]. Therefore it may be possible to control the thermal conductivity and mechanical properties according to the direction of the reinforcement through the macro-modification of fiber types or fiber micro-textures.

In this work, we are to investigate the characteristics of heat transfer for mesophase pitch-based round, hollow, and C-type carbon fibers-reinforced composites and to evaluate the effect of different cross-section types of reinforcement fibers in the mechanical properties studied.

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TABLE I Carbon fiber manufacturing conditions and their appearance

Fibers types	Treat temperature (°C)			Diameter (μm)	Thickness (μm)
	Spinning	Stabilization (Holding time)	Carbonization		
H-CF[a]	315 ± 5°C	295 (40)	1000	45 ± 3.2	12 ± 1.4
C-CF[b]	318 ± 5°C	295 (40)	1000	32 ± 4.0	10 ± 0.7
R-CF[c]	318 ± 5°C	295 (40)	1000	18 ± 2.6	18 ± 2.6

[a]H-CF: hollow-type carbon fiber.
[b]C-CF: C-type carbon fiber.
[c]R-CF: round-type carbon fiber.

2. Experimental

2.1. Materials and sample preparation

The reinforcements used were carbon fibers that are produced by mesophase pitch and the matrix system used was Epotoho YD-128 epoxy resin system (diglycidyl ether of bisphenol-A (DGEBA) and curing agent: m-phenylenediamine, supplied from Kuk-Do Chem. Co. of Korea). The fiber manufacturing conditions and appearances were shown in Table I.

Using the carbon fibers and epoxy resin, the prepregs were prepared by drum winding method and these were cut and laid unidirectional into a mold to manufacture composites. The prepregs are pressed and cured under 5 MPa pressure for 1 h at 90°C and 2 h at 150°C by hot-press machine according to the results of differential scanning calorimetry (DSC) and rheometer (RFS-2) and we could obtain specimens with fiber mass fraction of 15, 30, and 45%, respectively. The specimen for thermal conductivity was a disk type of 2.5 cm in diameter and 0.5 mm in thickness and the specimen for mechanical tests was prepared according to the desired dimension.

2.2. Measurements

For the measurement of thermal conductivity, the principle of the measurement was based on the heat transfer of Fourier's law [10]. The instrumentation for measuring the thermal conductivity provides accurate measurement of temperature and power supply as a steady-state method. Fast response temperature probes (thermocouples), with a resolution of 0.1°C give direct digital readout in °C. The power control circuit provides a continuously variable electrical output of 0–100 watts with direct readout. The measurements of the thermal conductivity were made at the temperature range of 40°C to 120°C.

The calculations of thermal conductivity, specific heat, and thermal diffusivity values follow the equation below:

For the thermal conductivity, k:

$$k = \frac{q \cdot t}{A(T_2 - T_1)} \tag{1}$$

For the specific heat, C_p:

$$C_p = \frac{-q}{m\Delta T} \tag{2}$$

For the thermal diffusivity, α:

$$\alpha = \frac{k}{C_p \cdot \rho} \tag{3}$$

where A is the area of heat conduction, $T_2 - T_1$ the temperature difference between heating and cooling part, t the sample thickness, m the sample weight, ρ the sample density, ΔT the temperature difference at steady-state, and q the Watt applied, respectively.

For the investigation of mechanical properties, Instron Model 1125 Tester was used to measure flexural properties of the composites according to the ASTM D-790. The span-to-depth ratio was 16 : 1 scale and cross-head speed was 2 mm/min. Interlaminar shear strength (ILSS) was measured by short-beam bending test according to the ASTM D-2344 ($L/d = 6$; cross-head speed = 0.5 mm/min). A Tinius Olsel Model 66 Izod Impact Tester was used for the measurement of impact strength of the specimens. Scanning electron microscope (SEM) was used to investigate the surface and cross-section of different carbon fibers-reinforced composites. The σ_f (flexural strength) and E_b (elastic modulus in flexure) for the specimens determined from three-point bending test were calculated using the following equations:

$$\sigma_f = \frac{3PL}{2bd^2} \tag{4}$$

$$E_b = \frac{L^3}{4bd^3} \cdot \frac{\Delta P}{\Delta m} \tag{5}$$

where P is the applied load, L the span length, b the width of specimen, d the thickness of specimen, ΔP the change in force in the linear portion of the load-deflection curve, and Δm the change in deflection corresponding to ΔP.

The ILSS was measured using the following equation:

$$ILSS = \frac{3}{4} \cdot \frac{F}{bd} \tag{6}$$

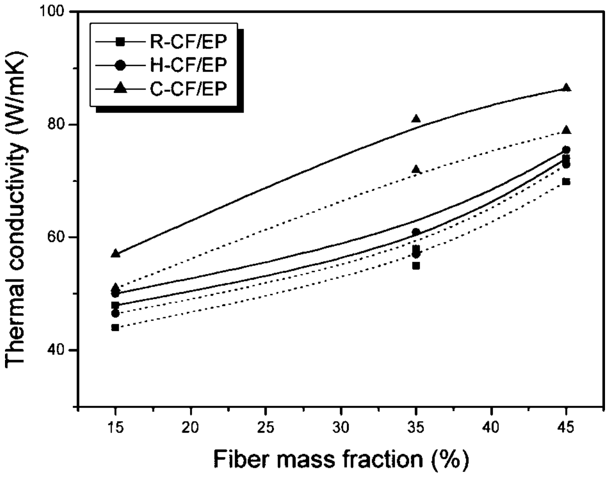
where F (N) is the failure load at the maximum moment, b (m) the width of the specimen, and d (m) the thickness of the specimen.

3. Results and discussion

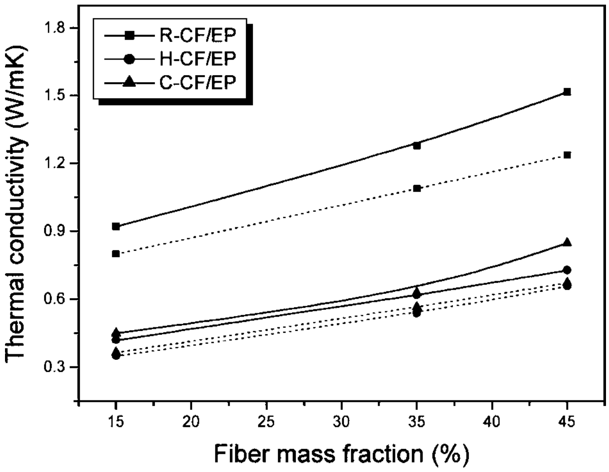
3.1. Thermal conductivity

High thermal conductivity materials are very important in system where high heat loads must be managed (transported or dissipated) and are critical in many applications to minimize weight and volume. One of them is the fiber-reinforced composite with high thermal conductive fiber [11]. The growing needs for materials dedicated to thermal management applications lead to the design of new composite materials. Indeed, with appropriate combination of selected matrices and reinforcement, it is now possible to tailor composite materials with almost the desired thermal conductivity as to the fiber direction and shape. Thus, we investigate how thermal transfer characteristics of the fiber-reinforced composites are affected by fiber orientations and fiber cross-sectional types.

Fig. 1a and b show the thermal conductivity of carbon fiber-reinforced composites in the parallel and perpendicular direction to the reinforcement according to the fiber mass fraction, respectively. From the figures we



(a)



(b)

Figure 1 Thermal conductivity of carbon fiber-reinforced composites according to the reinforcement directions; (a) parallel direction, (b) perpendicular direction. Dot line (- - - - - -): 40°C, solid line (——): 120°C.

can see that thermal conductivity of the composites depend on the three parameters, such as, measuring temperature, fiber content, and fiber cross-sectional type. Especially, C-CF/EP (C-type carbon fiber-reinforced epoxy composites) has the highest value of the thermal conductivity in the parallel direction to the fiber, $k_{//}$, while H-CF/EP (hollow-type carbon fiber-reinforced epoxy composites) has the lowest value of the thermal conductivity in the transverse direction to the fiber, $k_{\perp}$. And the difference between $k_{(//,\,120^{\circ}\mathrm{C})}$ and $k_{(//,\,40^{\circ}\mathrm{C})}$ of C-CF/EP are relatively larger as compared with that of R-CF/EP and C-CF/EP, while the difference between $k_{(\perp,\,120^{\circ}\mathrm{C})}$ and $k_{(\perp,\,40^{\circ}\mathrm{C})}$ of R-CF/EP are relatively larger than that of C-CF/EP and H-CF/EP. These mean that the higher thermal conductivity has the higher temperature effect [12].

Fig. 2 shows anisotropic factor of the composites as a function of temperature. At first, we can know that C- and H-CF/EP have higher anisotropy factor than that of R-CF/EP. All composites have decreasing the thermal anisotropy factor with increasing the temperature because the thermal conductivity of the composites in the transverse direction to the reinforcements is more increase with increasing temperature.

Fig. 3 shows anisotropic factor of the composites as a function of fiber content. The same tendency on

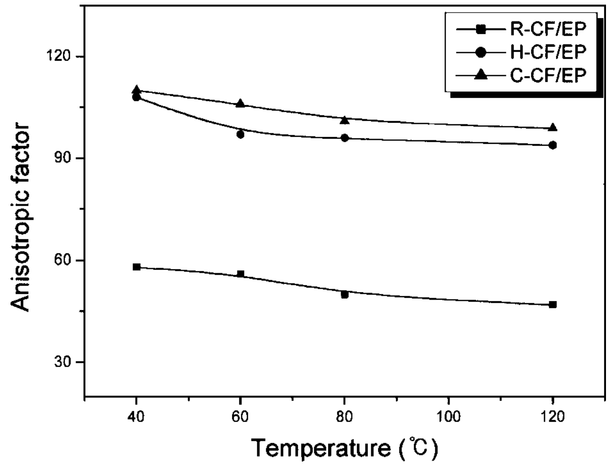


Figure 2 Thermal anisotropic factors of 45 wt% carbon fiber-reinforced composites according to the measuring temperatures.

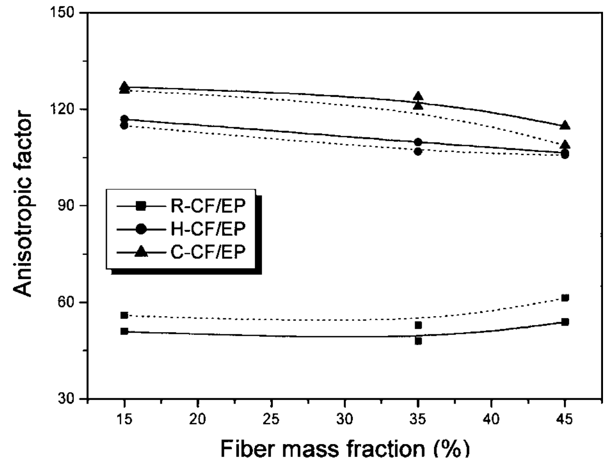


Figure 3 Thermal anisotropic factors of carbon fiber-reinforced composites according to the fiber mass fractions. Dot line (- - - - - -): 40°C, solid line (——): 120°C.

the thermal anisotropy factor is obtained. The actual difference between C-CF/EP or H-CF/EP and R-CF/EP shows more than two times and the highest factor of C-CF/EP is 130 and the lowest one of R-CF/EP is 45 in value.

In order to evaluate the thermal diffusivity, specific heats of the composites are required [13]. Fig. 4

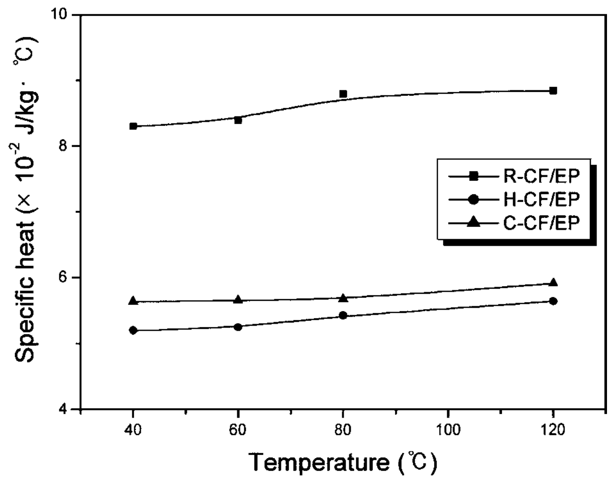


Figure 4 Specific heats ($C_{p(\perp)}$) of 45 wt% carbon fiber-reinforced composites in the transverse direction.

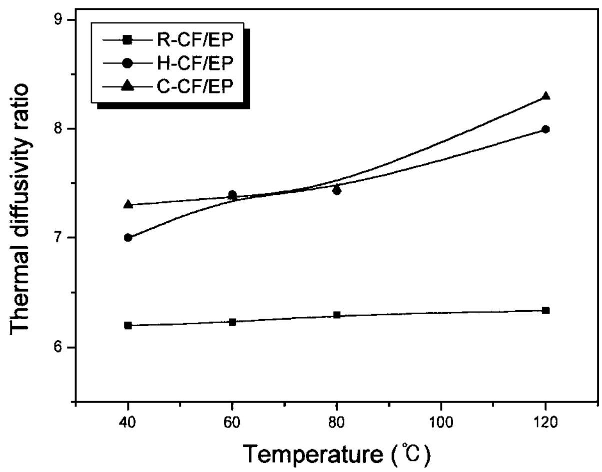


Figure 5 Thermal diffusivity ratios ($\alpha_{//}/\alpha_{\perp}$) of 45 wt% carbon fiber-reinforced composites according to the measuring temperatures.

shows the specific heat of transverse direction, $C_{p(\perp)}$ in three different types of composites. All specific heats are increasing with temperature and show somewhat different between R-CF/EP and the others (C-CF/EP and H-CF/EP). That is, R-CF/EP has about 8×10^{-2} [J/kg · °C], while H-CF/EP and C-CF/EP about 5×10^{-2} [J/kg · °C]. These results can be expected by fact that the specific heat of hollow and C-type fiber are able to be easily approached to graphite structure by wall shear stress of the spinneret during spinning a mesophase pitch, while the round-type carbon fiber is somewhat larger in specific heat. In general, the direction of the graphite basal plane (*c*-axis) has lower specific heat than that of the *a*-axis [14].

Fig. 5 shows the thermal diffusivity ratio, $\alpha_{//}/\alpha_{\perp}$ as a function of temperature, which shows slow increase with temperature. This is probably due to the more sensitive thermal diffusivity of composites in the parallel direction of reinforcement than that of perpendicular direction with measuring temperature, which is determined as the effect of the fiber orientation (macrostructure) [15]. C-CF/EP and H-CF/EP have similar thermal diffusivity, while R-CF/EP has relatively lower thermal diffusivity than that of non-circular fiber-reinforced composites. Also, the increasing rate of C-CF/EP and H-CF/EP is more or less great than that of R-CF/EP resulting from the microstructure of the fibers.

Generally, the thermal diffusivity ratio of C- and hollow-type fiber-reinforced composites is 0.8 to 1.8 higher than that of round-type fiber-reinforced one. For three types of composites, the major contributing factor for the higher thermal diffusivity ratio is that the axis of hollow- and C-type carbon fibers comparing with that of round-type carbon fiber coincides with the graphite basal plane. And this is good agreement with the direction of maximum thermal conductivity or diffusivity in the graphite crystal structure [16, 17]. Especially, C-CF/EP shows a high increasing tendency with increasing the temperature, which is due to its high anisotropic factor. The reason is that C-type has the hollowed-out surface area along the axis that offers greater contact area with matrix and greater resistance to the heat transfer in the perpendicular direction of the reinforcement [18].

TABLE II Mechanical properties of three cross-sectional types carbon fiber-reinforced composites (fiber weight fraction: 45 wt%)

Specimen	Flexural strength (MPa)	Transverse flexural strength (MPa)	Elastic modulus in flexure (GPa)	Interlaminar shear strength (MPa)	Impact strength ($kg_f \cdot$ cm/cm)
H-CF/EP[a]	236	6.18	1.96	7.39	13.32
C-CF/EP[b]	277	15.3	2.19	13.9	21.6
R-CF/EP[c]	127	8.3	0.98	8.85	9.5

[a]H-CF/EP: hollow-type carbon fiber composites.
[b]C-CF/EP: C-type carbon fiber composites.
[c]R-CF/EP: round-type carbon fiber composites.

3.2. Mechanical and mechanical interfacial properties

In structural mechanics, as to optimization of the stress distribution of materials, design engineer found out that tube or non-circular shape is more available than solid (round) one in the mechanical properties [19]. In this paper, thus, we mentioned about the mechanical properties of the composites that were reinforced with isotropic round-type, C-type, and hollow-type carbon fibers.

Table II represents all mechanical results studied on flexure, ILSS, and impact strength of the composites reinforced with three types of carbon fibers. These results indicate that the C-CF/EP composites show the highest values in all mechanical properties, while R-CF/EP the lowest values. The flexural strength and elastic modulus in flexure reveal that C-type carbon fiber-reinforced composites are improved by 218% and 223% respectively, comparing to round-type carbon fiber-reinforced one. This is probably due to the stiffness of C-type carbon fiber itself and the effective stress interaction between fiber and matrix [20, 21]. ILSS and transverse strength increase to 157% and 184%. The reasons are fact that C-CF/EP composites have the curved along the fiber axis and the contact area with matrix are wider leading to the greater friction force. The comparison values of impact strength also show the improvement of 227%. This tendency is evaluated as s result of the effective load transfer [22, 23].

We can verify it as observing the failure mode by using SEM pictures. Fig. 6a is SEM picture of the bundle of C-type carbon fiber, which has long hollowed-out along the fiber axis, making it expected to greater interface. Fig. 6b shows the failure surface of the sample after flexural test. Up to the curved area of the fibers, matrix is impartially contributed and has a good wettability, which is demonstrated by the failure mode of the fiber side and matrix side, respectively, as shown in Fig. 6c and d. These pictures represent that the matrix is engulfed by the hollowed-out area of the C-type fiber, which allow the matrix to secure more bonds. Also, in the case of the matrix side, the failure mode like scale (Fig. 6d) intimate the better adhesive force between two phases, which can effectively transfer the load applied to the fiber-reinforced composite system.

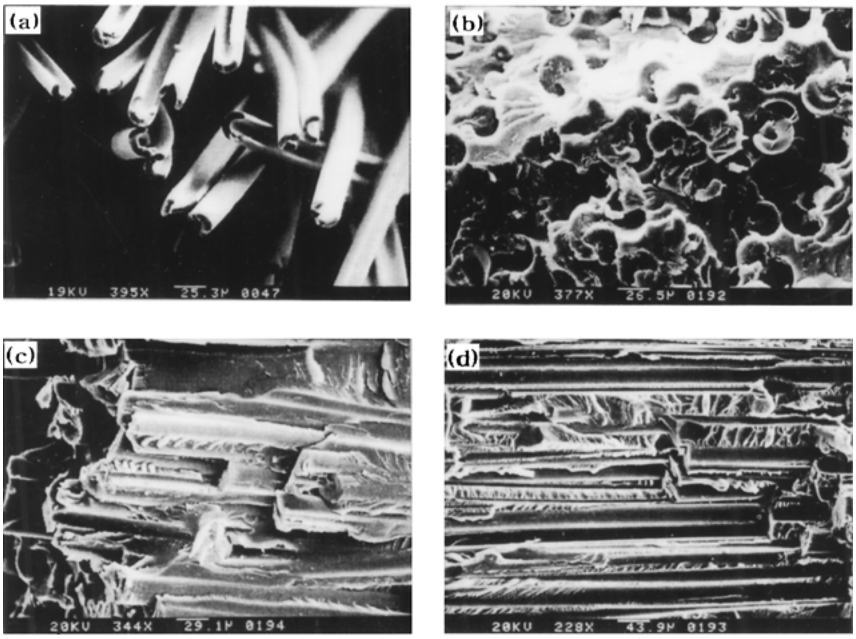


Figure 6 SEM photographs of C-CF/EP composites.

4. Conclusions

In this work, the effect of fiber cross-sectional type on thermal conductivity and mechanical properties of the fiber-reinforced composites was investigated. As a result, the thermal conductivity of carbon fiber-reinforced composites greatly depended on the cross-sectional type of the fibers. Among the three types of composites, C-type composites showed the highest thermal conductivity in the parallel direction to the reinforcements. On the other hand, hollow-type composites exhibited a little higher thermal conductivity than that of round-type one, but the lowest thermal conductivity in transverse direction. These results can be explained by fact that the specific heat of C-type carbon fiber are able to be easily approached to graphite structure by wall shear stress of the spinneret during spinning a mesophase pitch.

And, C-type composites showed the highest improvement in the all-mechanical properties. These results were probably due to the basic properties of non-circular (C and hollow-type) carbon fiber which would improve interfacial binding forces and widen interfacial contact area between reinforcement and matrix, resulting in effectively transferring the applied stress.

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