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Estimation of thermal conductivities of a novel fuzzy fiber reinforced composite

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ABSTRACT

The effective thermal conductivities of a novel fuzzy fiber reinforced composite (**FFRC**) have been determined by employing the effective medium approach in conjunction with the composite cylinder assemblage approach. The novel constructional feature of this **FFRC** is that the uniformly spaced carbon nanotubes (**CNTs**) are radially grown on the circumferential surfaces of the unidirectional carbon fiber reinforcements. The present study reveals that the transverse thermal conductivities of the **FFRC** are improved up to ~1040% and ~400% over those of the composite without **CNTs** when the values of **CNT** volume factions present in the **FFRC** are 6.88% and 4.27%, respectively. It is also found that the **CNT**/polymer matrix interfacial thermal resistance does affect the effective thermal conductivities of the **FFRC**, and the effective values of thermal conductivities of the **FFRC** are improved with the increase in the values of carbon fiber volume fraction and temperature.

1. Introduction

The research on the synthesis of molecular carbon structure by an arc-discharge method for evaporation of carbon led to the discovery of an extremely thin needle-like graphitic carbon nanotube [1]. Researchers probably thought that carbon nanotubes (**CNTs**) may be useful as nanoscale fibers for developing novel nanocomposites and this conjecture motivated them to accurately predict their physical properties (mechanical, thermal and electrical properties). Ruoff and Lorents [2] examined some aspects of the mechanical and the thermal properties of multi-walled carbon nanotubes (**MWCNTs**) and single-walled carbon nanotubes (**SWCNTs**) in terms of the known elastic properties of graphite. Many research investigations revealed that the axial Young's modulus of **SWCNTs** is in the terapascal range [3–6], and the thermal conductivities of **SWCNTs** and **MWCNTs** are more than 2500 W/mK [7–10]. The quest for utilizing such exceptional mechanical and thermal properties of **CNTs**, and their high aspect ratio and low density led to the opening of an emerging area of research on the development of **CNT**-reinforced nanocomposites.

In order to exploit the exceptional mechanical and thermal properties of **CNTs** for increasing the heat transport in **CNT**-reinforced nanocomposites, a great number of experimental studies have been carried out for investigating the thermal conductivities of **CNT**-reinforced composites. For example, Choi et al. [11] produced nanotube-in-oil suspensions in a two-step process and measured their thermal conductivities. They found that the measured thermal conductivity is greater than theoretical predictions and is nonlinear with **CNTs** loading. Single-walled **CNTs** were used to augment the thermal transport properties of industrial epoxy by Biercuk et al. [12]. In their experiment, samples loaded with 1 wt% unpurified **SWCNT**s showed a 125% increase in the value of thermal conductivity at room temperature. Their test results suggest that the thermal and the mechanical properties of **CNT**-reinforced composites can be improved without the chemical functionalization of **CNTs**. Bryning et al. [13] reported thermal conductivity measurements of purified **CNT**-reinforced composites prepared by using suspensions of **SWCNTs** in N-N-Dimethylformamide and surfactant stabilized aqueous **SWCNT** suspensions. Thermal conductivity enhancement is observed as 80% and 8% for N-N-Dimethylformamide processed composites and surfactant processed samples, respectively, at 1 wt% **SWCNT** loading. The difference in the enhancement of the thermal conductivity is attributed to a ten-fold larger **SWCNT**/matrix interfacial thermal resistance in surfactant processed composites compared to N-N-

Abbreviations: **AF**, Alignment Factor; **CCA**, Composite Cylinder Assemblage; **CFF**, Composite Fuzzy Fiber; **CNT**, Carbon Nanotube; **EM**, Effective Medium; **FE**, Finite Element; **FFRC**, Fuzzy Fiber Reinforced Composite; **MmCNT**, Multi-malled Carbon Nanotube; **PMNC**, Polymer Matrix Nanocomposite; **PMMA**, Poly(methyl methacrylate); **RVE**, Representative Volume Element; **SEM**, Scanning Electron Microscopy; **SWCNT**, Single-Walled Carbon Nanotube.

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Nomenclature

$\mathbf{a_k}$	Kaptiza radius m
D	Diameter of the **RVE** of the **FFRC** μm
d	Diameter of the carbon fiber μm
$\mathbf{d_n}$	Diameter of the **CNT** nm
$\mathbf{K_{ij}}$	Effective thermal conductivities of the **FFRC** W/mK
K_{ij}^{CFF}	Effective thermal conductivities of the **CFF** W/mK
$\mathbf{K^f}$	Thermal conductivity of the carbon fiber W/mK
$\mathbf{K^n}$	Thermal conductivity of the **CNT** W/mK
K_{ij}^{nc}	Effective thermal conductivities of the unwound lamina of the **PMNC** W/mK
$[K_{ij}^{nc}]$	Effective thermal conductivity matrix of the unwound lamina of the **PMNC** W/mK
$\mathbf{K^p}$	Thermal conductivity of the polymer W/mK
K_{ij}^{PMNC}	Effective thermal conductivities of the **PMNC** W/mK
L	Length of the **RVE** of the **FFRC** μm
$\mathbf{L_n}$	Length of the straight **CNT** nm
$(\mathbf{N_{CNT}})_{max}$	Maximum number of radially grown aligned **CNTs** on the circumferential surface of the carbon fiber
R	Radius of the **RVE** of the **FFRC** μm
$\mathbf{R_k}$	Interfacial thermal resistance between the **CNT** and the polymer m^2 K/W
[T]	Transformation matrix
V	Volume of the **RVE** of the **FFRC** μm^3
$\mathbf{V^i}$	Volume of the **i**-th phase μm^3
$(\mathbf{V_{CNT}})_{max}$	Maximum volume fraction of the **CNT** in the **FFRC**
$\mathbf{v_{CFF}}$	Volume fraction of the **CFF** in the **FFRC**
$\mathbf{v_f}$	Volume fraction of the carbon fiber in the **FFRC**
$\bar{v}_f$	Volume fraction of the carbon fiber in the **CFF**
$\mathbf{v_n}$	Volume fraction of the **CNT** in the **PMNC**
$\mathbf{v_p}$	Volume fraction of the polymer in the **PMNC**
$\mathbf{v_{PMNC}}$	Volume fraction of the **PMNC** in the **CFF**
$\bar{v}_P$	Volume fraction of the polymer in the **FFRC**

Dimethylformamide processed composites. Guthy et al. [14] fabricated **SWCNT/PMMA** composites by employing the coagulation method with 6% **CNT** loading and found 240% enhancement in the thermal conductivity of **SWCNT/PMMA** composites. Further increase in **SWCNT** loading does not result in significant increase in the thermal conductivity. Haggenmueller et al. [15] investigated the thermal conductivities of **SWCNT**/polyethylene nanocomposites in terms of **SWCNT** loading, polyethylene crystallinity and polyethylene alignment. They reported that the thermal conductivity of **SWCNT**/high density polyethylene is higher than that of **SWCNT**/low density polyethylene. They attributed this effect primarily due to the aligned polyethylene matrix which eventually reduces the interfacial thermal resistance between **CNTs** and high density polyethylene. The thermal conductivity of **SWCNT/PMMA** nanocomposites is determined by Pradhan and Iannacchione [16]. A large enhancement of the thermal conductivity is observed by them as the mass fraction of **SWCNTs** increases from 0.014 to 0.083. Chu and coworkers [17,18] synthesized **CNT**/copper nanocomposite by means of the particles-compositing process. They reported that the addition of **CNTs** in the pure copper matrix showed no enhancement in the overall effective thermal conductivity of **CNT**/copper composites due to the interfacial thermal resistance associated with the low phase contrast of **CNTs** to copper and the random orientations of reinforced **CNTs**. Chai and Chen [19] characterized the thermal conductivities of **CNT**/copper nanocomposite by using a novel electrochemical co-deposition process aiming to reduce the interfacial thermal resistance between **CNTs** and copper matrix. They reported that the effective thermal conductivity of **CNT**-reinforced copper nanocomposite is 180% greater than that of the pure copper. Cho et al. [20] fabricated the uniformly dispersed **CNT**/copper nanocomposite by using wet mixing and spark plasma sintering. Their results indicate that **CNTs** can be used as primary reinforcements in the copper matrix for improving the thermal conductivity of the resulting composite. Marconnet et al. [21] reported the experimental data for the thermal conductivity of densified, aligned **MWCNTs** arrays infiltrated with an unmodified aerospace-grade epoxy with maximum loading of **CNT** up to 20%. In their study, the axial thermal conductivity of the aligned **CNT**-epoxy composite is improved by a factor of 18.5 at 16.7% volume fraction of **CNT**.

The review of literature on the measurements of the thermal conductivities of two-phase **CNT**-reinforced composites reveals that the degree of enhancement of the thermal conductivity of nanocomposites varies substantially with the dispersion quality of **CNTs** and the **CNT**/matrix interfacial thermal resistance. The interfacial thermal resistance is also known as Kaptiza resistance. Wilson et al. [22] reported that the magnitude of the interfacial thermal resistance between nanoparticles and different matrices ranges from 0.77×10^{-8} m^2 K/W to 20×10^{-8} m^2 K/W. The **CNT**/matrix interfacial thermal resistance reported by Huxtable et al. [23] is about 8.3×10^{-8} m^2 K/W. In addition to the experimental endeavors, theoretical evaluations of the thermal conductivities of **CNT**-reinforced composites have also been reported by researchers incorporating such **CNT**/polymer interfacial thermal resistance. A simple equation has been derived by Nan et al. [24] for predicting the effective thermal conductivity of **CNT**-reinforced nanocomposite by implementing an effective medium (**EM**) approach. In particular, their model shows that the thermal conductivity enhancement in the nanocomposite is limited by the **CNT**/matrix interfacial thermal resistance. Subsequently, the effective thermal conductivities of **CNT**-reinforced nanocomposites are computed by several researchers [25–28] incorporating the **CNT**/matrix interfacial thermal resistance.

For structural applications, the manufacturing of two-phase unidirectional continuous **CNT**-reinforced composites in large scale has to encounter some manufacturing difficulties. In case of three-phase hybrid **CNT**-reinforced composite, short **CNTs** are grown on the circumferential surfaces of the advanced fiber reinforcements such as carbon fibers and alumina fibers. It seems that in comparison to the manufacturing of long **CNTs** and the dispersion of long **CNTs** in the polymer matrix, direct growth of short **CNTs** on the circumferential surfaces of the advanced fibers for achieving uniform distribution of **CNTs** throughout the composite is practically more feasible and advantageous. For example, Bower et al. [29] have grown aligned **CNTs** on the substrate surface using high-frequency microwave plasma-enhanced chemical vapor deposition technique. They have found that the growth rate of **CNTs** are approximately 100 nm/s with entire growth of 12 μm and such **CNT** growth always occurs perpendicular to the substrate surface regardless of the substrate shape. Qian et al. [30] experimentally investigated that the enhancement in the fiber/matrix interfacial shear strength can be achieved by growing **CNTs** on the circumferential surface of the fiber. Veedu et al. [31] demonstrated that the remarkable improvements in the interlaminar fracture toughness, hardness, delamination resistance, in-plane mechanical properties, damping and thermal behavior of laminated composite can be obtained by growing **MWCNTs** about 60 μm long on the circumferential surfaces of the fibers. Their test results suggest that the presence of **CNTs** in the transverse (i.e., thickness) direction of the composite enhances the effective thermal conductivity up to 51%