Anisotropic Heat Transfer in Composite Materials

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Abstract - *Many composite materials are composed of a matrix reinforced with fibers. Carbon fiber composites are currently being used for high heat transfer applications. Carbon fibers are known to have excellent thermal conductivities. However, if the interface between the matrix and fibers has poor thermal properties, it affects the overall thermal conductivity of the composite significantly. The goal of this project is to quantify the thermal conductivity of the matrix-fiber interface in a set of carbon fiber composites. As per the given data then we had concluded the numerical method to determine the fiber-matrix interface heat transfer coefficient.*

Key Words: Composite Materials, Thermal Properties, Carbon Fiber, Anisotropic Heat Transfer. Numerical Method.

1. INTRODUCTION

Composite materials are based on the concept that a combination of different materials can attain properties that the constituent materials cannot attain individually by themselves (Strong, 2008). This concept has been applied to create a variety of composite materials having a wide range of desirable properties superior to conventional materials.

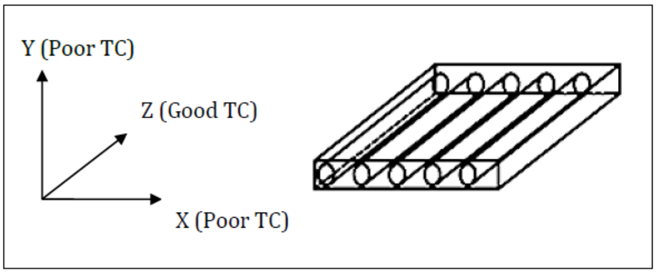

Fig -1: Anisotropic thermal conductivity (TC) in a composite with carbon fiber reinforcement.

In the case of continuous fiber laminates, as properties of fibers are strongest along their axial direction, fibers can be oriented in multiple directions in the plane of the laminate to achieve strength in multiple directions. However, in the direction perpendicular to the plane, properties are poor as none of the fibers are oriented in that direction (Chung, 2010). This project focuses on enhancing the thermal properties of composite laminates in the perpendicular direction. Figure 1 shows the directions in a composite along which the properties are good (x) or poor (y, z).

The concept of composite materials has been known to mankind since as early as 1500 B.C. when composites existed in various forms, for example, mud walls reinforced by bamboo or use of laminated metals in forging swords later in 1800 A.D (Kaw, 2006). Modern composites, however, were discovered in the 20th century, after the discovery of fiberglass in the 1930s, after which glass fiber reinforced resins were used in aircraft. The development and use of composite materials have been increasing ever since. After the development of carbon, boron, and aramid fibers, composites were widely used in the structural parts of aircraft especially during World War II. After World War II, composites were introduced in automobiles and have gained popularity in many other fields due to their superior mechanical properties (Strong, 2008).

1.1 Thermal Applications of Composite Materials

Polymers are currently being used in many applications as a replacement for metals. However, polymers are very poor thermal conductors. Polymer matrix composites can be designed to be much more conductive than polymers, especially with the use of carbon fibers. Carbon fiber composites, which are the subject of analysis in this project, are being used due to their good thermal properties in heat shields of missiles and rockets, brakes of automobiles where friction generates heat that must be dissipated, the housing of computers, motors and electrical control panels where heat is generated and needs thermally conductive covers for high heat dissipation rates. Enhancing the thermal conductivities of polymer materials beyond their current values becomes essential to meet the demands for the dissipation of ever-increasing power generation rates per unit area (Strong, 2008).

1.2 Transverse Properties

The material properties of a composite depend on various factors: individual properties of the components that form the composite, the volume fractions of both components, and the interfacial bonding between the two components. The fibers are the component that imparts strength to the composite. The matrix transfers the external load on to the fiber through their interfacial bonding. It follows that the strength of the composite as a whole depends on the integrity of the interfacial bonding between matrix and fibers and how well the load is transferred (Kaw, 2006; Strong, 2008). Similar to the mechanical strength of the composite, the quality of the interface also affects the thermal conductivity of the composite, but significantly only in the transverse direction to fiber axes (Grujicic et al., 2006). In the longitudinal direction of the fibers, the interface is not critical to longitudinal heat conduction, and since carbon fibers can have excellent longitudinal (axial) conductivity. In the transverse direction, heat flux must cross the fiber-matrix interface repeatedly. Therefore, the thermal characteristics of the interface have a major effect on the transverse thermal conductivity. This study involves the evaluation of the thermal interface quality in carbon fiber reinforced epoxy composites to determine the best way to enhance the thermal properties of the interface to increase transverse thermal conductivity.

2. ANISOTROPY IN CARBON FIBERS COMPOSITES

Since the fibers are strong in the axial direction and weaker in the transverse direction, fiber axial orientation is usually selected to be in the direction of the load. (Referring to Figure 1) To handle loads from multiple directions in-plane x-z, plies with varying orientation of carbon fibers are combined into a laminate. However, very often, the heat flux is perpendicular to the load (or fiber axes) and thermal conductivity of the laminate in a direction perpendicular to fiber axes (y-direction shown in Figure 1 repeated below) remains poor. The transverse thermal conductivity depends on the microstructure of the fiber in the transverse plane (plane x-y). The laminates that are the samples to be studied in this project have a similar arrangement of carbon fibers, which is why it is important to review the microstructures of carbon fibers to study heat transfer in such laminates.

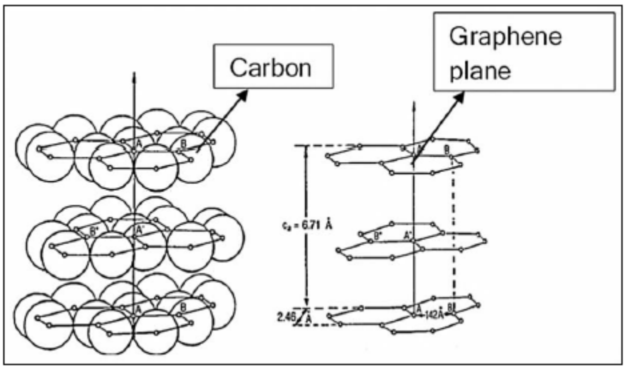

Fig -2(a): Layers of carbon atoms in an anisotropic structure of graphite crystal. Graphene planes, formed by a layer of carbon atoms (Fitzer & Manocha, 1998).

Carbon fibers consist of graphite crystals. The unique properties of these fibers are due to a highly anisotropic graphite lattice structure. Several flat-sheets like layers of carbon atoms, called "graphene layers", are arranged in a stack to form a graphite crystal as shown in Figure 2(a) (Fitzer & Manocha, 1998).

Figure 2 (a) is a modification of the original figure from the book 'Carbon Reinforcements and Carbon/Carbon Composites' (Fitzer & Manocha, 1998). Figure 2 (b) depicts the orientation of graphene planes concerning the fiber-axis. The basal planes of each layer are bonded by strong covalent bonds in the plane of the layer (or the crystallographic direction). But each layer of strongly bonded planes is bonded to other such layers by weaker van der Waals forces. Therefore, material properties have a high value along with strong covalent bonds (in the plane of each layer) and poor along with weak van der Waal's bonds (perpendicular to each layer) resulting in the anisotropy. Therefore, the properties of carbon fibers will depend on the orientation of these bonds. The thermal conductivity along a graphene plane is dominant compared to its value perpendicular to the planes (Fitzer & Manocha, 1998). It follows that the value of thermal conductivity of the composite in any direction will depend on the orientation of graphene planes concerning that direction. The carbon atoms form a nearly perfect graphite crystal structure, well-aligned along the fiber-axis giving a high axial thermal conductivity as shown in Figure 2 (b). Pitch fibers show the highest degree of orientation of graphite structure along the fiber axis and therefore, good axial thermal conductivities compared to any other types of carbon fibers (Campbell, 2010).

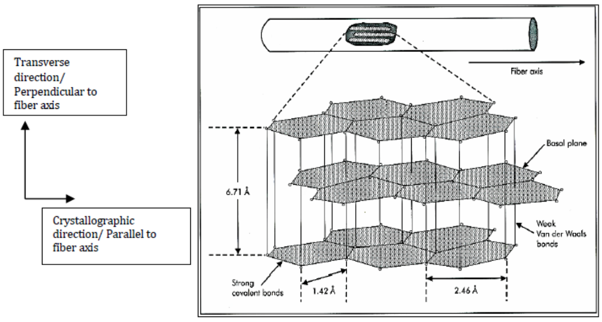

Fig -2(b): Orientation of graphene planes in carbon fibers. Strongly bonded planes in a layer run along the fiber axis. Weak bonds between layers are along the transverse direction to the fiber axis (Strong, 2008).

The path of the heat flux and hence the transverse thermal conductivity also depends on the arrangement of graphene planes in the x-y plane shown in Figure 3 (a) & (b). Looking at the circular cross-section of pitch carbon fibers, the graphene planes usually appear to be either fanning out radially from the center of the fiber as shown in Figure 3 (b) or arranged in concentric rings (like in an onion), around the center of the fiber as shown in Figure 3 (a) (Fitzer & Manocha, 1998).

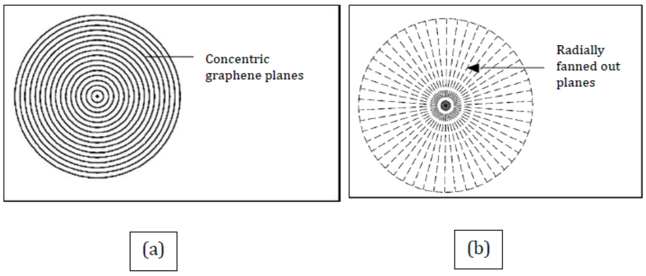

Fig -3(a): Transverse section of carbon fiber with radially arranged graphene planes.
(b): Carbon fiber cross-section with concentric graphene planes

It has been established that the thermal conductivity in carbon fiber will be dominant along graphene planes and poor otherwise. Since both structures are radially symmetric, the thermal conductivity of a single fiber studied for any one direction (x or y) holds for all directions in the x-y plane. In the following discussion, y-direction will be considered.

In a finite element study of heat transfer through composites with pitch carbon fibers (Grujicic et al., 2006), it was shown that the interfacial thermal resistance significantly reduces the thermal conductivity in the transverse direction. The microstructure of the fiber is such that the graphene planes are fanned out radially from the center of the fiber, resulting in heat flux vectors following the same path (Grujicic et al., 2006). The model by Grujicic et al. consisted of a cuboid Concentric graphene planes Radially fanned out planes (a) (b) composite structure consisting of four fibers of diameter 14 μm and the cube having dimensions to correspond with the volume fraction of the actual composite. Heat transfer in the longitudinal, as well as transverse direction to the fibers, were analyzed. Figure 4 shows the effect of the graphene plane orientation on the heat transfer is in the y-direction.

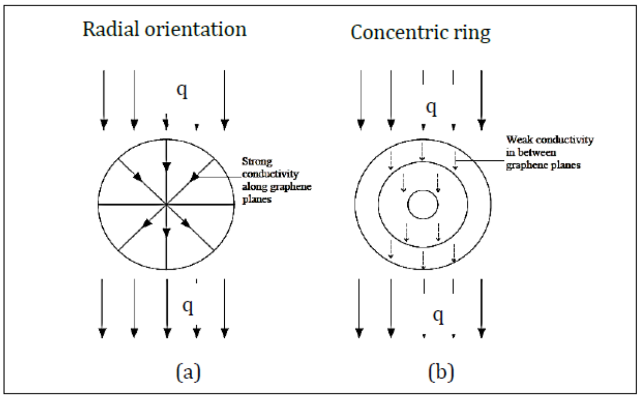

Fig -4(a): Strong conductivity along radial graphene planes can assist heat flux in Y direction due to heat flow along the graphene planes.
(b): Weak conductivity between graphene sheets may result in poor conduction of heat in the Y direction.

The radially oriented graphene planes will have strong radial conductivity. It will cause the transfer of heat in the desired y-direction by transferring heat flux along the radial graphene planes, as shown in Figure 4 (a). Therefore, a better value of conductivity in the y-direction can be expected. On the other hand, in the circumferentially arranged concentric graphene planes shown in Figure 3(b), the tangential conductivity will be strong, however; much of the desired heat flux must pass from one graphene plane to another as shown in Figure 4 (b); where the bonding forces are weak, therefore the conduction of heat may be comparatively poor.

Table -1: Comparison of thermal conductivities of a composite having radial, circumferential, and isotropic fiber conductivity.

	Type of fiber conduction		
	Radial	Concentric	Isotropic
The conductivity of composite W/mK	7.84	6.09	17.24

3. THEORETICAL STUDIES

Transverse thermal conductivity in a composite laminate with aligned continuous fibers is given by-

$$k_{composite} = k_m \frac{k_p(1+\propto)+k_m+f[k_p(1-\propto)-k_m]}{k_p(1+\propto)+k_m-f[k_p(1-\propto)-k_m]}$$

Where

k_f is the fiber conductivity

k_m is the matrix conductivity

f is the fiber volume fraction

$$\propto = \begin{cases} \frac{a_k}{a_1}, for\ p \geq 1 \\ \frac{a_k}{a_3}, for\ p \leq 1 \end{cases}$$

$$p = aspect\ ratio = a_3/a_1$$

a_3 is the length of fiber

a_1 is the radius of fiber

$$a_k = kapitza\ radius = \frac{1}{h_i} \times k_m$$

4. CONCLUSIONS

The numerical model also demonstrated that the interface heat transfer coefficient is not the dominant factor in the heat transfer process within the composite. Much of the resistance to heat transfer comes from the polymer matrix; therefore, increasing the heat transfer coefficient beyond the hi,max=1x10^6 W/m^{2}K does not improve the conductivity significantly. A polymer matrix can reduce the thermal conductivity by about a factor of ten. Therefore, to improve the conductivity of the composite, the improvement in the interface heat transfer coefficient should be accompanied by improvement in the conductivity of the matrix. The third factor that controls the composite conductivity is the dispersion of fibers from the ideal geometric layout, where each fiber location varies along the direction of the fiber axis and fibers touch each other randomly along their length. The effect of the deviation of the fiber location from the ideal geometry has a very strong effect on the thermal conductivity of the composite. In this study, this effect resulted in the conductivity changing by a factor of five, which appears to be higher than the effect of the interface thermal conductivity. Therefore, it is recommended that, in future work, additional experiments are carried out on samples with known interfacial properties, and the conductivities be compared with simulation results to determine the exact value of the dispersion factor. If the exact value of the dispersion factor is known, this model can be used to predict either the composite sample conductivity when the interface heat transfer coefficient hi is known or the value of hi when the composite conductivity is known.
An analytical or numerical approach to the study of the dispersion factor is to add a fiber dispersion model in a two or three-dimensional geometry.

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