



## THERMAL CHARACTERIZATION OF AS4/3501-6 CARBON-EPOXY COMPOSITE

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### ABSTRACT

Thermal diffusivity, specific heat, and thermal conductivity are important thermophysical properties of composite materials. These properties play a significant role in the engineering design process of space systems, aerospace vehicles, transportation, energy storage devices, and power generation including fuel cells. This paper examines these thermophysical properties of the AS4/3501-6 composite using the xenon flash method to measure the thermal diffusivity in accordance with ASTM E1461 and differential scanning calorimetry to measure the specific heat in accordance with ASTM E1269. The thermal conductivity was then calculated using a proportional relationship between the density, specific heat, and thermal diffusivity.

**Keywords:** Thermal Diffusivity; Specific Heat; Thermal Conductivity; Xenon Flash Method

### 1. INTRODUCTION

As today's technology continues to develop at a rate that was once unimaginable, the demand for new materials that will outperform traditional materials also increases dramatically. To meet these challenges, monolithic materials are being combined to develop new unique materials called composites. The formation of composites provides properties unobtainable separately with either constituent. Besides improvements in the mechanical properties such as tensile strength, stiffness, and fatigue endurance, materials must retain functionality at much higher operating temperatures than before. Due to extreme temperatures, material properties may alter in operation resulting in severely reduced properties which may lead to catastrophic failures during usage. Thermal properties play a significant role in design applications, determining safe operating temperatures, process control characteristics, and quality assurance of these materials.

The objective of this paper is to develop a thermal properties database for the carbon-epoxy AS4/3501-6 composites. The AS4 carbon fiber used is a unidirectional continuous PAN based fiber. The 3501-6 epoxy resin is amine cured and provides low shrinkage during the curing process while maintaining excellent resistance to chemicals and solvents. The 3501-6 was developed to operate in a temperature environment up to 350°F (177°C). The AS4/3501-6 carbon-epoxy composite used in the investigation is an 8-ply laminate compiled of laminas alternating between 0° and 90° orientations. The composite material has a high gloss and smooth black finish that was surface treated to improve the fiber-to-resin interfacial bond strength which met the Hexcel aerospace specification, HS-CP-5000.

The thermophysical properties of AS4/3501-6 carbon-epoxy have been investigated using experimental methods. The flash method was used to measure the thermal diffusivity of the composite. This method is based on the American Society for Testing and Materials standard, ASTM E1461. In addition, the Differential Scanning Calorimeter was used in accordance with the ASTM E1269 standard to measure the specific heat. The measured thermal diffusivity, specific heat, and density data were used to compute the thermal conductivity of the

AS4/3501-6 carbon-epoxy composite. Thermal conductivity is the property that determines the working temperature levels of the material; it plays a critical role in the performance of materials in high temperature applications, and it is an important parameter in problems involving heat transfer and thermal structures.

The materials used in the investigation were developed and fabricated at the Center for Composite Materials Research (CCMR) at North Carolina A&T State University. The mechanical properties of the AS4 composite have been measured (Akangah and Shivakumar, 2013). The AS4/3501-6 autoclave processed carbon/epoxy composite was made from a unidirectional [non-woven] carbon fiber/epoxy tape pre-preg molded in its particular [8-ply 0/90-degree] stacking sequence of the following specification: fiber area weight of 150 g/m<sup>2</sup> with a resin content of 33% [that is 33% weight portion of the uncured pre-preg tape, which is the area weight of the fiber plus the area weight of the resin = 150 g/m<sup>2</sup> (fiber) + 74 g/m<sup>2</sup> (resin) = 224 g/m<sup>2</sup> (total area weight of the uncured pre-preg)]. AS4/3501-6 is a carbon composite commonly used and recommended for general purpose structural applications (United States, 1999). Manufactured by Hexcel Corporation, the AS4's epoxy resin has properties that allows for the composite to withstand temperatures up to 200°C as well as provide a high strength to weight ratio. In short, it can withstand some high temperature applications and also provide the light weight desired in industries to reduce fuel consumption. For example, this material can be used for wind power turbine blade applications (3501-6, 1998; HexTow, 2010).

### 2. THERMAL DIFFUSIVITY MEASUREMENTS

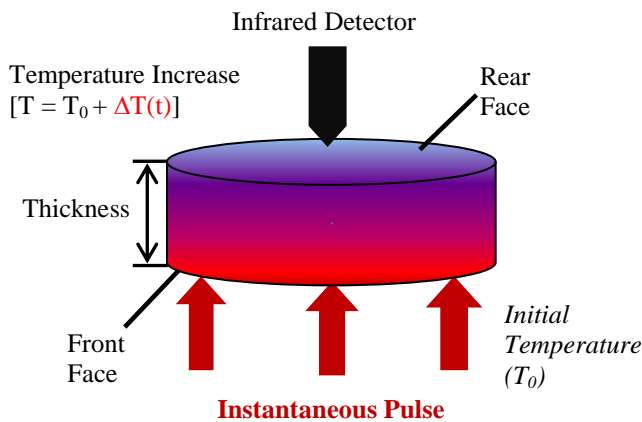
In order to determine the working temperature levels of a material, it is expedient to measure how rapidly heat will pass through that material. This measurement, or property, is called thermal diffusivity. Thermal diffusivity plays a critical role in the performance of materials in high temperature applications, and this material property can be measured in several different ways. There are steady-state methods as well as transient techniques. Available procedures include Thermal Wave Interferometry (TWI), Thermographic methods, the Flash Method, the

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Hot-wire method, and others. Transient techniques have been preferred in measuring thermal properties of materials more recently; however, the Flash Method is the most common of these methods (Nunes dos Santos, 2007; Patrick and Saad, 2012).

## 2.1 The Flash Method

In 1961, W.J. Parker founded the Flash method, and it is the most frequently used transient photothermal technique and has the versatility of using a xenon lamp or laser as the energy source. In many countries, it is considered a standard for thermal diffusivity measurements of solid materials (Cernuschi *et al.*, 2004). As adopted by the United States, the laser flash method is a standard test method and is defined by the American Society for Testing and Materials E1461 standard. It involves a small cylindrical, thin disk specimen being heated to a desired temperature, usually between 20 and 500°C. Once the disk has reached the specified temperature the front face is subjected to a quick radiant energy pulse as shown in Fig. 1. The energy source can be a laser or a lamp. A detector measures the resulting temperature change with respect to time on the rear face of the sample. The data acquisition system then records the temperature change of the rear face of the specimen versus time. A graphical representation of this data is called the thermogram of the flash. Figure 2 displays the theoretical model thermogram. The time in which it takes the rear face of the specimen to reach half the maximum temperature rise is called the half-time,  $t_{1/2}$ .



**Fig. 1** Schematic of the Flash Method

Employing Carslaw and Jeager's equation of the temperature distribution within a thermally insulated solid of uniform thickness  $L$ , Parker *et al.* (1961) was able to derive a mathematical expression to calculate thermal diffusivity (Carslaw *et al.*, (1959). An abbreviated version of this derivation is given as:

$$T(x, t) = \frac{1}{L} \int_0^L T(x, 0) dx + \frac{2}{L} \sum_{n=1}^{\infty} \exp\left(\frac{-n^2 \pi^2 \alpha t}{L^2}\right) \cos \frac{n\pi x}{L} \int_0^L T(x, 0) \cos \frac{n\pi x}{L} dx \quad (1)$$

where  $\alpha$  is the thermal diffusivity of the solid material. If a pulse of radiant energy,  $Q$ , is instantaneously and uniformly absorbed into a small depth referred as  $g$ , at the front face ( $x=0$ ) of the thermally insulated solid material, the temperature distribution at that initial point is given by:

$$T(x, 0) = \frac{Q}{\rho \cdot c_p \cdot g} \quad \text{for } 0 < x < g \quad (2)$$

$$T(x, 0) = 0 \quad \text{for } g < x < L \quad (3)$$

These initial conditions are substituted into the temperature distribution equation above. It is considered that the very small depth  $g$  of an opaque solid will yield a small angle. Additionally, it is known that for a very small angle,  $\theta$ ,  $\sin(\theta) \approx \theta$  and  $\cos(n\pi x/L) = (-1)^n$ . Once this is applied, the temperature distribution at the rear face ( $x=L$ ) is expressed as:

$$T(L, t) = \frac{Q}{\rho \cdot C \cdot L} \left[ 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp\left(\frac{-n^2 \pi^2}{L^2} \alpha t\right) \right] \quad (4)$$

Parker *et al.* (1961) then defined two dimensionless parameters,  $V$  and  $\omega$  as:

$$V(L, t) = \frac{T(L, t)}{T_m} \quad (5)$$

$$\omega = \frac{\pi^2 \alpha t}{L^2} \quad (6)$$

where  $T_m$  is the maximum temperature at the rear face. Combining equations 4, 5, and 6 results in (Parker *et al.*, 1961):

$$V = 1 + 2 \sum_{n=1}^{\infty} (-1)^n (e^{-\omega n^2}) \quad (7)$$

Setting  $V = 0.5$  allows for the determination of  $\omega$ , and then substitution into equation 7 allows for a mathematical equation for thermal diffusivity to be stated as:

$$\alpha = 0.1388 \frac{L^2}{t_{1/2}} \quad (8)$$

This derivation by W.J. Parker is a theoretical model of the flash method and is the ideal case. It assumes that the specimen is mostly homogeneous and isotropic, that there is one dimensional heat flow, and that there are no heat losses from the specimen (Cernuschi *et al.*, 2002). It also assumes that energy pulse is uniformly subjected across the front face of the specimen and that the pulse is instantaneous. Because of this assumption, many researchers have developed correction factors since the time of Parker's original derivation. These included but are not limited to Cowan, Clark and Taylor, Koski, and Heckman. Each of these correction factors use different methods or a combination of methods to reanalyze the theoretical model and impose additional parameters. The Clark and Taylor correction factor accounts for radiation heat losses and is used in the research conducted in this experiment. Clark and Taylor (1975) examined the thermogram at different points before the maximum temperature rise was reached and developed a correction factor. The correction factor is calculated using the following equation:

$$K_r = -0.3461467 + 0.361578 \left( \frac{t_{3/4}}{t_{1/4}} \right) - 0.06520543 \left( \frac{t_{3/4}}{t_{1/4}} \right)^2 \quad (9)$$

Specifically, they analyzed the time to reach 25 percent and 75 percent of the maximum temperature change. The corrected thermal diffusivity equation as defined by Clark and Taylor is

$$\alpha_{corrected} = \frac{\alpha K_R}{0.13885} \quad (10)$$

## 2.2 Experimental Apparatus

In general, the ASTM E1461 standard (2007) provides the minimum requirements for the apparatus. The key components are the flash source, specimen holder, temperature response detector, recording device, and an environmental enclosure is needed when testing above and below room temperature (ASTM, 2007). The flash source can be any device able to emit a quick energy pulse, usually a lamp or laser. The apparatus used in this facility was commercialized and purchased from Anter Corporation. The name of the apparatus is the FlashLine™ 2000, and it utilizes a high intensity xenon lamp as the pulse source. The pulse duration time should be less than 2% half-time of the specimen to be measured in order to keep the error due to finite pulse less than 0.5%. The apparatus is automated and capable of testing up to four specimens in each run.

The thermal property analyzer also contains a vacuum capable environmental enclosure in which nitrogen gas is used to evacuate the chamber. The detector should be any sensor that can measure a linear electrical output proportional to a small temperature rise, and it, along with its amplifier, must have a response time of no more than 2% of the half-time. The Indium Antimonide (InSb) Infrared Detector outputs a linear electrical signal proportional to a small temperature change experienced by the rear face of the specimen after the energy pulse has been initiated. The data acquisition system can be pre-programmed within one time period for the acceptable resolution of at least 1% for the quickest thermogram the system can deliver (ASTM, 2007). Figure 2 shows the normalized temperature versus the normalized time.

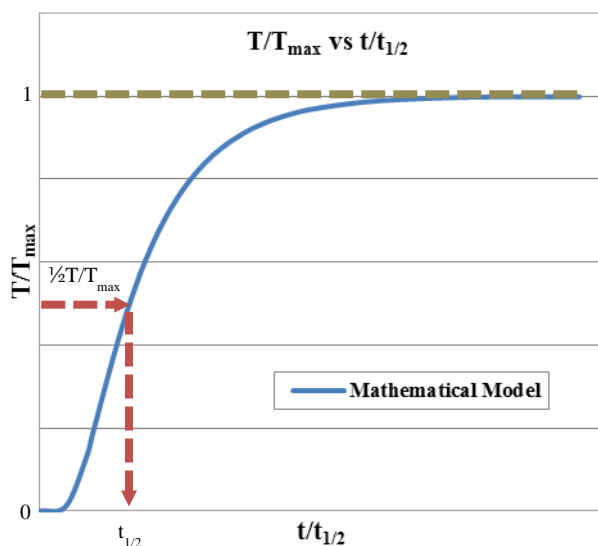


Fig. 2 Characteristic Thermogram of the Flash Method

## 2.3 Test Specimen Preparation

The test specimens were prepared to be thin circular disks of 10 to 30 mm in diameter, whose front face surface area is less than that of the energy pulse beam. According to ASTM E1461 standard (2007) each specimen should be thick enough to be representative of the test material but remain within 1 to 6 mm range. Overall, the optimum thickness depends upon the magnitude of the estimated thermal diffusivity and should be chosen so that the time to reach half of the maximum temperature falls within the 10 to 1000 ms range. In order to accomplish these specified dimensions, a drill press equipped with a diamond plated drill bit was used to cut the material to the appropriate diameter. When necessary, the specimens were milled to achieve the preferred thickness.

Both the rear and front faces were flat and parallel within 0.5% of their thickness to maintain pulse uniformity. The standard suggests that a thin, uniform layer of graphite be applied to both faces of the specimens to improve the capability of absorbing the applied energy flash by reducing the reflection from the specimen. This was not necessary for the experiments performed in this work due to the material nature of the AS4 composite.

## 2.4 Experimental Procedure

The experiments were conducted following the testing standard, ASTM E1461. 12.7 mm (0.5 inch) and 25.4 mm (1 inch) diameter samples were used depending on the availability or size limitations of the material. This will not account for any changes in the thermal diffusivity. The diameter, thickness, mass, and density were documented. Each sample was placed in the specimen holder housed inside a vacuum sealed environmental enclosure. The environmental enclosure was purged using nitrogen gas to form an inert environment for the samples.

Approximately 1 L of liquid nitrogen was manually poured in the receptacle of the IR detector. The sample thickness, diameter, and mass were input into the FlashLine™ 2000 System, and the test was initiated at ambient temperature. Each sample was tested to a maximum temperature of 175°C which is the service temperature of the material for general purpose structural applications. At each designated temperature, a minimum of three flashes were performed at a time. The results were compiled, analyzed, and necessary corrections were made. The time required for each experimental run varies depending on the range of temperatures tested and the temperature increment.

## 3. SPECIFIC HEAT MEASUREMENTS

Specific heat is a measurement of the amount of heat per unit mass that is required to raise the temperature of a material one degree Celsius. The differential scanning calorimetry (DSC) technique was used to measure the specific heat of the materials. This technique is based on the measurement of the change of the difference in the heat flow rate to the sample and to a reference sample while they are subjected to a controlled temperature program. Using the measured heat flow rate of the sample, differential scanning calorimetry can determine how a material's heat capacity varies with respect to temperature.

### 3.1 Differential Scanning Calorimetry (DSC)

Widely used for the measurement of specific heat, differential scanning calorimetry (DSC) is a thermoanalytical technique. Its methodology is defined by the ASTM E1269 standard. When performing a differential scanning calorimetry measurement, a test specimen and reference are enclosed in the same furnace together on a metallic block with high thermal conductivity within the calorimeter. The metallic block ensures a good heat-flow path between the specimen and reference. The sample and the reference are subjected to an identical temperature program. The heat capacity change in the specimen differs from that of the

reference. The calorimeter measures the temperature difference and calculates heat flow from calibration data. As a result, the specific heat of the sample can be calculated using the heat flow results. Differential scanning calorimetry is an ASTM test method standard for determining specific heat capacity (ASTM, 2005).

To calculate the specific heat of an unknown material, the heat flux of the unknown and a reference must be measured using the differential scanning calorimeter. Using the measured heat flux and the known specific heat of the reference, the specific heat of the unknown material can be calculated by using the ratio method technique. Since the differential scanning calorimeter is at constant pressure, the change in enthalpy of the reference is equal to the heat absorbed or released by the reference (ASTM, 2005). The depiction mathematically is:

$$dQ = (m)dh \quad (11)$$

Equation (11) leads to the following relationship:

$$\dot{Q} = m \frac{dh}{dt} = m \frac{dq}{dt} \quad (12)$$

where  $dq/dt$  is the specific heat rate, and  $dh/dt$  is the change of enthalpy with respect to time. At constant pressure, the relationship for specific heat can be written as:

$$c_p = \frac{1}{m} \frac{dH}{dT} \quad (13)$$

Using the chain rule, the equation can be rewritten as:

$$c_p = \frac{1}{m} \frac{dt}{dT} \frac{dH}{dt} = \frac{1}{m} \frac{dQ}{dt} \frac{dt}{dT} \quad (14)$$

From equation (14), the specific heat can be written as:

$$c_p = \frac{\left(\frac{dQ}{dt}\right) \left(\frac{dt}{dT}\right)}{m} \quad (15)$$

where  $dt/dT$  is the inverse temperature distribution over time. Using equation (15) and the ratio method, the calibration constant,  $E$ , is multiplied through the specific heat equation for the reference:

$$c_{p_{ref}} = E \frac{\left(\frac{dQ}{dt}\right)_{ref} \left(\frac{dt}{dT}\right)}{m_{ref}} \quad (16)$$

Solving for the calibration constant:

$$E = \frac{c_{p_{ref}} m_{ref}}{\left(\frac{dQ}{dt}\right)_{ref} \left(\frac{dt}{dT}\right)} \quad (17)$$

To determine the specific heat of the unknown material, equation (16) is used again but in terms of the sample:

$$c_p = \frac{E}{m} \left(\frac{dQ}{dt}\right) \left(\frac{dt}{dT}\right) \quad (18)$$

Substituting equation (17) into equation (18):

$$c_p = \left[ \frac{c_{p_{ref}} m_{ref}}{\left(\frac{dQ}{dt}\right)_{ref} \left(\frac{dt}{dT}\right)} \right] \left(\frac{1}{m}\right) \left(\frac{dQ}{dt}\right) \left(\frac{dt}{dT}\right) \quad (19)$$

The above equation can be reduced to:

$$c_p = c_{p_{ref}} \frac{m_{ref}}{m} \frac{\left(\frac{dQ}{dt}\right)}{\left(\frac{dQ}{dt}\right)_{ref}} \quad (20)$$

### 3.2 Experimental Apparatus

The calorimeter used in this research is the DSC 200 F3 Maia®, Differential Scanning Calorimeter manufactured by NETZSCH. It is a heat flux system that combines high stability, high resolution, and fast response time throughout a substantial temperature range. With the addition of the Intracooler 40, the temperature range extends from ambient temperature to cryostatic temperatures covering a larger temperature spectrum (-40°C to 600°C). The heating rate is adjustable from as low as 0.001K/min to as high as 100K/min while keeping a temperature accuracy of 0.1 K.

The DSC 200 F3 Maia® Differential Scanning Calorimeter consists of a furnace block, sample chamber, cooling system, heat flux sensor, and purge gas. The furnace block contains a miniature jacketed heater that provides the source of heat during the experiment. The furnace temperature is measured by a thermocouple integrated into the furnace walls. The sample chamber is sealed within the instrument's lid and has two additional lids to prevent a contamination from outside sources. The system's temperature can be reduced by using an Intracooler device. The calorimeter uses a high sensitivity type E heat flux sensor for its measurements (NETZSCH, 2008).

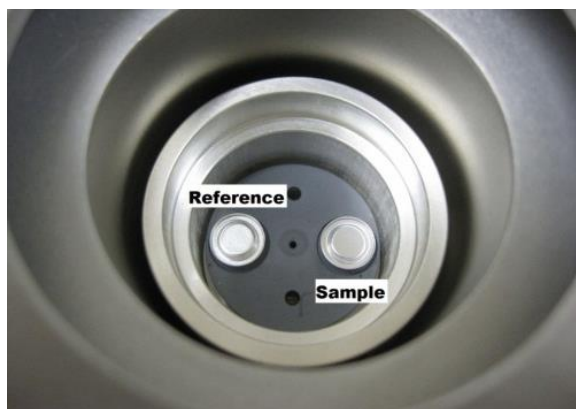
### 3.3 Test Specimen Preparation

Good thermal contact between the heat flux sensor and sample is vital for optimum results. To achieve this, the sample should lay as flush as possible with the bottom of the aluminum crucible. A 4-mm or 6-mm diameter and 1-mm thick sample can be used with this equipment using the corresponding crucible size. Then each sample was weighed three times, and the average mass was documented. Each sample was placed into the crucible, and a lid was positioned on top of the crucible to fully enclose the sample. Using tweezers, the crucible was then carefully placed on the heat flux sensor making sure the crucible was centered on the sensor.

### 3.4 Experimental Procedure

The differential scanning calorimetry experiment was performed following the ASTM E1269 testing standard for determining specific heat. The differential scanning calorimeter and data acquisition system were initialized and were allowed to reach thermal equilibrium. During this period the apparatus was purged with argon gas at a rate of 50 mL/min to produce an inert testing atmosphere. To measure the specific heat of a sample, a minimum of three runs must be performed.

Before the specific heat of the AS4 composite was determined, baseline and reference tests were performed. Since the samples were placed inside an aluminum crucible for testing, the crucible will add a contact resistance to the samples. The baseline corrects for this contact resistance increasing the accuracy of the results. The initial baseline run was performed by placing two empty crucibles in the designated location on heat flux sensors as seen in Fig. 3. The furnace was heated to the designated initial temperature of the program and held there isothermally at least four minutes while the calorimeter recorded the thermal curve. The crucibles were heated to the final temperature at a rate of 20°C/min and held isothermally again while the calorimeter recorded the thermal curve.



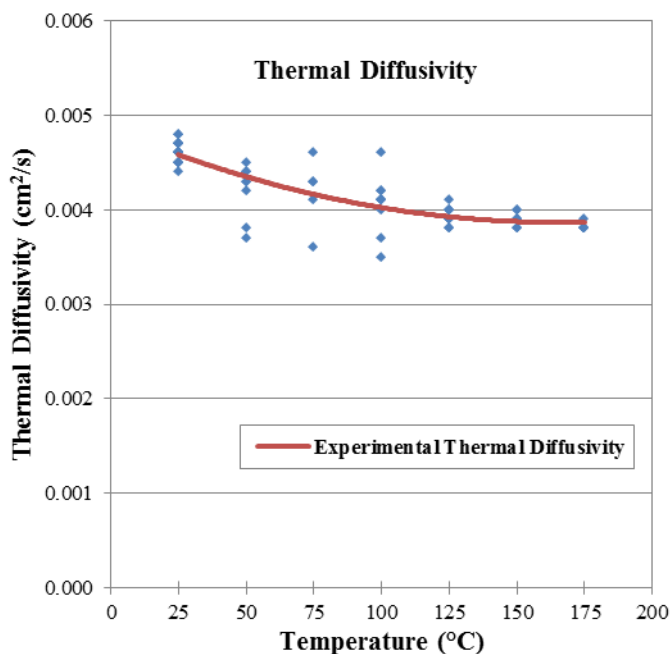
**Fig. 3** Crucibles Placed on the Heat Flux Sensor

Following the baseline run, the calorimeter testing chamber was cooled to ambient temperature. The crucible on reference location in the testing chamber was replaced with a sapphire reference. After applying the previous baseline to correct for the aluminum crucible, the same temperature program used for the baseline was executed for the sapphire reference. The measured specific heat of the sapphire was compared to the known specific heat value for sapphire to determine the error. The test was repeated for the AS4/3501-6 samples. To verify that the baseline did not alter, a baseline was established after every fourth test. Using the measured sapphire as a reference, the ratio method was used to determine the specific heat of the AS4 carbon-epoxy.

#### 4. RESULTS AND DISCUSSIONS

The flash method was used to measure the thermal diffusivity of the AS4/3501-6 composite. The thermal diffusivity was measured between room temperature and 175°C which is the temperature limitation for this material. Thermal diffusivity decreases over the temperature range by approximately 15% as shown in Fig. 4. This is apparent because the energy pulse will travel through the material faster at room temperature. In other words, the specific heat will be higher because it will take more heat to raise the temperature of the material by one degree Celsius thus signifying that the material has a lower threshold for heat at higher temperatures.

Three shots were recorded at each temperature during the experiment for each test. The data points represent the shots, or flashes, and the error at two standard deviations is displayed in Fig. 5. While there is more variation at the temperature range of 50° to 100°C, which is depicted by larger error bars, all of the data still falls within two standard deviations. This indicates that the error is minimal.



**Fig. 4** Thermal Diffusivity of the AS4/3501-6 Composite

The error was calculated at each temperature, and the error bars shows the interval where 95% of the data collected at each shot should lie. Population data sets provide the statistical estimates known as the population mean value and the population standard deviation defined by (Figliola and Beasley, 2011):

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (a_i - \bar{a})^2} \quad (21)$$

The results from each temperature tested are considered as a population where N is the total number of measurements,  $a_i$  represents a single  $i^{\text{th}}$  measurement, and  $\bar{a}$  is the mean value of the data at each temperature. Additionally, the margins of error were calculated for each temperature using standard error of the mean as shown in equation (22).

$$SE = \frac{\sigma}{\sqrt{N}} \quad (22)$$

The critical value from the normal distribution chart based on 95% confidence is 1.96, and the margin of error,  $e$ , is determined by the following:

$$e = (\pm 1.96)SE \quad (23)$$

The percent error can now be found using:



$$\text{error \%} = \frac{e}{\text{mean}} \times 100 \% \quad (24)$$

The results for the thermal diffusivity percent error at the corresponding temperatures have been calculated and are displayed in Table 1.

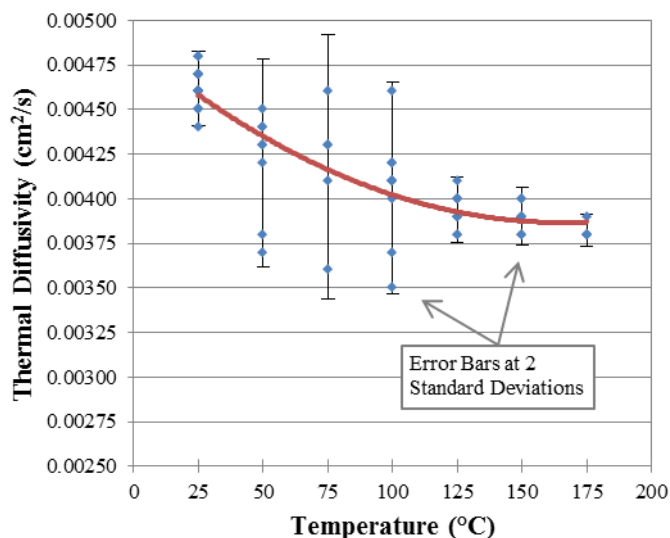


Fig. 5 Magnified View of the Thermal Diffusivity Error Bars

Table 1 Percent Error of the Thermal Diffusivity

Temperature (°C)	Mean (cm <sup>2</sup> /s)	Standard Deviation (cm <sup>2</sup> /s)	Margin of Error (± cm <sup>2</sup> /s)	Percent Error (%)
25	4.615E-03	1.01366E-04	4.44255E-05	0.96
50	4.200E-03	2.73861E-04	1.20025E-04	2.86
75	4.180E-03	3.31059E-04	1.45093E-04	3.47
100	4.073E-03	2.69986E-04	1.18327E-04	2.91
125	3.936E-03	8.81396E-05	3.86289E-05	0.98
150	3.900E-03	7.55929E-05	3.31300E-05	0.85
175	3.813E-03	3.30719E-05	1.44944E-05	0.38

According to the testing standard, the optimum thickness of the tested samples should be chosen so that the time to reach half of the maximum temperatures (half-time),  $t_{1/2}$ , falls within the 10 to 1000 ms (0.01 to 1 s) range (ASTM, 2007). To verify that the samples were the proper thickness, an initial test was performed to check the half-times of the tested material. The half-times attained at each temperature were recorded. The corresponding half-times at different temperatures are shown in Fig. 6. The half-time for each sample fell within the acceptable range according to the testing standard verifying that the proper thickness was chosen. According to the ASTM standard, the thickness may vary (1 to 6 mm) based on the thermal conductivity of the material (i.e., the more conductive a material is, the larger the thickness can be). The optimum thickness of the AS4 composite used in this research was 1.140 mm.

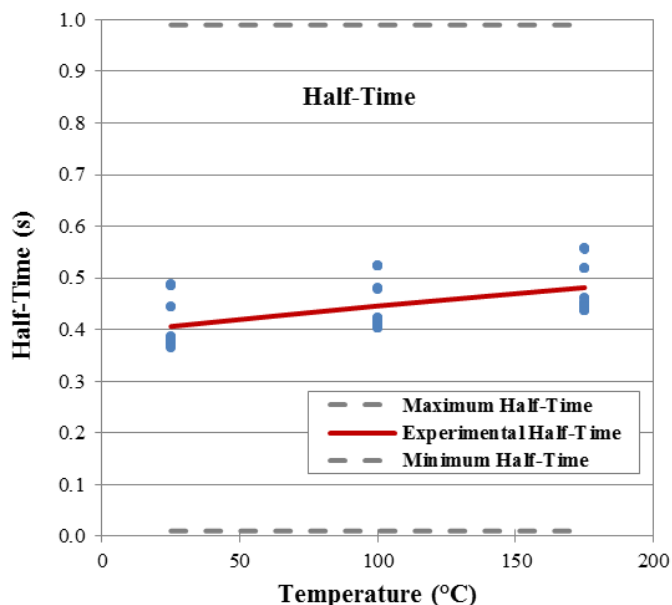


Fig. 6 Half-Times of the AS4/3501-6 Composite

The material has also been tested at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. The apparatus at ORNL is capable of attaining cryogenic thermal diffusivity measurements. The subzero results for the AS4 composite are displayed and compared with the results from North Carolina A&T's Thermal Characterization Research Laboratory (TCL) as shown in Fig. 7. The TCL apparatus uses an infrared detector to measure the temperature changes; on the other hand, ORNL uses thermocouples instead. The results of the thermal diffusivity at both labs were consistent and within a 5% margin of error.

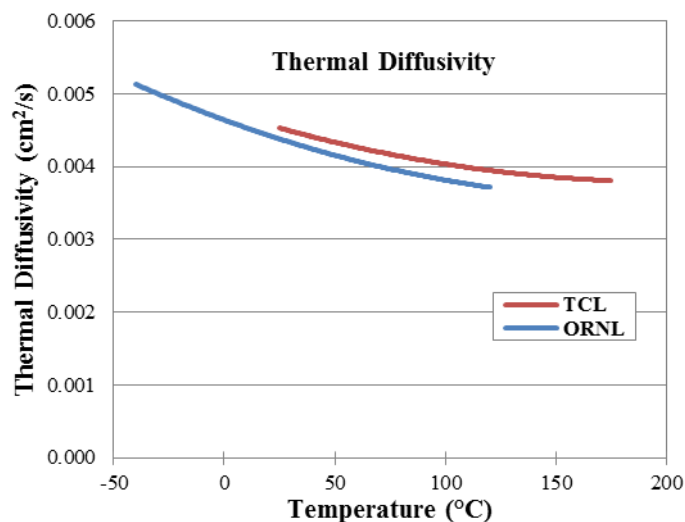
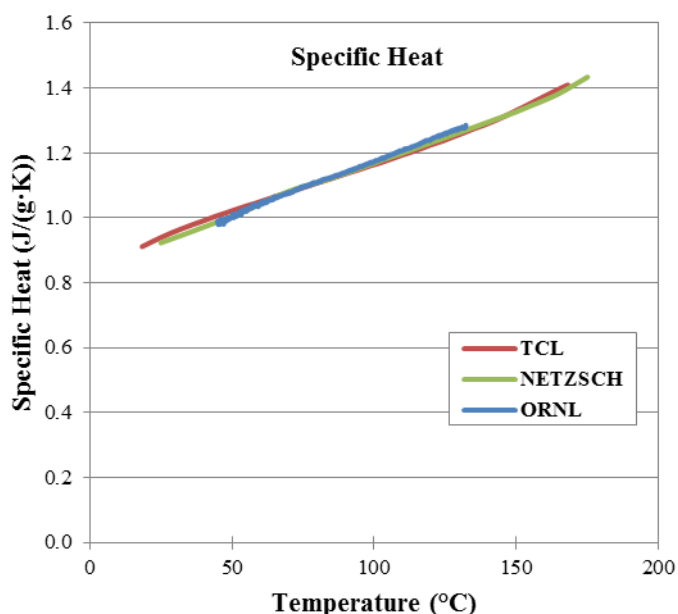


Fig. 7 Thermal Diffusivity of the AS4/3501-6 Composite

The specific heat of the AS4/3501-6 composite consistently increases from approximately 0.9 J/g °C at room temperature to 1.4 J/g °C at 175°C as shown in Fig. 8. The material has been tested at the TCL and also at ORNL. An agreement has been achieved at both labs. Figure 8 displays the specific heat measurements of TCL versus ORNL. The material has been tested at NETZSCH, and the data is also displayed in Fig. 8. All three specific heat results overlap indicating accurate and precise measurements. The heating curve was used in the analysis.

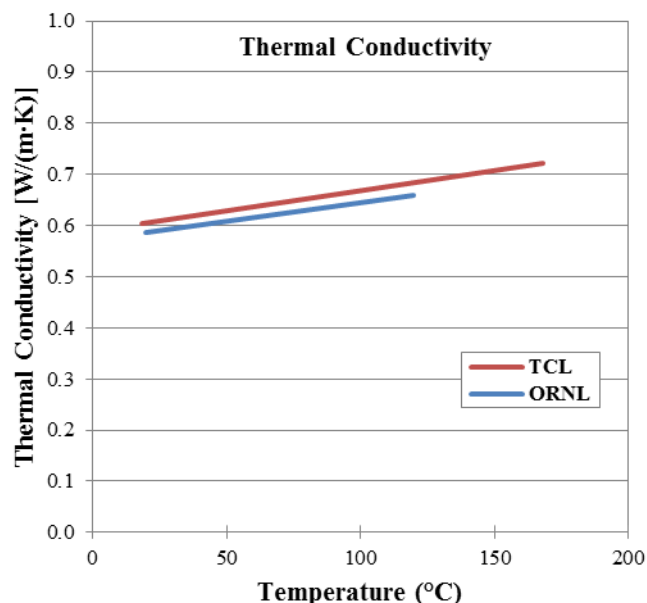


**Fig. 8** Specific Heat of the AS4/3501-6 Composite

Using the density (the density for the tested AS4/3501-6 composite was 1.46 g/cm<sup>3</sup>), specific heat, and thermal diffusivity, the thermal conductivity of the AS4/3501-6 composite was determined using the following relationship:

$$k = \rho c_p \alpha \quad (25)$$

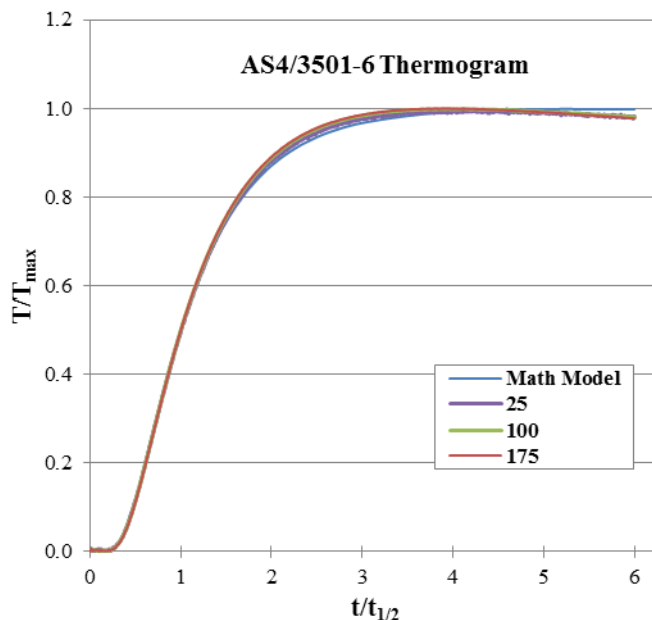
The results for the thermal conductivity of the AS4/3501-6 composite are shown in Fig. 9. There is a 20% increase in the thermal conductivity of the composite over the service temperature range.



**Fig. 9** Thermal Conductivity of the AS4/3501-6 Composite

Figure 10 shows the thermogram of the AS4/3501-6 carbon-epoxy composite as it compares with the mathematical model. The thermogram displays the relationship between the temperature divided

by the maximum temperature versus the time divided by the half-time. The data acquisition system can be pre-programmed within one time period for the acceptable resolution of at least 1% for the quickest thermogram the system can deliver which is represented by the mathematical model.



**Fig. 10** Thermogram of the AS4/3501-6 Composite

As shown in Figure 10, immediately before the temperature reaches its maximum, it is noticed that there is slightly more radiation heat loss at room temperature than the 100°C and 175°C measurements. After the flash occurs, the heat will radiate more from the sample in a lower temperature environment than in a higher temperature environment. The AS4/3501-6 composite shows relatively no heat loss with respect to temperature. Table 2 shows the sample specifications of the AS4 composite while table 3 shows the measured thermal properties.

**Table 2** Specifications of AS4/3501-6 Testing Specimens

Test	Diameter mm (inch)	Thickness mm (inch)	Mass (g)
Specific Heat	4.00 (0.157)	0.960 (0.038)	0.02013
Thermal Diffusivity	12.69 (0.50)	1.135 (0.447)	0.21000

**Table 3** Thermal Properties of AS4/3501-6

Temperature (°C)	Density (g/cm <sup>3</sup> )	Thermal Diffusivity (cm <sup>2</sup> /s)	Specific Heat (J/g·K)	Thermal Conductivity (W/m·K)
25	1.4629	0.004615	0.94171	0.6127445
50	1.4629	0.004200	1.02508	0.6347415
75	1.4629	0.004180	1.09773	0.6492697
100	1.4629	0.004073	1.16040	0.6622167
125	1.4629	0.003936	1.23705	0.6803271
150	1.4629	0.003900	1.32987	0.7088875
175	1.4629	0.003813	1.40960	0.7376534

## 5. CONCLUSIONS

The thermophysical properties database of the AS4/3501-6 composite has been developed over the service temperature range of the material. Using the flash method, the thermal diffusivity was measured through the thickness. Specific heat was measured using the differential scanning calorimeter. The thermal conductivity was determined using the density, specific heat, and thermal diffusivity of the composite. The thermophysical properties have been validated using different apparatuses at ORNL and TCL from 25°C to 175°C. This composite material is suitable for general purpose structural applications.

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## NOMENCLATURE

$\bar{a}$	measurement mean
$a_i$	$i^{\text{th}}$ measurement of the sample
$c_p$	specific heat (J/kg·K)
$E$	calibration constant
$e$	margin of error
$g$	small depth into sample (cm)
$h$	specific enthalpy (J/kg)
$k$	thermal conductivity (W/m·K)
$K_r$	correction factor
$L$	sample thickness (cm)
$m$	mass (kg)
$N$	number of measurements
$Q$	heat (J)
$t$	time (s)
$T$	temperature (K)
$V$	dimensionless quantity
$x$	distance (cm)
<i>Greek Symbols</i>	
$\alpha$	thermal diffusivity (cm <sup>2</sup> /s)
$\Delta$	differential quantity
$\rho$	density (kg/m <sup>3</sup> )
$\sigma$	population mean
$\omega$	dimensionless quantity
<i>Subscripts</i>	
$0$	initial time step
$1/2$	half
$max$	maximum
$ref$	reference

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