ANGSTROM'S METHOD FOR THERMAL PROPERTY MEASUREMENTS OF CARBON FIBERS AND COMPOSITES

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Introduction

One of the remarkable properties of carbon or graphite fibers is the extremely high value of thermal conductivity that can be achieved by suitable manufacture. Applications that take advantage of this property usually employ composite construction. Thermal conductivity measurements need to be made of both the fibers going into the composite and of the fabricated pieces themselves in order to be sure that unacceptable degradation has not occurred due to handling. To make these measurements, we have adapted Angstrom's method of measuring the thermal diffusivity D of a copper bar [1].

Thermal Diffusivity

The usual method of measuring thermal conductivity involves measuring the amount of heat flow through a specimen with a given temperature gradient. Angstrom devised an alternative method of quantitatively evaluating the thermal conductivity by measuring the diffusion of heat along a bar that was alternately heated and cooled at one end. The temperature is measured as a function of time at two positions along the bar and, from analysis of the progression of the heat wave, the thermal diffusivity D is obtained. The thermal conductivity K is related to thermal diffusivity by the expression

$$K = \rho D c \tag{1}$$

where ρ is the specimen density and c is the specific heat. The method has the advantage that it takes into account the heat loss from the sides of the bar and thus avoids inaccuracy from this very significant effect.

Rather than the steam and cold water alternation (square wave) which Angstrom employed, we use a sine wave from a function generator to drive a thermoelectric element at the end of the specimen. We employ a vacuum to reduce as much as possible the sidewall heat loss. This is necessary because poor fiber to fiber thermal contact can cause temperature variation across the strand. We use a computer controlled data acquisition system to get accurate time and temperature measurements at two locations along the strand of fibers. Very fine thermocouples are used to avoid disturbing the progression of the heat wave along the fibers. The heat wave amplitude of approximately 1° C and frequency of 16 millihertz were appropriate for our specimens, which were approximately 45 cm long.

In this manner a heat wave of the form

$$T = T_0 \exp(-ax + i(\omega t - bx - \gamma)) \tag{2}$$

is sent down the specimen, which may be a strand of thousands of carbon filaments or, alternatively, a uniaxial composite strip. The strand is slightly twisted and weakly pulled into what may be regarded as a one dimensional thermal conductor. The temperature T along the strand varies with time according to the equation

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial x^2} - BDT, \tag{3}$$

where B is the heat loss parameter.

Substituting the wave form into the differential equation and doing some algebra [2,3] yields an expression for the diffusivity

$$D = \frac{l^2}{2(\Delta t)\ln(T_1 / T_2)}, \tag{4}$$

where l is the distance between thermocouples, T_1 and T_2 are the temperature wave amplitudes at the two thermocouples, and Δt is the time delay of the wave from thermocouple 1 to thermocouple 2.

In the experiment, data is taken by computer for 17 minutes in order to allow time for 16 complete cycles of the sine wave. A typical data plot is shown in Figure 1.

Table 1 gives the measured values of the thermal diffusivity and the calculated values of the thermal conductivity for a series of BP Amoco Thornel® carbon fibers.

Specific Heat

The accuracy of the thermal conductivity depends on the density and the specific heat c as well as D. The density is measured by a version of the method of Archimedes and apparently poses no problem. The specific heat, however, varies with the structural perfection of graphitic materials [4,5] so we devised a means to measure this property for our fibers.

The method was to pass an electric current through the strand while it was mounted for the Angstrom measurement. Using one of the thermocouples, we measured the rate of temperature rise due to the ohmic heating. As with the heat wave data, computer control of the function generator was employed to turn the current on and off. Current reversal was used to compensate for bias. The data acquisition system collected some 600 data points and performed a least squares fit which corrected for transverse heat loss. Included in Table 1 are specific heat values measured this way. The values all appear to be slightly lower than the values for commercial graphite [4], 0.72 J/(g K). This difference is expected in light of the excellent crystallinity of these fibers.

References

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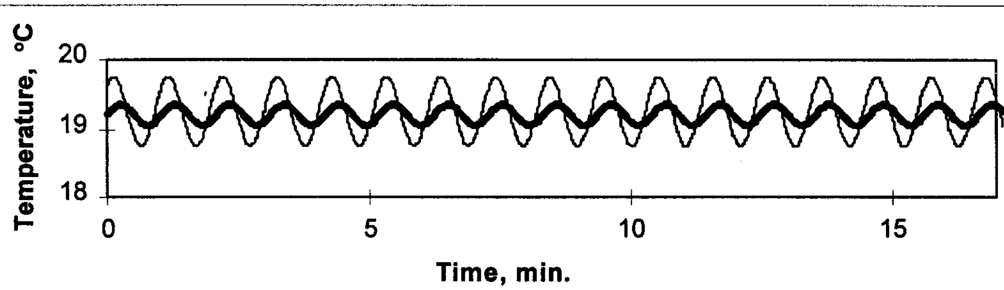

Figure 1. Typical data plot for thermal conductivity measurement.

Table 1. Typical thermal properties of BP Amoco Thornel® pitch based carbon fibers. All fibers were measured with standard finishing coating applied during manufacturing.

Product	Thermal Diffusivity, cm^2/s	Specific Heat Used for Thermal Conductivity Calculation, J/(g K)	Thermal Conductivity, W/(m K)
P-75	1.150	0.72[1]	173
P-100	3.200	0.72[1]	495
P-120	4.550	0.72[1]	714
K-800X, lot #1	5.445	0.70[2]	831
K-800X, lot #2	5.122	0.69[2]	788
K-800X, lot #3	4.832	0.72[1]	765
K-1100	5.830	0.72[1]	923

[1] Specific heat assumed to be equal to that of commercial graphite
[2] Specific heat measured on Angstrom unit