Thermal conductivity and thermal diffusivity of palm fiber reinforced binary phenolformaldehyde composites

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Received 3 June 1999; revised 23 September 1999; accepted 26 November 1999

Thermal conductivity and thermal diffusivity of binary dispersed composites prepared by reinforcing varying volume fractions of palm fiber in phenolformaldehyde (PF) matrix have been measured at room temperature and normal pressure employing the transient plane source technique (TPS). Composites obtained by reinforcing 20, 30, 40, 50 weight percentage of fibers in the phenolformaldehyde matrix have been studied. It has been found that thermal conductivity as well as thermal diffusivity of the composites decreases, from that of the matrix, as the fraction of the fiber increases in the composites. Further, the experimental results are used to evaluate the thermal conductivity of the fiber employing Y Agari model. Results obtained by Y Agari model are compared with that obtained from two models and by extrapolation, using thermal conductivity value of the matrix and thermal conductivity of the fiber, effective thermal conductivity of the composites have been estimated employing different models and compared with the experimental results. Quite good agreement between experimental and theoretical results has been found.

1 Introduction

Transport properties of composite materials viz. effective thermal conductivity, thermal diffusivity etc. have been a subject of paramount importance to scientists and engineers in the field of thermal insulation and structural applications. Generally it is found that effective thermal conductivity is a function of geometric distribution and the volume fraction of each component.

There have always been a renewed interest in new materials. Earlier in this century polymers were the materials of great interest. Now a days the technique of blending and reinforcing of polymers have become the center of attraction because one can design the materials of required properties by these techniques. A new step in this direction is the invention of composites, which are generally fabricated by mechanical mixing of two components and are generally heterogeneous in terms of microstructures. In a binary composite two components having different properties have been mixed and the resulting composite exhibits a set of properties which are not obtainable by the single component. Thermosetting resins are the preferred matrices for composites as they resist swelling, solvent-attack better than all except a few thermoplastics.

Oil palm is one of the most economical and very high potential perennial oil crops and belongs to the species Elaeis guineensis. Oil palm empty fruit bunch (OPEFB) comprises of a bunch of fibers in which the palm fruit if embedded. After extracting oil from the seed of the fruit, it is thrown as an industrial waste by the oil mills. It creates severe environmental problems, within the time span, it takes to decompose. Hence its further use in composite materials is environmentally friendly and cheap.

The study of the thermal properties of these composites is important from the view point of low cost, high performance and abundance of fibers in nature. On the other hand synthetic fibers are expensive in comparison to the natural fibers. If these natural fiber filled composites can replace the synthetic fiber reinforced composites, it will be beneficial not only from the point of view of economy but also of ecology also as synthetic fibers takes decades to decompose, whereas natural fibers take much smaller time to decompose. These composites can offer a combination of properties which are unobtainable with metals, polymers or ceramics alone.

2 Experimental Details

2.1 Materials preparation

Resole type of phenolformaldehyde resin has been supplied by West Coast Polymers Pvt Ltd, Kannur.
Kerala, India. Solid content of the resin was 50 ± 1 % and caustic soda was used as the catalyst during manufacture. Oil palm empty fruit bunches were obtained from Oil Indus Ltd., Kottayam, Kerala.

Composites have been fabricated by Hand lay-up followed by compression molding at 100 °C for about 30 minutes. Empty fruit bunches have been subjected to the retting process and the pithy material was removed. Then fibers were cut into 40 mm length fibers and randomly oriented mats have been prepared. Composites having 20, 30, 40, 50 weight percentages of palm fibers have been prepared. Volume percentage of palm fibers in a particular composite has been evaluated by the knowledge of the density values of the palm fiber and the matrix.

2.2 Measurements

Simultaneous measurements of thermal conductivity and thermal diffusivity of all the composites have been made at room temperature and normal pressure using TPS method. The sample size used for the study is 1.3 x 1.3 sq cm. Thickness of the samples is approximately 0.4 cm. The TPS technique has proved to be a precise and convenient method for measuring the thermal transport properties of electrically insulating materials. The TPS method consists of an electrically conducting pattern (Fig. 1) in the form of a bilafilar spiral, which also serves as a sensor of the temperature increase in the sample. In Fig. 1, K-4521 is the design no. of the sensor and K stands for kaptor. The sensor is sandwiched between the thin insulating layers of kapton. Assuming the conductive pattern to be in the Y-Z plane of a coordinate system, the rise in the temperature at a point Y-Z at time \( t \) due to an output power per unit area \( Q \) is given by

\[
\Delta T(y, z, t) = \frac{1}{4 \pi^2 \omega^2 a \lambda} \int_0^t \int_{\eta}^{\infty} \frac{d \sigma^{\prime}}{\sigma^2} \left[ \left( \frac{y - y'}{\sigma^2} \right)^2 + \left( \frac{z - z'}{\sigma^2} \right)^2 \right] \exp \left[ - \left( \frac{(y - y')^2 + (z - z')^2}{\sigma^2} \right) \right] d\eta' d\zeta' \quad (1)
\]

where \( \kappa(t, \omega) = \sigma^2 a^2 \), \( \Theta = \sigma^2 / \kappa \), \( \tau = (\omega \theta)^2 \), \( a \) is the radius of the hot disc which gives a measurement of the overall size of resistive pattern and \( \Theta \) is known as the characteristic time. \( \sigma \) is a constant variable and \( \lambda \) is the thermal conductivity in the units of W/mK. The temperature increase \( \Delta T(t) \) because of flow of current through the sensor gives rise to a change in the electrical resistance \( \Delta R(t) \) which is given as

\[
\Delta R(t) = \alpha R_0 \Delta T(t) \quad (2)
\]

where \( R \) is resistance of TPS element before the transient recording has been initiated, \( \alpha \) is the temperature coefficient of resistance (TCR) and \( \Delta T(t) \) is the mean value of the time dependent temperature increase of the TPS element. \( \Delta T(t) \) is calculated by averaging the increase in temperature of TPS element over the sampling time because the concentric ring sources in TPS element have different radii and are placed at different temperatures during the transient recording \( ^{11} \).

\[
\Delta T(t) = \frac{P_0}{\pi \sqrt{2} a \lambda} D_0 (\tau) \quad (3)
\]

where

\[
D_0 (\tau) = \left[ \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{k e^{-\left( \frac{m^2 + n^2}{2} \right) \frac{L_0}{\pi}}} {2 \sigma^m \left( \frac{1}{2 \sigma^m \pi} \right)} \right]^{\frac{1}{2}} \quad (4)
\]

\( P_0 \) is the total output power, and \( L_0 \) is the modified Bessel function. To record the potential difference variations, which normally are of the order of a few milivolts during the transient recording, a simple bridge arrangement as shown in Fig. 2 has been used. If we assume that the resistance increase will cause a potential

![Fig. 1 — Schematic diagram of the TPS sensor](image)

![Fig. 2 — Bridge circuit diagram for TPS technique. \( R_1 \) and \( R_2 \) are the resistances, \( R_p \) is the effective resistance of the wires outside the arms of the bridge, \( R \) is the resistance of the TPS element and DVM is the digital voltmeter](image)
difference variation $\Delta U(t)$ measured by the voltmeter in the bridge, the analysis of the bridge indicates that

$$\Delta E(t) = \frac{R_s}{R_s + R_o} I_s \Delta R(t) = \frac{R_s}{(R_s + R_o)} \lambda_{TPS} \frac{1}{\pi R_o^2} D_s(t)$$

...(5)

where

$$\Delta E(t) = \Delta U(t) [1 - C \Delta U(t)]$$

and

$$C = \frac{1}{R_s I_s \left[ 1 + \frac{\gamma R_o}{\gamma (R_s + R_o) + R_p} \right]}$$

...(7)

The definition of various resistance is found in Fig. 2. $R_s$, is a standard resistance with a current rating that is much higher than $I_s$, which is the initial heating current through the arm of the bridge containing the TPS-element. $\gamma$ is a constant which is chosen to be 100 in the present measurement. Calculating $D_s(t)$ using a computer programme and recording the change in potential difference $\Delta U(t)$ one can determine $\lambda$. Thermal conductivity and thermal diffusivity of all the samples have been measured using the TPS (Gustaffson 1991) method, which are reproducible within 2%.

3 Model Used

The thermal conductivity (Table 1) of the oil palm fiber has been calculated using the Y Agari Model12-14. According to the model the logarithm of the thermal conductivity of the composite is linearly related to the volume percentage of the filler

$$\log \lambda = A \cdot V + B$$

...(8)

where $A = C_o \log \left[ \lambda_f / \lambda_{TPS} \right]$; $B = \log \left( C_p \lambda_{TPS} \right)$

Here $\lambda_f$ and $\lambda_{TPS}$ are the thermal conductivity of the fiber and matrix respectively. $C_o$ and $C_p$ are the constants and $V$ is the volume percentage of the filler in the composite. The thermal conductivity of the matrix has been measured experimentally and by extrapolating the experimental values of thermal conductivity to zero. The logarithm of the experimental values of the thermal conductivity has been plotted as a function of the volume percentage of the fiber and using Eq. (8), the thermal conductivity of the fiber has been evaluated.

Effective thermal conductivity of two phase composites has been explored by using two different approaches. In the first approach effective thermal conductivity ($\lambda$) is evaluated by considering a random distribution of the dispersed phase and in the second the homogeneous dispersion of dispersed phase. Rayleigh and Maxwell15,16 derived the expression for a two phase dispersion of spherical particles in a medium of thermal conductivity $\lambda_{TPS}$. Relation can be written as:

$$\lambda / \lambda_{TPS} = (2 - 2 \cdot V + (1 + 2 \cdot V) \lambda_f / \lambda_{TPS} / (2 + V + (1 - V) \lambda_f / \lambda_{TPS})$$

...(9)

where $V$ is the volume fraction of the filler and $\lambda_f$ is the thermal conductivity of the filler.

According to Meredith and Tobias17 effective thermal conductivity of the two phase materials can be calculated by the following expression:

$$\lambda = \lambda_{TPS} \left( A - 2 \cdot V + 0.409 B V^{7/3} - 2.133 C V^{10/3} \right)$$

$$(A + V + 0.409 B V^{7/3} - 0.906 C V^{10/3})$$

...(10)

where $K = \lambda_f / \lambda_{TPS}, A = (2+K)/(1-K), B = (6+3K)/(4+3K), C = (3-3K)/(4+3K)$

4 Results and Discussion

In Fig. 3 the experimental results of effective thermal conductivity have been plotted as a function of volume percentage of palm fiber. From Fig. 3 it is clear that as the volume percentage of the palm fiber increases the thermal conductivity of the composites decreases. To explain this behaviour thermal conductivity of the palm fiber has been evaluated using Y Agari model. Log of the experimental values of the thermal conductivity of

Table 1 — Thermal conductivity of the fiber obtained by Y Agari model and by extrapolation

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$C_f$</th>
<th>$C_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y Agari Model</td>
<td>0.24</td>
<td>0.7011</td>
</tr>
<tr>
<td>Extrapolation</td>
<td>0.239</td>
<td></td>
</tr>
</tbody>
</table>
the composites are plotted as a function of volume percentage of the fiber in Fig. 4. Thermal conductivity of the fiber comes out to be 0.24 W/mK by the Y Agari model. The value of thermal conductivity of the fiber is also obtained by extrapolating the effective thermal conductivity of the composites to 100 fiber volume percentage and it comes out to be 0.239 W/mK. The thermal conductivity of the palm fiber is smaller than the thermal conductivity of the PF matrix (0.348 W/mK).

The behaviour of the thermal conductivity of different composites can now be explained using thermal conductivity value of the fiber. As a small fraction (20) of the PF is replaced by palm fiber, thermal conductivity value of the composite decreases from that of the matrix. As more and more amount is replaced by the fiber, conductivity shows a decreasing trend. This behaviour seems to be justified as more amount is replaced by the less conducting filler, thermal conductivity exhibits a decreasing trend.

Fig. 3 also shows the theoretical values of effective thermal conductivity of composites as obtained through the model calculations. Models used to predict the effective thermal conductivity are Rayleigh Maxwell model and Tobias model. Rayleigh and Maxwell considered the shape of the fiber to be spherical however for our composites the shape of the fiber is not the spherical. It has been found that results obtained through the model calculations are in quite good agreement with the experimental results. This may be due to the fact that the particle size and shape are not considered in the formula (Eq. (9)). Also, the particle size and shape are important either at low temperatures or if the filler’s thermal conductivity is much higher (100 times) than the conductivity of the matrix. Meredith and Tobias observed that no particle size and shape effect had been detected for quartz and diamond composites.

Variation of the thermal diffusivity with volume fraction of the filler is plotted in Fig. 5. Thermal diffusivity (β) of the composites shows the same trend as obtained in the case of the thermal conductivity, since it is directly proportional to conductivity. Measurements of the thermal conductivity and thermal diffusivity show that the derived values of the specific heat remain constant with the volume fraction of the fiber and hence maintaining the proportionality between λ and β.

5 Conclusions

Thermal conductivity of the composites are by the fiber percentage present in the composites. Any combination of the fibers is unable to increase the thermal conductivity value of the composites above the thermal conductivity value of the matrix (PF), concluding that oil palm fibers are less conductive than PF.

Acknowledgements

Thanks are due to Prof S E Gustafsson, Department of Physics, Chalmers University of Technology, S-41296, Gothenburg, for providing us small TPS sensor for the small samples in these measurements. We are also indebted to him for his help in computer program for the analysis of the thermal properties.

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