Thermal conductivity measurements of some glass fibre- and carbon fibre-reinforced plastics

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Thermal conductivity experiments are reported on unidirectional composites over the temperature range −150 to 130° C. Results for R-glass/Fibredux 914 specimens, and for carbon fibre GY-80/Code 69 resin specimens, in directions parallel and perpendicular to the fibre directions have been interpreted using standard theories. Experiments were also made on specimens in which the carbon fibres made angles of 30°, 45° and 60° to the temperature gradient. An attempt was made to understand these data using a finite difference model.

1. Introduction

Fibre-reinforced plastic materials are considered as replacements for metals in situations where they have better mechanical properties, e.g. strength/weight and/or stiffness/weight ratios. While such composites may have other advantageous properties over metals, e.g. corrosion resistance, they also have characteristics which may not be so beneficial in some applications. Among the latter is thermal conductivity, where not only is the magnitude of the conductivity of composites, on average, much lower than of metals, but it is also anisotropic. Hence, in general, it is much more difficult to dissipate heat in a fibre-reinforced plastic than in a metal, and in some situations this can be an important consideration, particularly if electronic components are situated next to the material. It is clearly of interest to be able to tailor the thermal conductivities of composites, but the basic properties must first be known.

The present experiments were made to determine the thermal conductivities between −150 and 130° C of samples of unidirectional R-glass fibres in Fibredux 914 resin, and of unidirectional carbon fibres GY-80 and GY-70 in Code 69 resin. The effects of using different angles between the fibre direction and the temperature gradient were determined. An attempt has been made to analyse the results in terms of the properties of the separate components of the composites.

A fibre-reinforced plastic is a very inhomogeneous material. In directions parallel to the fibres it is possible for the fibres to carry much of the thermal flux, and this is the case for carbon fibres. However, perpendicular to the fibres the conductivity is determined more by the properties of the matrix. For a composite laminate fabricated from plies in which the fibres lie in different directions, the distribution of the thermal flux will be complicated.

The thermal conductivity of a fibre-reinforced plastic in the direction parallel to the fibres is well understood in terms of the conductivities of the fibres and matrix. The physical situation is analogous to electrical conduction through parallel high and low resistances, and a law of mixtures is appropriate [1-4]. A similar approach has been applied to understand the thermal conduction in directions perpendicular to the fibres, with a modification to allow for touching fibres [3], but it has been found to be inadequate. Other models have been based on analogies with the in-plane shear field in composites [2], with models for the axial shear loading modulus [5] and with an elastic moduli model [1]. The models of Springer and Tsai [2] and of Hashin [5] give the same expression for the conductivity of the composite, and it has been validated by Gogol and Furmanski [6] for fibre volume fractions less than 0.5. It has been assumed here that this model is also valid for fibre volume fractions of 0.6.

For a unidirectional fibre composite with the temperature gradient making an angle $(90 - \theta)°$ to the fibre direction, it is possible to express the effective conductivity, K, in terms of the conductivities of the composite parallel to the fibres, K_{11}, and perpendicular to the fibres, K_{22}. Springer and Tsai [2] have shown that

$$K = K_{11} \sin^2 \theta + K_{22} \cos^2 \theta \qquad (1)$$

It might be expected that this expression would only apply to an infinite specimen, and it will be seen that it does not give a good description of the experimental results obtained in the present study.

2. Specimens

Two specimens were prepared of R-glass in a matrix of Fibredux 914 resin, one with fibre angle θ of 0° and the other with angle 90°. Two further specimens were

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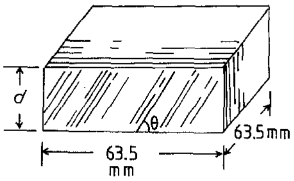

Figure 1 Specimen geometry. d was either 25.4 mm or 12.7 mm.

prepared of GY-80 carbon fibres in a matrix of Code 69, again with fibre angles 0° and 90°. Finally, three specimens were prepared of GY-70 carbon fibres in a matrix of Code 69 resin. These details are summarized in Table I.

The sizes of the specimens were either 63.5 × 63.5 × 25.4 mm^3 or 63.5 × 63.5 × 12.7 mm^3, as illustrated in Fig. 1. For each specimen a 300 × 300 mm^2 panel consisting of 16 layers of 250 μm thick pre-preg tape was laid up to form a unidirectional composite laminate. The panels were cured at 175° C for 8 h at a pressure of 4.2 atm. On cooling, a panel was cut into 63.5 × 25.4 mm^2 rectangles, each with the correct fibre alignment. Of these rectangles, 30 were then placed in a jig with two layers of uncured pre-preg, cut to the same size and fibre alignment, placed between each piece. The jig was put into an oven and heated to 175° C for 4 h. The completed specimen was then allowed to cool and excess resin was ground off. The block was ground until all the faces were smooth and the top and bottom faces were parallel. The same procedure was used for the specimens which were 12.7 mm deep. In each case the fibre volume fraction was approximately 0.6.

3. Experimental details

The experimental measurements were performed on a model TCFCM Comparative Thermal Conductivity Instrument, reference number TES-5, manufactured by the Dynatech Research and Development Company of Cambridge, Massachusetts, USA. The apparatus uses a comparative method which employs a constant heat flow through both the specimen and two samples of material with a known thermal conductivity. The specimen and reference samples are placed in a test stack, illustrated in Fig. 2, having a 63.5 × 63.5 mm^2 cross-section. Chromel–alumel thermocouples were used, with their reference junctions compensated by an ACROMAG solid state electronic temperature compensation unit. Either water or liquid nitrogen was used to cool the bases of the stack and the guard furnace, depending on the temperature required. The guard furnace was maintained at the same temperature gradient as the stack in order to reduce heat losses

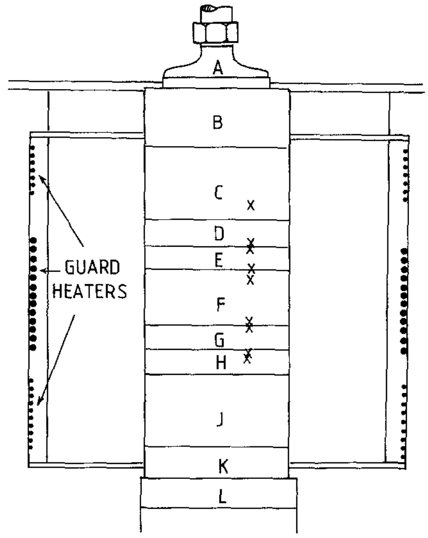

Figure 2 Test stack with Pyrex or Pyroceram reference samples.

by radiation. Convection losses were minimized by having the main heater near the top of the stack.

Four different reference samples were employed, as indicated in Table I. These were the glass Pyrex 7740 and the ceramic Pyroceram 9606, both with dimensions 63.5 × 63.5 × 12.7 mm^3, an electrolytic iron and the precipitated steel Inconel 718, both with dimensions 63.5 × 63.5 × 25.4 mm^3. The reference samples contained suitable grooves and holes to take the thermocouples. When either the iron or Inconel references were used, the top surface plate and the bottom surface plate shown in Fig. 2 were removed.

Measurements were made under equilibrium conditions on the composite specimens at temperatures in the range − 150 to 130° C. The distances between the six thermocouples across the two reference samples and the composite specimen were measured with a travelling microscope. Typical values for the temperature drops across these three elements of the stack and for the corresponding heat flows are given in Table II.

4. Results and discussion

The measured thermal conductivities of the glass fibre composite are displayed as a function of temperature in Fig. 3. The results for the carbon fibre-reinforced resin samples 3 to 7 are presented in Figs 4 to 8, respectively.

The thermal conductivities of fibre composites in directions parallel to and perpendicular to the fibres, K_{11} and K_{22}, respectively, are reasonably well understood in terms of the properties of the component materials. In the parallel direction a law of mixtures

TABLE I Details of specimens used. The fibre volume fraction was 0.6 in all cases

Sample	Fibre	Resin	Fibre angle, θ	Thickness, d (mm)	Reference material
1	R-glass	Fibredux 914	0	12.7	Pyrex
2	R-glass	Fibredux 914	90	25.4	Pyrex
3	GY-80	Code 69	0	12.7	Pyroceram
4	GY-80	Code 69	90	25.4	Iron
5	GY-70	Code 69	30	25.4	Pyroceram
6	GY-70	Code 69	45	25.4	Inconel
7	GY-70	Code 69	60	25.4	Inconel

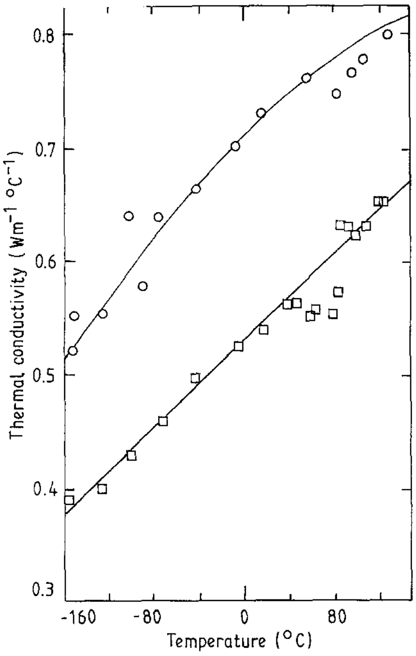

Figure 3 Thermal conductivities of unidirectional R-glass/Fibredux 914 specimens.

[1–4] is appropriate:

$$K_{11} = (1 - v_f)K_m + v_f K_{11f} \quad (2)$$

where K_m is the conductivity of the matrix, assumed to be isotropic, K_{11f} is the conductivity of the fibres along their axis, and v_f is the fibre volume fraction. In directions perpendicular to the fibres it has been proposed [2, 5] that

$$K_{22} = K_m \left[\frac{(1 + v_f)K_{22f} + (1 - v_f)K_m}{(1 - v_f)K_{22f} + (1 + v_f)K_m}\right] \quad (3)$$

where K_{22f} is the thermal conductivity of the fibres perpendicular to their axis. It has been found [6] that Equation 3 works well for fibre volume fractions of up to 0.5, and it has been assumed here that it is valid for $v_f \simeq 0.6$.

The thermal conductivity of glass fibres is assumed to be isotropic, so that $K_{11f} = K_{22f} \equiv K_f$ say, and the experimental results for K_{11}, sample 1, and for K_{22}, sample 2, have been used with Equations 2 and 3, respectively, to determine K_f and K_m. Typical values obtained are $K_f \simeq 1.0\,\mathrm{W\,m^{-1}\,K^{-1}}$ and $K_m \simeq 0.25\,\mathrm{W\,m^{-1}\,K^{-1}}$. The variations of these quantities with temperature are displayed in Figs 9 and 10.

Carbon fibres have anisotropic thermal conductivity properties, $K_{11f} > K_{22f}$, and it is therefore not

TABLE II Typical results for specimens at temperatures near 0° C

Specimen	Temp. drop across specimen + references (° C)	Mean temp. (° C)	Heat flow (W)	Conductivity, K (W m^{-1} K^{-1})
1	24.8	−3.7	1.93	0.527
2	28.8	−7.1	2.48	0.706
3	31.3	−2.9	8.6	2.071
4	15.3	−0.5	71.0	107.4
5	66.4	1.4	17.5	4.41
6	70.5	−3.3	43.1	17.7
7	54.5	1.7	34.9	36.26

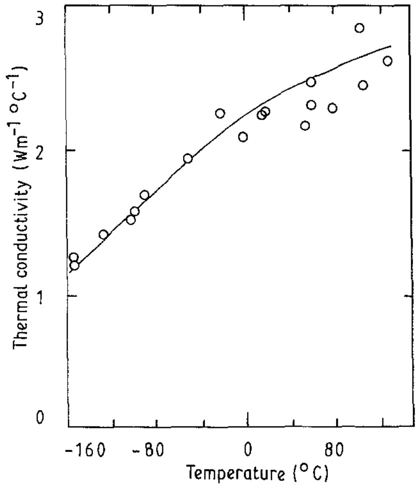

Figure 4 Thermal conductivity of unidirectional GY-80/Code 69 specimens parallel to the fibre direction.

possible to analyse the data for samples 3 and 4 in the same way as that for the glass fibre composites. However, consistent values for K_{11f} and K_m were obtained by employing an estimate for K_{22f}.

The conductivity of the carbon fibre composite parallel to the fibre direction, sample 3, is almost entirely determined by the value of K_{11f} for the fibres. Employing Equation 2 with $v_f = 0.6$ it was found that the experimental results for K_{11} at 0° C could be fitted with $K_{11f} \simeq 176\,\mathrm{W\,m^{-1}\,K^{-1}}$, independent of the exact value of the matrix conductivity, provided it was in the range 0.2 to $1.0\,\mathrm{W\,m^{-1}\,K^{-1}}$, which is appropriate for the type of resin studied. Unfortunately, it was not possible to make a direct determination of K_m for the Code 69 resin. The value obtained for K_{11f} agrees well with the results of measurements on single GY-70 carbon fibres [7]. Fig. 11 shows the predicted variation of K_{11f} with temperature obtained from K_{11} using a value of $K_m = 0.6\,\mathrm{W\,m^{-1}\,K^{-1}}$ independent of temperature.

The thermal conductivity of the carbon composite perpendicular to the fibre direction, sample 4, is dominated by the conductivity of the resin. It has been

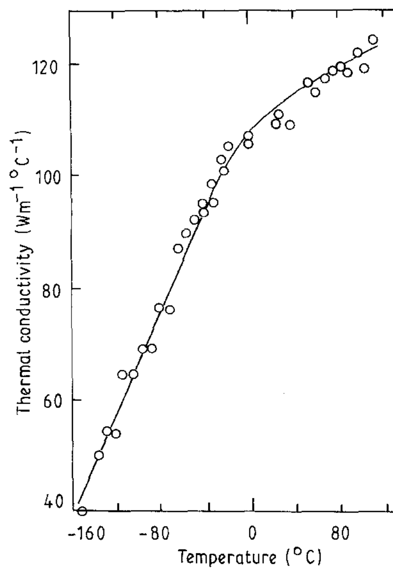

Figure 5 Thermal conductivity of unidirectional GY-80/Code 69 specimens perpendicular to the fibre direction.

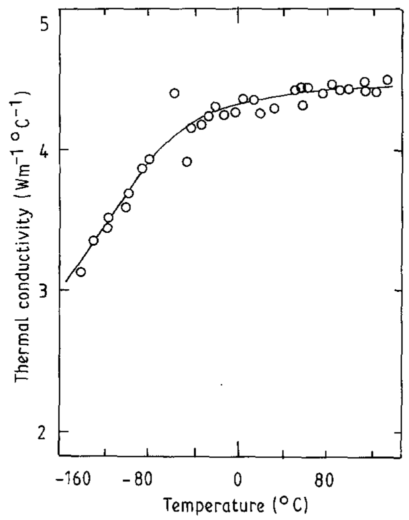

Figure 6 Thermal conductivity of unidirectional GY-70/Code 69 specimens in which the fibres make an angle of 30° with the temperature gradient.

estimated [8] that the transverse conductivity of carbon fibres K_{22f} is typically 20 to 40 W m^{-1} K^{-1}. Employing these values in Equation 3, with the experimental K_{22} data and $v_f = 0.6$, it is predicted that K_m is 0.57 to 0.60 W m^{-1} K^{-1}. Hence the value of K_{22f} has a small effect on the calculated conductivity K_m and a constant value of $K_f = 30$ W m^{-1} K^{-1} was employed to determine K_m as a function of temperature. The results are presented in Fig. 12.

The analysis of the data for samples 5 to 7, in which the fibres are neither parallel nor perpendicular to the temperature gradient, was more difficult. It was assumed that the thermal conductivities K_{11f} and K_{22f} of the GY-70 fibres were the same as those deduced for the GY-80 fibres. In the simplest model of Springer and Tsai [2], Equation 1 relates the conductivity of the composite to K_{11}, K_{22} and the fibre angle θ. Using the measured values of K_{11} and K_{22} for samples 3 and 4, it was found that Equation 1 predicted values of K higher than the values measured for samples 5 to 7, corresponding to $\theta = 30°$, 45° and 60°, respectively.

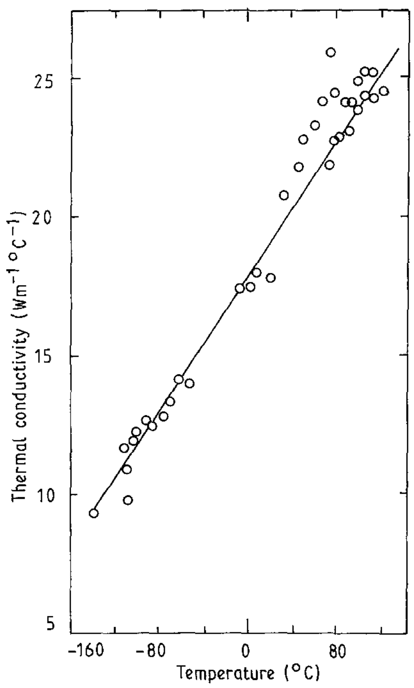

Figure 7 Thermal conductivity of unidirectional GY-70/Code 69 specimens in which the fibres make an angle of 45° with the temperature gradient.

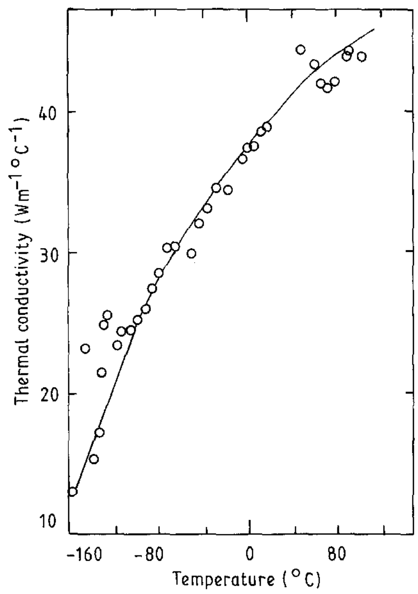

Figure 8 Thermal conductivity of unidirectional GY-70/Code 69 specimens in which the fibres make an angle of 60° with the temperature gradient.

A finite difference method was earlier employed to calculate the thermal conductivity of a two-dimensional model of an infinite resin sample containing fibres at an angle θ. The method has been described previously [9], and some comparative results for K for fibre angles θ between 65° to 90° were given then. A similar method has now been used to predict K for fibre angles less than 60° in specimens of finite dimensions, in which some fibres do not completely cross the specimen in the direction of the temperature gradient.

It was found that the results of the numerical modelling for $\theta < 75°$ could best be fitted by an expression

$$K = (K_{11C} \sin^2 \theta + K_{22C} \cos^2 \theta) + \left(\frac{K_{22D} - K_m}{\cos^2 \theta} \right) \tag{4}$$

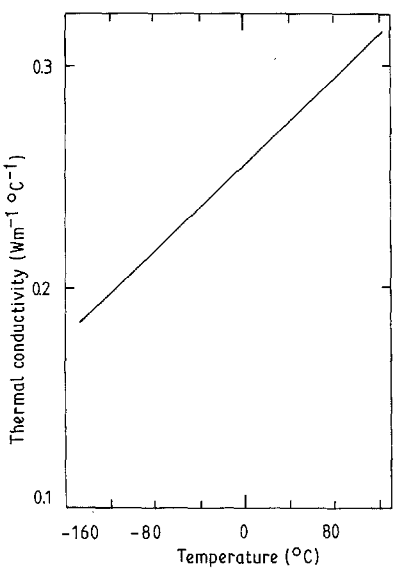

Figure 9 Thermal conductivity of Fibredux 914 resin.

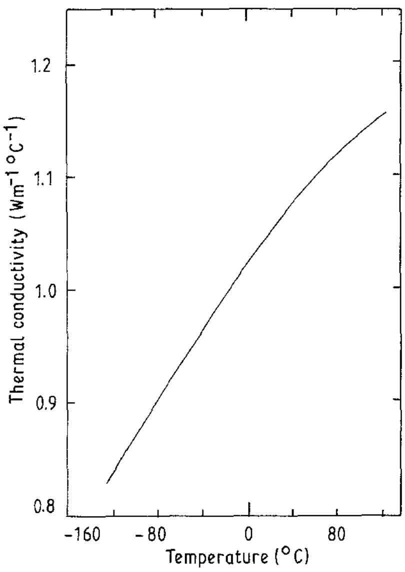

Figure 10 Thermal conductivity of R-glass.

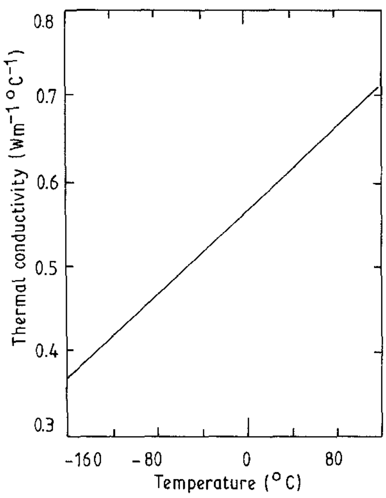

Figure 12 Thermal conductivity of Code 69 resin.

where the first term is the contribution of the region of the composite where the fibres completely cross the specimen, subscripts C, and the second term is the contribution from the remainder of the specimen, subscript D. If L_y is the specimen dimension parallel to the temperature gradient and L_x the dimension perpendicular to the gradient, then no fibres cross the specimen in the parallel direction if $L_x \tan \theta < L_y$. For the specimens used in the experiments the critical value of θ was approximately 22°. The values of K_{11C}, K_{22C} and K_{22D} employed in the analysis were obtained from the separate fibre and matrix thermal conductivities using Equations 2 and 3 with volume fractions v_{fC} and v_{fD} scaled for each region, and normalized so that

$$v_f = v_{fC} + v_{fD} \tag{5}$$

For $\theta > 75°$ it was assumed that the simpler Springer and Tsai Equation 1 was valid.

Fig. 13 presents a comparison of the Springer and Tsai formula with the results of the two-dimensional finite difference calculations, as represented by Equation 4. It was assumed that the properties of the GY-70 fibres were the same as those of the GY-80 fibres, and the parameters used were appropriate for 0° C. The experimental results for $\theta = 0°, 45°, 60°$ and 90° are also indicated.

It is clear from Fig. 13 that the results of the finite difference calculations do not agree well with the measured thermal conductivities of the specimens with fibre angles 45° and 60°. The predicted values in these cases are too high by a factor of almost 2.0. On the other hand, by taking into account the aspect ratio effect, the finite difference model is better than that of Springer and Tsai for all θ below 75°, and is very much better at smaller θ, e.g. $0 < \theta \leqslant 30°$. There are a number of possible reasons for the discrepancy between the finite difference calculations and the experimental results, including, for example, uncertainties in the value of K_{22f} for the fibres. However, probably the most important reason is that a two-dimensional model is not good enough, and a three-dimensional one is required to model the greater resistance to heat flow transverse to the fibre direction due to the matrix.

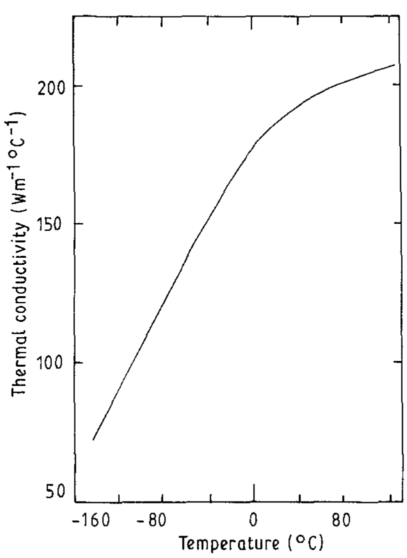

Figure 11 Thermal conductivity of GY-80 carbon fibres in the axial direction.

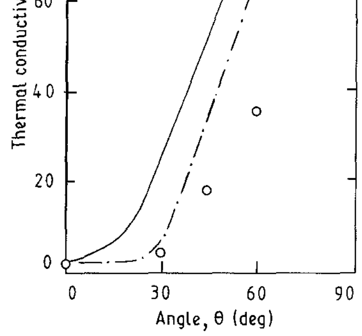

Figure 13 Thermal conductivity of unidirectional carbon fibre/Code 69 specimens as a function of fibre angle θ. (○) present experiments; (——) Springer and Tsai model; (—·—) present finite difference model.

5. Conclusions

The thermal conductivities of unidirectional R-glass/Fibredux 914 composites have been measured as functions of temperature in directions parallel and perpendicular to the fibres. The results have been analysed using standard theories to deduce the variations of the separate conductivities of the glass and resin as functions of temperature.

Similar experiments have been performed on unidirectional GY-80/Code 69 composites and the temperature variations of the fibres parallel to their axis, and of the matrix, deduced from the results.

Measurements have been made on unidirectional carbon fibre-reinforced Code 69 resin specimens in which the fibres make angles of 30°, 45° and 60° with the temperature gradient. Attempts have been made to interpret the results in terms of the component properties using a two-dimensional finite difference method, with limited success for the higher angles. It has been shown that it is important to take into account the finite sizes and aspect ratios of the specimens in analysing the results.

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