Archives of Materials Science and Engineering

Volume 48
Issue 1
March 2011
Pages 25-32

International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

Thermal diffusivity measurements of selected fiber reinforced polymer composites using heat pulse method

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Received 11.01.2011; published in revised form 01.03.2011

ABSTRACT

Purpose: The objective of this paper was to examine the effect of fiber content on the thermal diffusivity in selected fiber reinforced polymer composites. The influence of fiber type on the thermal diffusivity was also considered and discussed.

Design/methodology/approach: The experiments have been performed using a heat pulse method for the thermal diffusivity measurements of engineering materials. For the purpose of the present study, two different types of composite materials with glass or aramid fiber and with different fiber content were prepared.

Findings: For the GFRP composites, the obtained results indicate that the higher is glass fiber content the higher is the thermal diffusivity value. These results shows a linear relationship between fiber content and thermal diffusivity. In the case of KFRP composites, the thermal diffusivity decreases marginally with an increase of fiber content.

Research limitations/implications: Due to the relatively high thickness of investigated specimens, in comparison with standard specimens for thermal diffusivity measurements, the obtained values of thermal diffusivity are affected by several factors, e.g. heat losses or temperature-dependent thermo-physical properties. This indicates that the real quantity determined in the present study, was, so-called, apparent thermal diffusivity.

Practical implications: The method applied in this work allows to obtain quantitative results, which would be satisfactory to industrial or laboratory applications in the field of non-destructive testing of composite materials.

Originality/value: The method initially proposed by Parker et al. in 1961 for the thermal diffusivity measurements of homogeneous solids was successfully applied to determine the thermal diffusivity of non-homogeneous glass and aramid fiber reinforced polymer composites.

Keywords: Non-destructive testing; Heat pulse method; Thermal diffusivity; Polymer matrix composites

Reference to this paper should be given in the following way:

G. Wróbel, S. Pawlak, G. Muzia, Thermal diffusivity measurements of selected fiber reinforced polymer composites using heat pulse method, Archives of Materials Science and Engineering 48/1 (2011) 25-32.

PROPERTIES

1. Introduction

Nowadays, the polymer matrix composites are regarded as one of the most attractive and relatively new materials. Many scientific investigations concerning these materials have been carried out in the Institute of Engineering Materials and Biomaterials (Gliwice, Poland) in recent years [1-9]. Fiber reinforced polymer composites such as CFRP, GFRP or KFRP are increasingly used in many high-performance applications due to their widely described advantages [10,11]. Due to the new applications of these composites, there is an increasing need for reliable thermo-physical properties data. A reliable thermal properties values are essential in a selection of a material in order to get the best performance of this material in a specific application. In the case of fiber reinforced polymer composites - their thermal behavior can be modified by the addition of different fibers (with different thermo-physical properties) to polymer matrix and using different fiber contents.

The three most important thermo-physical properties of a material, that are needed for heat transfer calculations, are: thermal conductivity, thermal diffusivity and specific heat. The equation that relates these properties is given by

$$\alpha = \lambda/\rho c_p, \tag{1}$$

where:
α - thermal diffusivity [m^2/s],
λ - thermal conductivity [W/mK],
ρ - density [g/cm^3],
c_p- specific heat [J/kgK].

The thermal diffusivity is an important property in all problems involving a non-steady state heat transfer. There are many examples where the knowledge of the precise value of the thermal diffusivity and its fiber content dependence is essential. As can be seen from Eq. (1), a high thermal diffusivity is achieved for composites that contain fibers with high thermal conductivity, low density and low specific heat.

Approximate thermal properties for variety of composite materials can be found in the literature (including manufacturers catalogs). It is also possible to derive these properties from the properties of constituent materials. Thermal properties of the composite, obtained in such a way, might be different from exact values, which can be only obtained by using experimental techniques.

Nowadays, several different techniques for the determination of the thermal diffusivity can be found in the literature [12]. Recently, transient techniques have become the preferable way for measuring the thermal properties of a wide variety materials. It requires specimens with small size and simple geometry and allows rapid data acquisition, which is highly advantageous when compared to the steady-state methods for measuring thermal conductivity [13].

In the present paper, the heat pulse method was employed in the experimental determination of the thermal diffusivity of GFRP and KFRP composites.

Previously, the authors used the heat pulse method for thermal diffusivity measurements of carbon/epoxy composites using transient thermography approach [14-16]. The results showed that the thermal diffusivity is a linear function of fiber content in CFRP composites with the range of carbon fiber content from approximately 10 to 30vol.% [15].

2. Theory of heat pulse method

Parker et al. [17] in 1961 proposed the heat pulse method (or flash method) to measure the thermal diffusivity of homogeneous materials. In this technique, a uniform heat pulse Q of short duration compared to the transient time through a specimen is transferred to its front surface and temperature rise at the rear surface is recorded. If the heat losses are neglected, the temperature of rear surface is given by [12,17]:

$$U(L,t) = 1 + 2\sum_{n=1}^{\infty}(-1)^n \exp(-n^2\omega) \tag{2}$$

where:

$$\omega = \pi^2 \alpha t / L^2 \tag{3}$$

and $U(L,t)$ are dimensionless parameters, n is an integer and L - specimen thickness, and

$$U(L,t) = \Delta T(L,t)/\Delta T_M \tag{4}$$

where:
$\Delta T(L,t)$ is the temperature above ambient at the time t
ΔT_M is the maximum temperature rise.
Equation (2) is plotted in Fig. 1 [17].

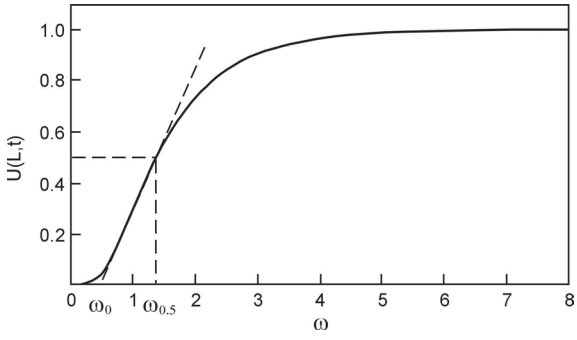

Fig. 1. Dimensionless plot of rear surface temperature history [17]

Parker et al. [17] suggested two ways of determining the thermal diffusivity α from Eq. (2) and Fig. 1. First, at half the maximum temperature rise (U = 0.5), $\omega_{0.5} = 1.38$ and the thermal diffusivity can be calculated using equation [12,17]

$$\alpha = 1.38 L^2/\pi^2 t_{0.5} \tag{5}$$

where $t_{0.5}$ is the time taken to reach half maximum temperature.

Second relation suggested by Parker et al. is when the extrapolated straight line portion of the curve in Fig. 1 intercepts the time axis (ω) at zero temperature rise and $\omega_0 = 0.48$, and the thermal diffusivity can be calculated using equation [12,17]

$$\alpha = 0.48L^2/\pi^2 t_0 \quad (6)$$

where t_0 is the time corresponding to the interception of the extrapolated straight line portion of the curve with ω axis.

3. Experimental

3.1. Methodology

The heat pulse method was applied to evaluate the thermal diffusivity values of GFRP and KFRP composites with different fiber content. The method consists of heating the front surface of specimen using short uniform heat pulse and measuring the temperature evaluation at its rear surface [17-20]. The thermal diffusivity values were obtained from normalized temperature - time plots using a procedure described in the literature [21].

3.2. Materials and specimen preparation

The constituent materials for manufacturing of GFRP and KFRP composites were made of cross-ply woven [0/90] E-glass fabric (RT, Saint-Gobain Vetrotex, Finland), aramid fabric (Kevlar® 49, Du-Pont, USA) and epoxy resin (Epidian 53, Z.Ch. "Organika-Sarzyna", Poland). Selected details of the fibers are shown in Table 1.

Table 1.
Selected properties of fibers used in GFRP and KFRP composites

Parameter	E-glass fiber	Kevlar® fiber
Density [g/cm^3]	2.56	1.44
Areal weight of fabric [g/m^2]	350	170
Thermal conductivity [W/mK]	1.2-1.5	0.04

Composites were fabricated by conventional hand lay-up. The variation of fiber content was achieved using different amount of fabric layers with approximately the same total thickness of the specimens. The chosen properties of prepared specimens are shown in Table 2.

Table 2.
Properties of specimens tested

No.	Specimen symbol	Layers amount	Fiber content [vol.%]	Thickness [mm]
		GFRP specimens		
1	G06	6	16.22	6.13
2	G08	8	21.64	6.14
3	G10	10	26.50	6.22
4	G11	11	28.37	6.35
5	G12	12	31.23	6.20
		KFRP specimens		
6	K04	4	10.61	6.57
7	K06	6	14.79	6.30
8	K08	8	18.84	6.22
9	K10	10	21.05	6.19
10	K12	12	22.94	6.13

The epoxy resin was cold-cured under ambient conditions (~21ºC) and after curing process the specimens were thermally hardened at 50ºC for 24 hours. The specimens for measurements of thermal diffusivity were prepared in the form of square plates (100x100 mm) and with thickness of about 6 mm. All specimens were painted with a thin matt black coating (with an emissivity value of 0.95) in order to eliminate reflections and to ensure homogeneity in the specimen surface emissivity, and also to increase the amount of energy absorbed.

3.3. Apparatus and measurements

To provide a high accuracy and repeatability of all measurements, an automatic testing station (Fig. 2) was used. The apparatus was designed and built to provide a uniform heating conditions such as stable specimen mounting, constant distance between heating source and specimen and also precise heating time for all measurements.

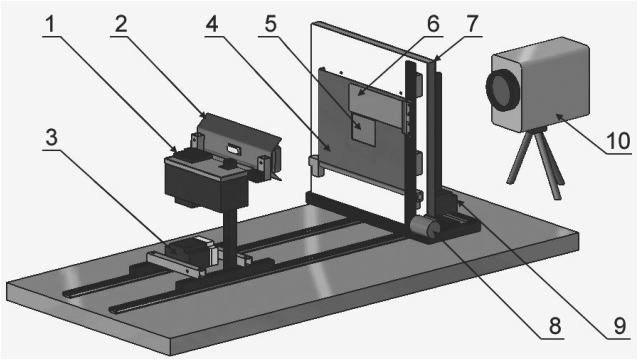

Fig. 2. Scheme of the testing station; 1 - temperature control unit, 2 - infrared radiator, 3 - relay with safety device, 4 - stationary shield, 5 - specimen, 6 - moveable shield, 7 - temperature barrier, 8 - moveable shield drive, 9 - PLC controller, 10 - IR camera

The measurement procedure consisted of heating the front surface of each specimen using infrared radiator and recording the temperature response at its rear surface with IR camera, analogically to the typical thermography investigations reported in the literature [22-28].

Due to the relatively low conductivity of considered composites, a long-pulse approach was selected to ensure a linear temperature response at the rear surface as was suggested in other publication [22]. The heating time of 3.0 sec and distance between thermal wave source and specimen (20 mm) was determined experimentally when the temperature difference between heated specimen surface and neighbourhood was satisfactory for the measurements (the temperature rise was kept below 5ºC, according to [21]). The measurements were carried out at room temperature in laboratory conditions.

The temperature variations at the rear surface of the heated specimen was measured and recorded using IR camera (ThermaCAM^{TM}SC640, Flir Systems, Sweden) with focal plane array (FPA) detector.

4. Results and discussion

The obtained results from all measurements are presented in the form of normalized temperature versus time curves (Figs. 3-12). The infrared camera recorded the temperature data at a rate of 7.5 measurements per second, so the time of e.g. 100 seconds in Figs. 3-12, represents 750 data points.

It can be seen from Figs. 3-7 (for GFRP composites) that the values of $t_{0.5}$ have decreasing trend (with increasing fiber content), and all observed departures from that rule are caused by slight differences in specimens' thickness (see Table 2). In the case of KFRP composites (Figs. 8-12), the $t_{0.5}$ values decrease marginally with an increase of fiber content. However, due to the lower thermal conductivity of aramid fibers than the thermal conductivity of epoxy matrix, the opposite situation was expected. Decreasing values of $t_{0.5}$ for KFRP composites are caused only by non-uniformity of specimens' thickness.

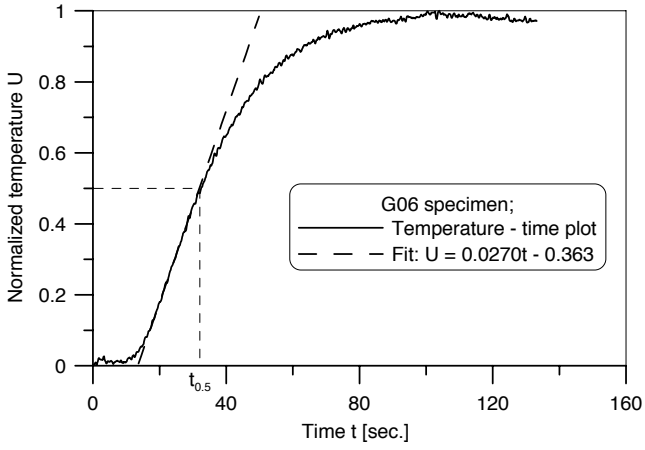

Fig. 3. Normalized temperature versus time at the rear surface for G06 specimen

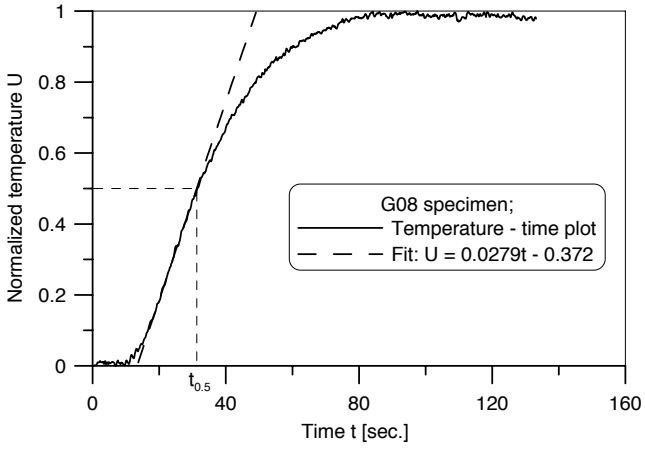

Fig. 4. Normalized temperature versus time at the rear surface for G08 specimen

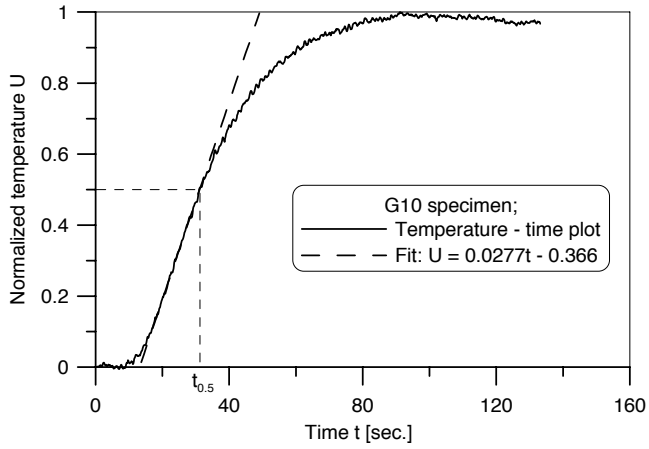

Fig. 5. Normalized temperature versus time at the rear surface for G10 specimen

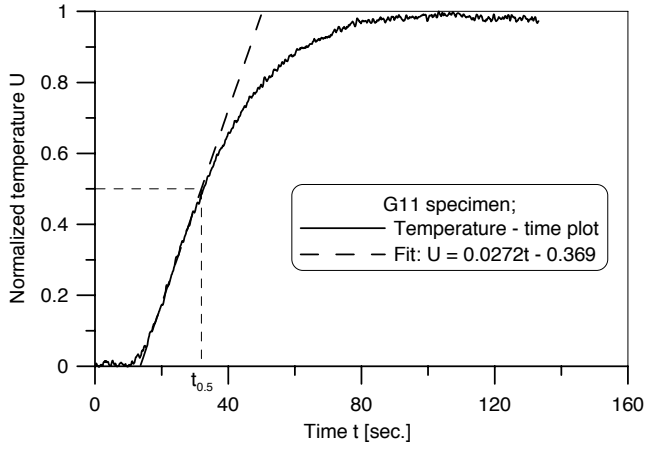

Fig. 6. Normalized temperature versus time at the rear surface for G11 specimen

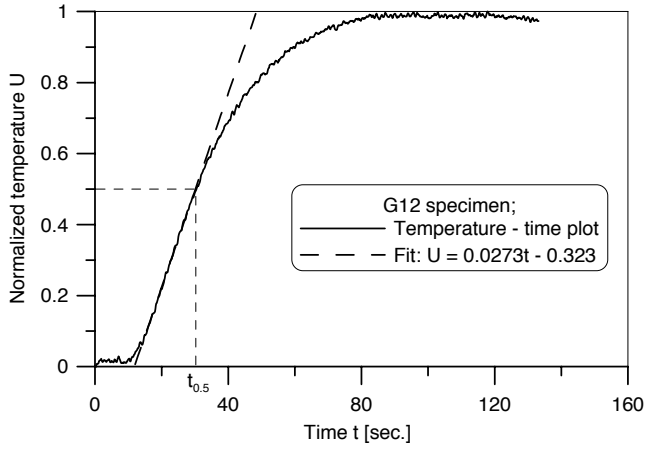

Fig. 7. Normalized temperature versus time at the rear surface for G12 specimen

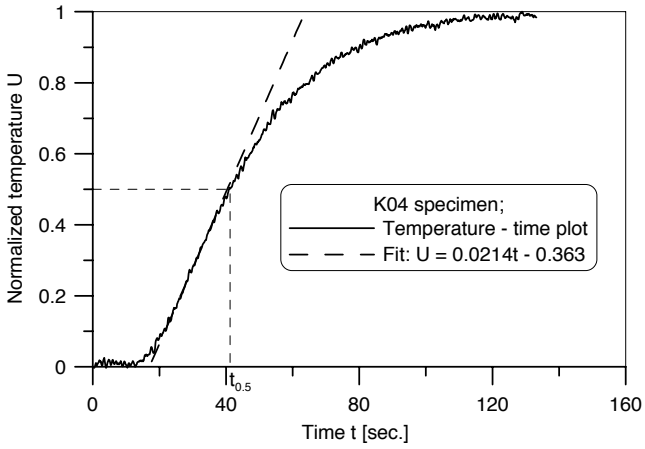

Fig. 8. Normalized temperature versus time at the rear surface for K04 specimen

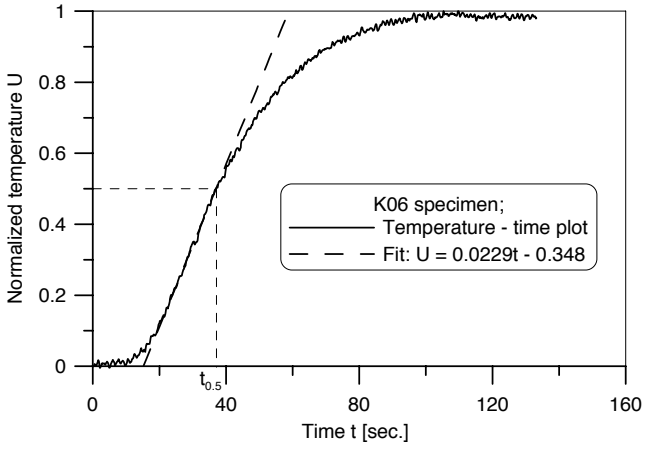

Fig. 9. Normalized temperature versus time at the rear surface for K06 specimen

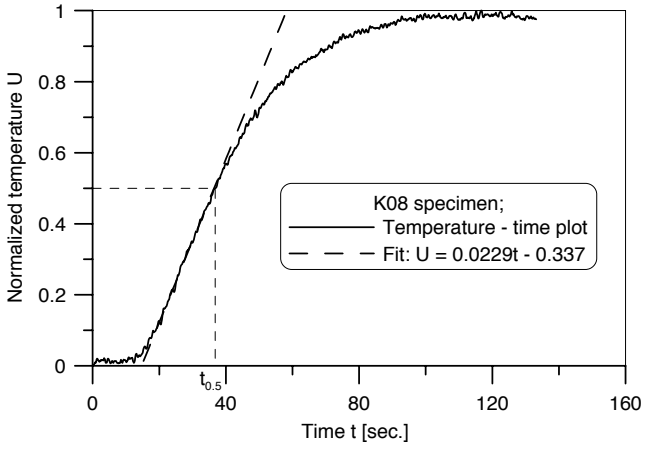

Fig. 10. Normalized temperature versus time at the rear surface for K08 specimen

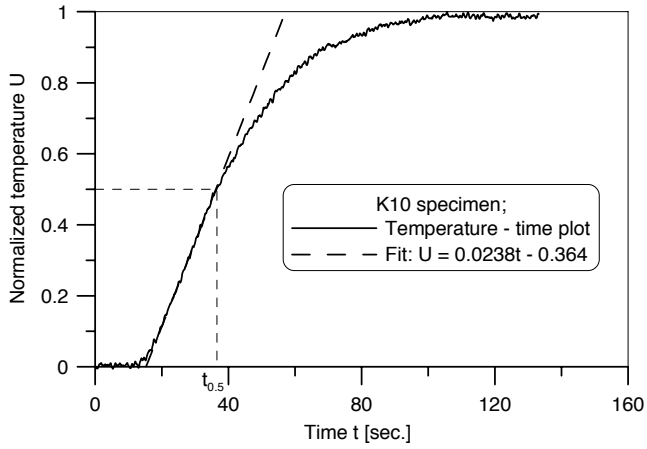

Fig. 11. Normalized temperature versus time at the rear surface for K10 specimen

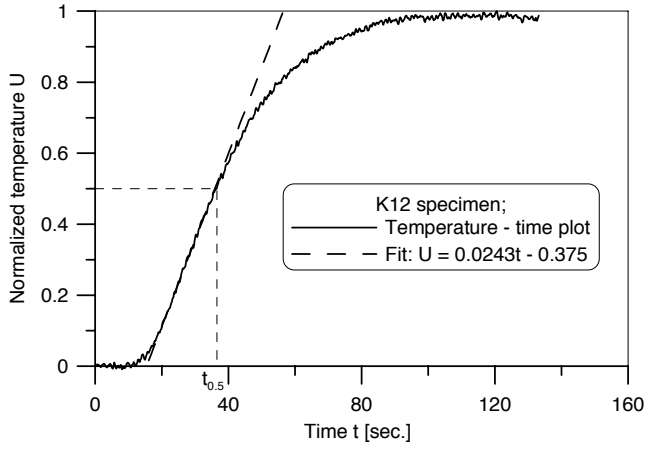

Fig. 12. Normalized temperature versus time at the rear surface for K12 specimen

A relatively high value of $t_{0.5}$ for K04 specimen (Fig. 8 and Table 3), is a result of much higher thickness for that specimen than thickness of others KFRP specimens (Table 2), and should not be attributed only to its lower fiber content.

The $t_{0.5}$ values taken from normalized temperature-time plots (Figs. 3-12), together with specimen thickness (L), were used to calculate the thermal diffusivity, according to Parker's equation (Eq. (5)). Obtained values of the thermal diffusivity (shown in Table 3 and Fig. 13) show that the higher the glass content the higher are the thermal diffusivity values. These results have been further processed using standard regression technique to achieve the best fitting line, which expresses increasing trend of that relationship. It has been found that the thermal diffusivity increases linearly with an increase of glass fiber content (Fig. 13). The thermal diffusivity values of glass fiber reinforced epoxy composites are much higher than that obtained for Kevlar® fiber reinforced epoxy composites due to the approximately 30 times higher thermal conductivity of glass than that given for Kevlar® (see Table 1). For example, the thermal diffusivity of epoxy resin

is increased from 1.44 (for ~6 mm specimen, Fig. 15 [15]) up to $1.77x10^{-7}$ [m^2/s] with 31vol.% of glass fiber. On the other hand, the increase in thermal diffusivity of GFRP is relatively poor in comparison with e.g. carbon/epoxy composites (Fig. 14 [15]), due to the higher thermal conductivity of carbon fibres.

Table 3.
Results of the measurements

No.	Specimen	Time $t_{0.5}$ [s]	Thermal diffusivity [m^2/s]
		GFRP specimens	
1	G06	31.96	1.63E-07
2	G08	31.24	1.68E-07
3	G10	31.26	1.72E-07
4	G11	31.95	1.75E-07
5	G12	30.15	1.77E-07
		KFRP specimens	
6	K04	40.33	1.49E-07
7	K06	37.03	1.49E-07
8	K08	36.55	1.47E-07
9	K10	36.30	1.47E-07
10	K12	36.01	1.45E-07

For example, as can be seen from Fig. 14 [15], the carbon/epoxy composite including 28vol.% of carbon fibers has the thermal diffusivity of about $2.1x10^{-7}$ [m^2/s], which is in good agreement with data published in the literature (Navarrete et al. [29] reported the value of about $3.3x10^{-7}$ [m^2/s] for carbon/epoxy composites with 50vol.% of carbon fibers - similar value is obtained by extrapolating the experimental results, from present experiment (Fig. 14), to fiber content of 50vol.%).

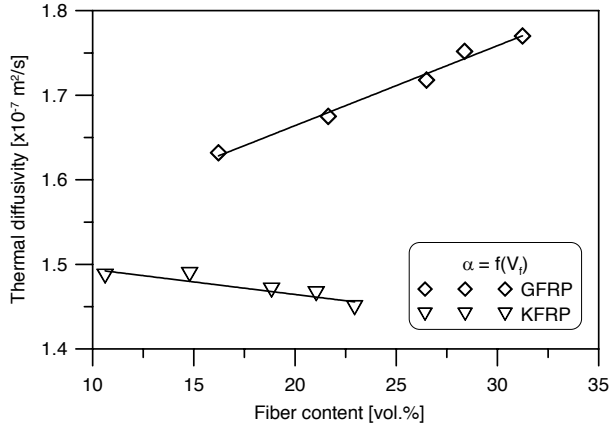

Fig. 13. Comparison of the thermal diffusivity values of GFRP and KFRP composites for different fiber content

In the case of KFRP composites, the thermal diffusivity decreases marginally with an increase of fiber content (at fibre contents of 10-23vol.%), Fig. 13.

The thermal transport properties (e.g. thermal diffusivity) of the composites cannot be explained solely by the differences in the properties of the fiber materials (or properties of constituent materials), but also the interconnectivity has to be taken into account, and therefore further research is required to clarify the experimental results.

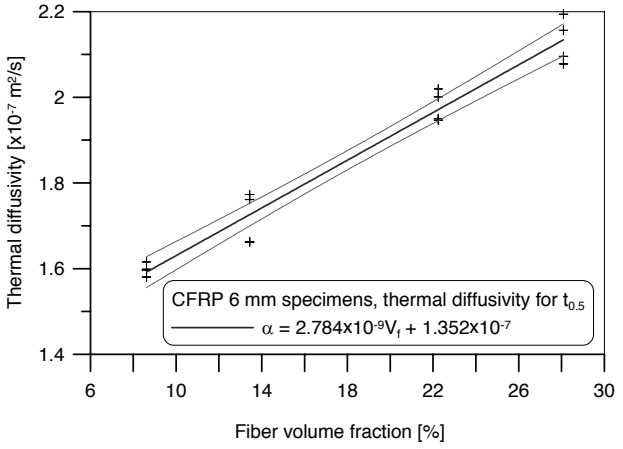

Fig. 14. Thermal diffusivity of CFRP composites with different fiber content [15]

Due to the relatively high thickness of investigated specimens, in comparison with standard specimens for thermal diffusivity measurements, the obtained values of thermal diffusivity are affected by several factors, e.g. heat losses or temperature-dependent thermo-physical properties.

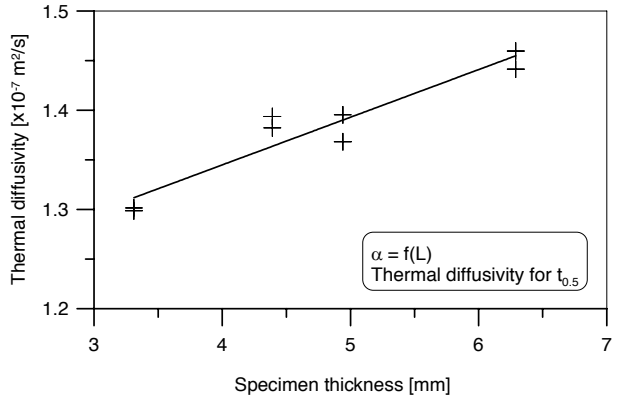

Fig. 15. Effect of specimen thickness on measured values of the thermal diffusivity of neat epoxy resin specimens [15]

This indicates that the real quantity determined in the present study, was, so-called, "apparent thermal diffusivity" [13]. This phenomenon is presented using an example of measured thermal diffusivity values for neat epoxy resin specimens (Fig. 15 [15]), where the obtained values of the thermal diffusivity increase with an increase of specimen thickness.

Increasing thermal diffusivity value with increasing specimen thickness was observed earlier by other researchers for several materials, e.g. graphite, stainless steel, iron, molybdenum, copper, aluminium nitride [13].

According to Hasselman and Donaldson [13], the effect of specimen size on measured value of the thermal diffusivity has

been attributed to laser-beam (heat source) nonuniformity, temperature-dependant thermal diffusivity, nonlinearity of the IR detector, and a contribution of radiative heat transfer between the front and rear surface of the specimen.

If the effect of specimen thickness is not taken into consideration during analysis of the data, the resulting values for the thermal diffusivity are expected to be different from the true values.

In order to eliminate the effect of specimen thickness on measured values of the thermal diffusivity a suitable corrections need to be employed in the calculations. However, due to the purpose of the present study, the knowledge of exact absolute values of the thermal diffusivity was of less importance. More important and sufficient was to determine a relative values, which express the effect of fiber content on the thermal diffusivity of GFRP and KFRP composite materials.

5. Conclusions

The heat pulse method was used to measure the thermal diffusivity of GFRP and KFRP composites with different fiber content. The method initially proposed by Parker el al. for the thermal diffusivity measurements of homogeneous solids was applied to determine the thermal diffusivity values of non-homogeneous fiber reinforced polymer composites. For GFRP composites the thermal diffusivity is a linear function of fiber glass content (thermal diffusivity increases with an increase of glass fiber content). In the case of KFRP composites the thermal diffusivity decreases marginally with an increase of fiber content, due to the lower thermal conductivity of aramid fibers than that given for epoxy matrix.

The study indicates that aramid fibers allow to obtain the composite material which exhibit relatively low and approximately constant thermal diffusivity value, regardless of fiber content. To increase the strength and stiffness of a composite material, without increasing its thermal diffusivity, aramid fiber reinforced composites seem to be a good choice since they are not sensitive to fiber content dependent thermal properties. It is important feature in the cases where a high strength and stiffness with relatively low thermal diffusivity are required.

Acknowledgements

The authors would like to thank Mr Jerzy Miśków, (MSc) (PPH Opticup, Gliwice, Poland) for helpful discussions about the manufacturing of fiber reinforced polymer composites and supplying materials tested in the present study.

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