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The application of transient thermography for the thermal characterisation of carbon fibre/epoxy composites

G. Wróbel [a], Z. Rdzawski [b,c], G. Muzia [c], S. Pawlak [a,*]
[a] Division of Metal and Polymer Materials Processing, Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
[b] Division of Materials Processing Technology, Management and Computer Techniques in Materials Science, Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
[c] Institute of Non-Ferrous Metals, ul. Sowińskiego 5, 44-101 Gliwice, Poland
* Corresponding author: E-mail address: sebastian.pawlak@polsl.pl

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Properties

ABSTRACT

Purpose: Primary purpose of the present experimental study was to evaluate the local fibre content in carbon fibre/epoxy composites using transient thermography.
Design/methodology/approach: The experiments have been performed using transient thermography to obtain the thermograms for carbon/epoxy specimens with different carbon fibre content. From obtained thermograms the thermal diffusivity values were determined and compared for each specimen and correlated with carbon content. The composites were two times tested using two different heating conditions to check the conformity of determined diffusivity values.
Findings: It was found from obtained results that composites with different carbon fibre content had different values of thermal diffusivity, indicating that transient thermography can be considered as a non-destructive testing method for fiber content evaluation in CFRP composites.
Research limitations/implications: Developed empirical formula is not universal for any other fibre reinforced polymer composite, so different relationships should be determined for different composites.
Practical implications: The results obtained from present experiment would be of great importance in the industrial applications to obtain first estimate of carbon fibre content in fibre reinforced composite materials.
Originality/value: The originality of present investigation is in application of transient thermography for local fibre content evaluation in polymer composite materials. The method should be of interest for the industrial quality control applications and is of great importance for composite products with high failure-free requirements.
Keywords: Non-destructive testing; Transient thermography; Thermal diffusivity; Carbon fibre content

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1. Introduction

Fiber reinforced composite materials such as CFRP are increasingly used in many high-performance applications due to their widely described advantages especially high specific strength and stiffness [1-4]. It is well known that the mechanical and other properties of considered materials are fiber content dependent. Many researchers have studied the effect of fiber content on chosen characteristics of composite materials [5-7]. Local fiber content variations which occur during processing, decide about out-of-control variations of mechanical or other properties in given area of finished product. The knowledge of fiber content distribution within the part is highly desirable especially for products with high failure-free requirements. Such products often are subjected to a hundred percent inspection which eliminate any known standard destructive methods of fiber content determination. That indicates the need for searching a reliable non-destructive testing (NDT) method able to monitor effectively mentioned above parameter.

During the last few years, the industrial interest has been oriented towards the development of new non-destructive testing techniques in order to achieve high accuracy, cost effectiveness and more efficient testing methods [8]. In a wide range of different NDT techniques, thermography was until recently considered as an emerging technology [9] and nowadays is widely used in characterization of composite materials [10]. The use of infrared thermography is recommended whenever a fast inspection method, involving no contact with tested part is required. It is also known that infrared (IR) thermography is able to detect defects and anomalies in many engineering materials [11-13]. In the case of polymer composite materials, it is applicable to the detection of cracks, impact damages and fatigue degradation [14,15].

Previously, the authors evaluated the local fiber content in glass/epoxy composites measuring ultrasonic wave velocity [16,17] and also using active thermography, correlating the carbon content with chosen parameters determined from obtained thermograms such as temperature growth rate or upper limit temperature [18].

In the present study, authors made an attempt to apply the transient thermography to evaluate local fiber content in CFRP composites by determining thermal diffusivity values from obtained thermograms for specimens with different fiber content.

Other researchers have correlated thermal diffusivity values with e.g. porosity of sintered metal oxides, moisture content in building bricks, filler volume fraction in filled polymers [19,20].

So far, no information is available on application of transient thermography for the purpose of fiber content evaluation by determining thermal diffusivity values.

2. Theory of the method

Thermo-physical properties, namely thermal conductivity, thermal diffusivity and specific heat are the free most important properties of material that are needed for heat transfer calculations. The equation that relates these properties is given by

$$\alpha = \lambda/\rho c_p \quad (1)$$

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 can be used as an indicator of how quickly a material will change temperature in response to the application of heat [21].

Parker et al. [22] in 1961 proposed the heat pulse method or "flash diffusivity 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 material is incident on the front surface of specimen and temperature rise on the rear surface is recorded. If the heat losses are neglected, the temperature of rear surface is given by [21,22]:

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

where:

$$\omega = \pi^2 \alpha t / L^2 \quad (3)$$

and V(L,t) are dimensionless parameters, n is an integer and L – specific thickness, and

$$V(L,t) = \Delta T(L,t)/\Delta T_M \quad (4)$$

where: $\Delta T(L,t)$ is the temperature above ambient at the time t and ΔT_M is the maximum temperature rise.

Equation (2) is plotted in Fig. 1 [21].

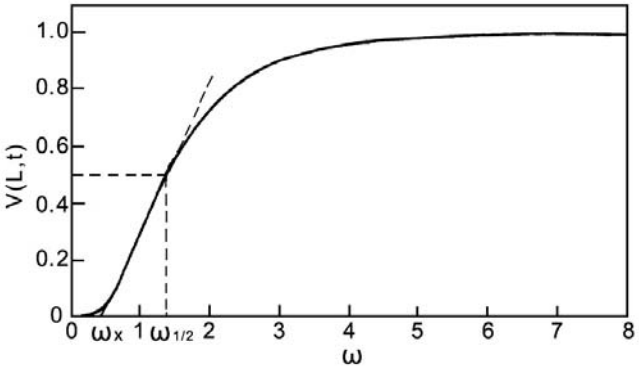


Fig. 1. Dimensionless temperature history on the rear surface [21]

Parker et al. [22] suggested two ways of determining the thermal diffusivity α from Eq. (2) and Fig. 1. First, at half the maximum temperature rise (V = 0.5), ω = 1.38 and the thermal diffusivity can be calculated using equation [21,22]

$$\alpha = 1.38L^2/\pi^2 t_{1/2} \quad (5)$$

where, $t_{1/2}$ 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 ω = 0.48 and the thermal diffusivity can be calculated using equation [21,22]

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

where t_x is the time corresponding to the interception of the extrapolated straight line portion of the curve with ω axis. It is not necessary to know the amount of energy absorbed in the front surface in order to determine the thermal diffusivity [22].

3. Experimental

3.1. Methdology

Transient thermography was applied to evaluate the thermal diffusivity values from carbon/epoxy specimens with different fiber content. The method consists of heating the front surface of specimen using short uniform heat pulse and measuring the temperature evaluation on the rear surface. The thermal diffusivity values were obtained from temperature – time plots (thermograms) using Parker's method [22]. Finally, the obtained thermal diffusivity values were correlated with carbon fibre content.

3.2. Specimen preparation

The materials used in the present experiment were made of cross-ply woven [0/90] carbon fabric (Sigratex", "SGL Carbon Group", Germany), epoxy resin („Epidian 53", "Organika-Sarzyna", Poland) and hardener ("Z-1", "Organika-Sarzyna", Poland). The selected details about constituent materials are shown in Table 1.

Table 1.
The properties of constituent materials [18]

Parameter	Carbon fibre (* fabric)	Epoxy resin
Density	1.65 [g/cm^3]	1.13 [g/cm^3]
Areal weight	240 [g/m^2]*	-
Thermal conductivity coef.	~15.0 [W/mK]	~0.22 [W/mK]

Carbon fiber reinforced epoxy composites were fabricated by hand lay-up with a variation of carbon content. The variation of fibre content was achieved using different number of carbon layers with the same total thickness of the specimens. The epoxy resin was cold-cured under ambient conditions (~21 ºC) and after curing process was thermally hardened at 50 ºC for 24 hours. The specimens were 100 mm by 100 mm square and ~6.2 mm thick. The chosen properties of prepared specimens are shown in Table 2.

Table 2.
The properties of prepared specimens

Specimen no.*	Density [g/cm^3]	Thickness [mm]	Fibre content [%vol.]
4	1.18	6.41	8.8
6	1.20	6.22	13.7
10	1.25	6.22	22.7
12	1.28	6.01	28.5

* specimen number also indicates amount of carbon-fiber layers

All specimens were painted with a thin matt black coating with an emissivity value of 0.95 in order to eliminate reflections from sunlight, overhead lights or humans and to ensure homogeneity in the specimen surface emissivity as was recommended in other study [9].

3.3. Apparatus and measurements

The measurement procedure consisted of heating the front surface of each specimen using infrared radiator and recording the temperature response at rear surface with IR-camera.

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.

Each specimen was mounted vertically (parallel to the infrared radiator) in a hole of the thermal shield. As a thermal wave source a 1200 W black-ceramic infrared radiator ("SHTS", "Elstein", Germany) with surface dimensions of 250 x 62 mm and wavelength range of 2-10 μm was used.

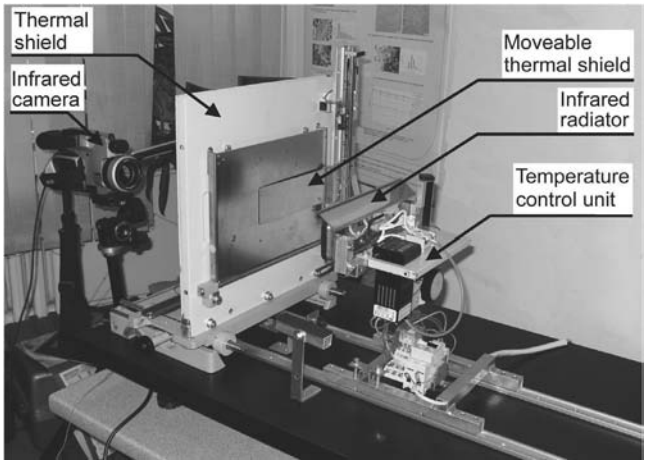


Fig. 2. View of the thermography testing station

Due to the low conductivity of considered CFRP composites a long-pulse transient thermography approach was selected to ensure a linear temperature response on rear surface as was suggested in other publication [21]. The heating time of 3.0 sec and distance between thermal wave source and specimen (Table 3) was determined experimentally when the temperature difference between heated specimen surface and neighbourhood (~21 ºC) was satisfactory for the investigations [21,22].

Table 3.
Heating conditions

Condition	Specimen to radiator distance [mm]	Radiator temperature [ºC]	Heating time [sec]
A	15.0	600	3.0
B	30.0	745	3.0

The temperature variations on the rear surface of the heated specimen was measured and recorded using IR camera

("ThermaCAM^{TM}SC640", made by "Flir Systems", Sweden) with focal plane array (FPA) detector. Infrared camera as well as testing station were connected to PC system. A schematic view of the experimental configuration is shown in Fig. 3.

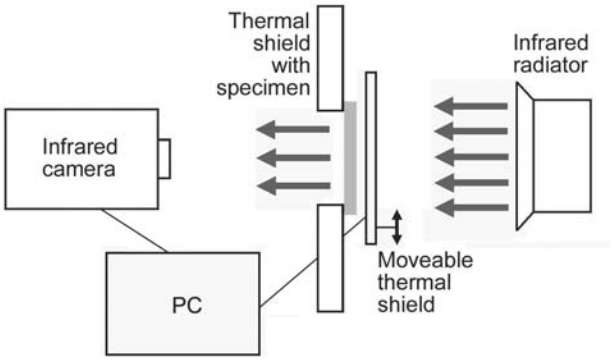


Fig. 3. Scheme of the experimental arrangement [18]

4. Results and discussion

The thermal images of the investigated specimens obtained during transient thermography inspection for heating conditions B (see Table 3) are presented in Figs. 4, 5, 6 and 8.

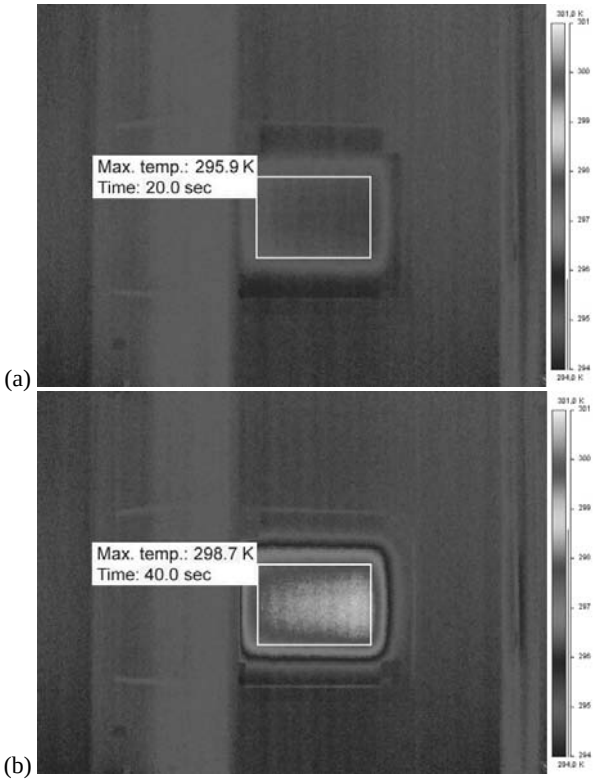


Fig. 4. Thermal images of 8.8vol.% carbon fiber specimen captured on the rear surface after: a) 20.0, b) 40.0 seconds

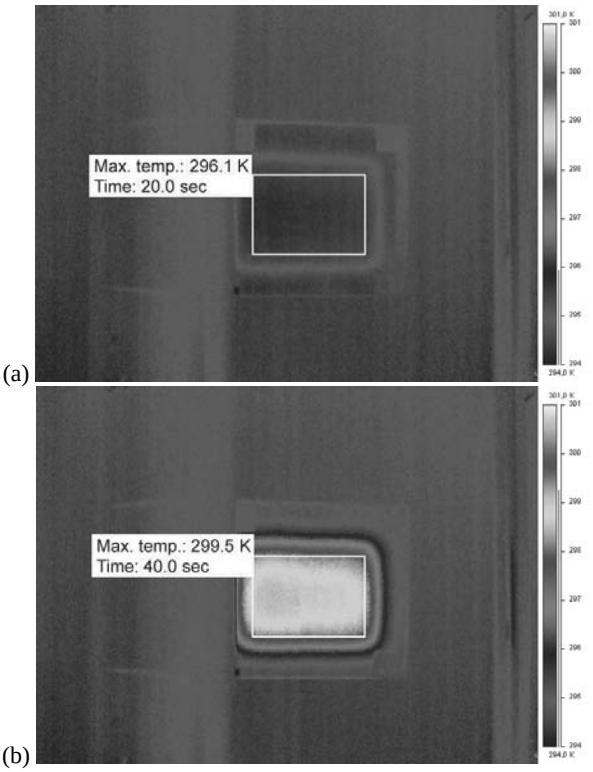


Fig. 5. Thermal images of 13.7vol.% carbon fiber specimen captured on the rear surface after: a) 20.0, b) 40.0 seconds

The presented thermal images consist of a view of the heated specimen (inside the drawn rectangle) and the neighbourhood. At the time of 0 seconds to about 5 seconds the specimen as well as the neighbourhood were represented by the same colour on thermal images due to the same emissivity values (~0.95) for mat black coating.

Presented thermal images were captured at the time of 20.0 and 40.0 seconds counting from the beginning of the heating process.

These images were chosen to be representative from all captured images due to the highest temperature differences on the surface of all specimens tested.

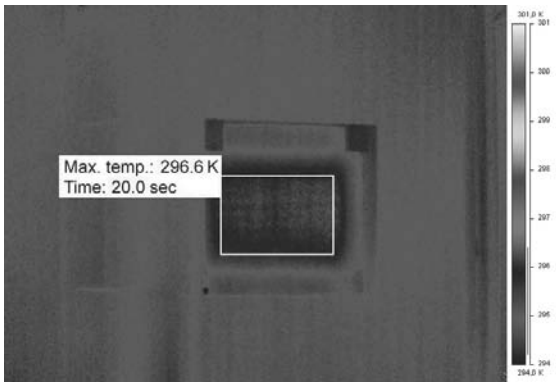
It was clearly seen from thermal images captured at the same time, that for each specimen, the higher is carbon content the higher is the temperature obtained. Other differences such as temperature growth rate can be observed on "temperature variations versus time" plots (Figs. 7, 9, 10 and 11) obtained during the temperature recording for all investigated specimens.

The highest temperature differences were obtained at times of about 20 seconds and 40 seconds counting from the beginning of heating process (Figs. 4, 5, 6 and 8).

The infrared (IR) system recorded the temperature data at a rate of 7.5 measurements per second, so the time of 100 seconds on Figs. 7, 9, 10 and 11, represents 750 data points.

From all presented plots for temperature variations versus time, the dimensionless temperature history plots were created according to the procedure described in other publications [21,22].

a)



b)

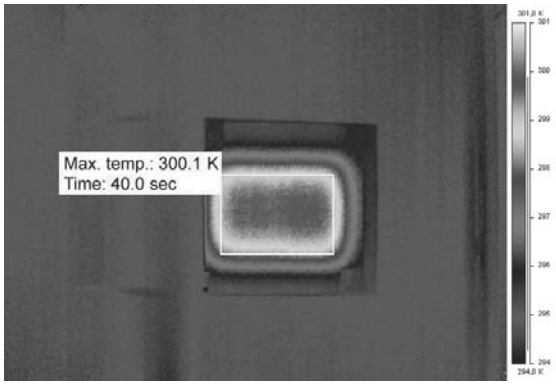
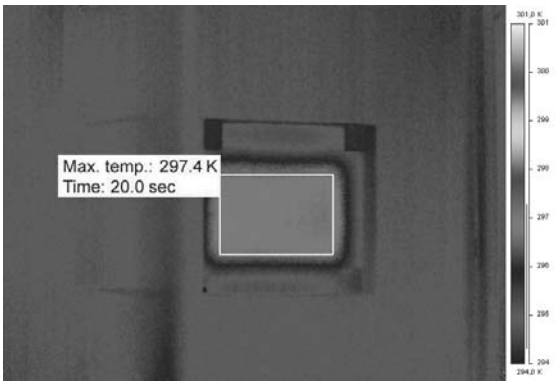


Fig. 6. Thermal images of 22.7vol.% carbon fiber specimen captured on the rear surface after: a) 20.0, b) 40.0 seconds

a)



b)

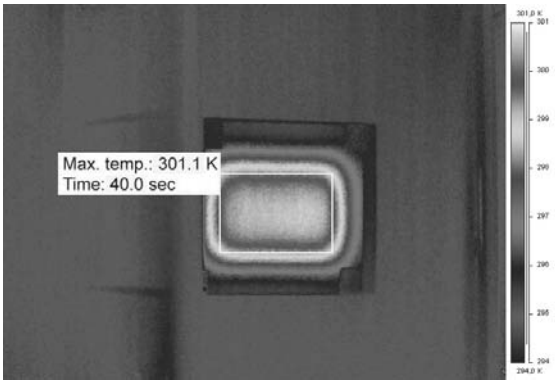


Fig. 8. Thermal images of 28.5vol.% carbon fiber specimen captured on the rear surface after: a) 20.0, b) 40.0 seconds

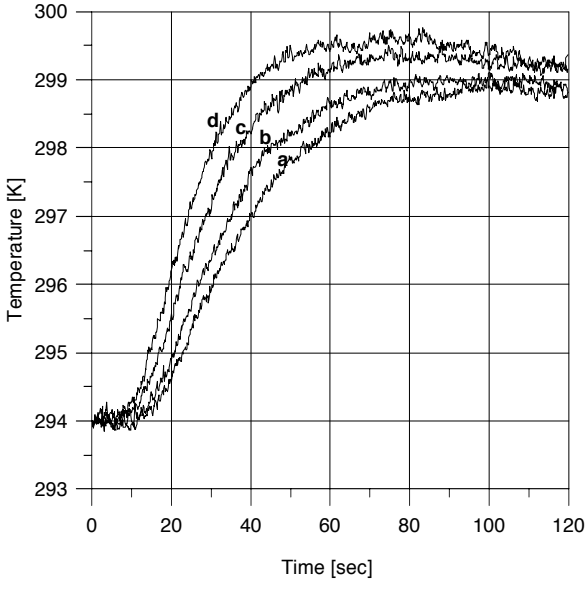


Fig. 7. Max. temperature variations vs. time for specimens: a) 8.8, b) 13.7, c) 22.7, d) 28.5vol.% carbon content (conditions A)

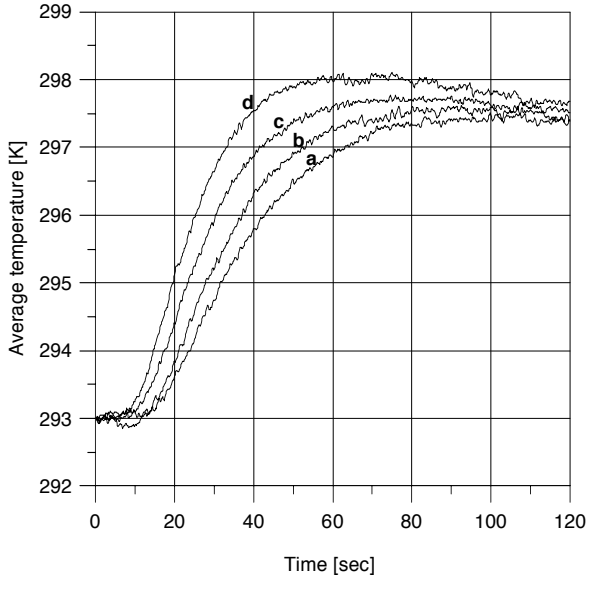


Fig. 9. Av. temperature variations vs. time for specimens: a) 8.8, b) 13.7, c) 22.7, d) 28.5vol.% carbon content (conditions A)

The two different temperature values, namely maximal and average temperatures from thermograms were taken into consideration to check the conformity of the obtained thermal diffusivity values. Four chosen curves of normalized average temperature increase on the rear surface for each specimen and heating conditions "B" have been shown in Figs. 12-15.

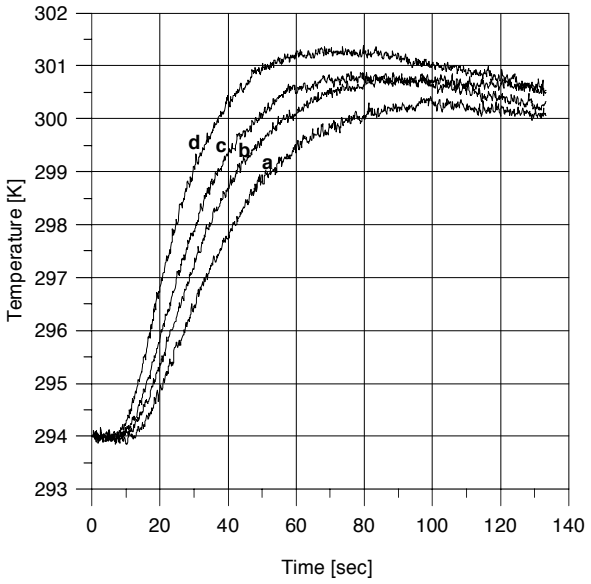


Fig. 10. Max. temperature variations vs. time for specimens: a) 8.8, b) 13.7, c) 22.7, d) 28.5vol.% carbon content (conditions B)

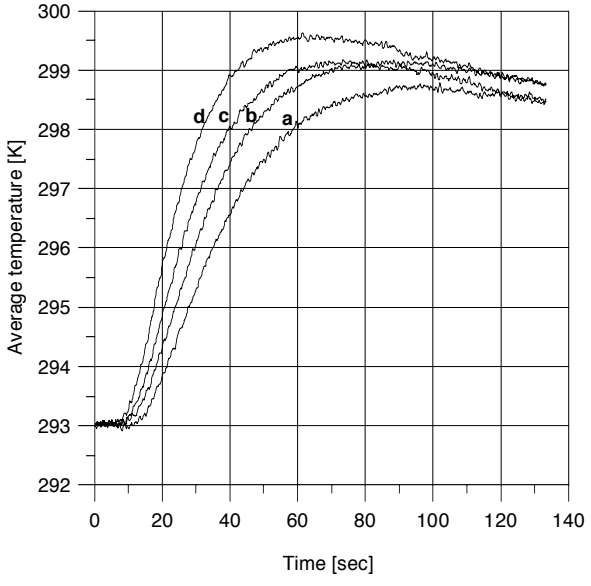


Fig. 11. Av. temperature variations vs. time for specimens: a) 8.8, b) 13.7, c) 22.7, d) 28.5vol.% carbon content (conditions B)

Figures 12-15 also show the decreasing values of $t_{1/2}$ corresponding to the specimens with an increasing carbon content. The same normalization procedures have been performed for all specimens and heating conditions "A" and "B", considering also maximal and average temperatures, so four values of thermal diffusivity per one specimen were obtained giving a scatter of results presented in Fig. 16.

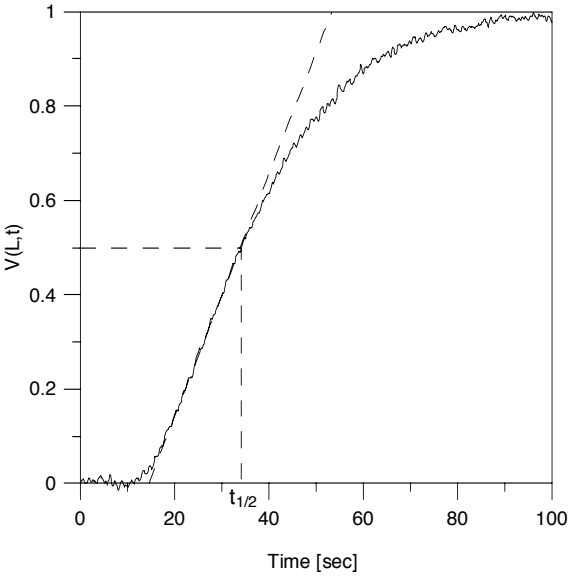


Fig. 12. Normalized temperature increase on the rear surface of 8.8vol.% specimen. Half maximum temperature rise time ($t_{1/2}$) is equal to 34.0 sec. (conditions B)

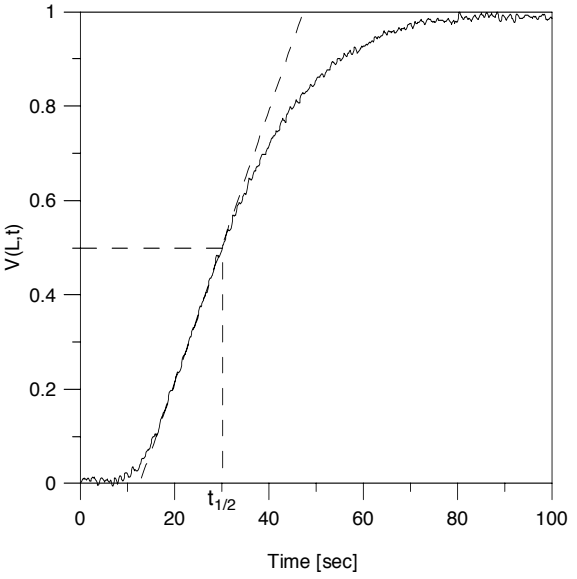


Fig. 13. Normalized temperature increase on the rear surface of 13.7vol.% specimen. Half maximum temperature rise time ($t_{1/2}$) is equal to 30.0 sec. (conditions B)

The $t_{1/2}$ values taken from normalized temperature increase plots together with specimen thickness (L) were used to calculate the thermal diffusivity values according to Parker's equation (Eq.

5). Obtained values of the thermal diffusivity (shown in Fig. 16) show that the higher the carbon content the higher are the thermal diffusivity values. These results have been further processed using standard regression technique to achieve the best fitting line, from which the empirical formula able to predict the local fiber content was created. It has been found that the thermal diffusivity increases linearly with an increase of fiber volume fraction (Fig. 16).

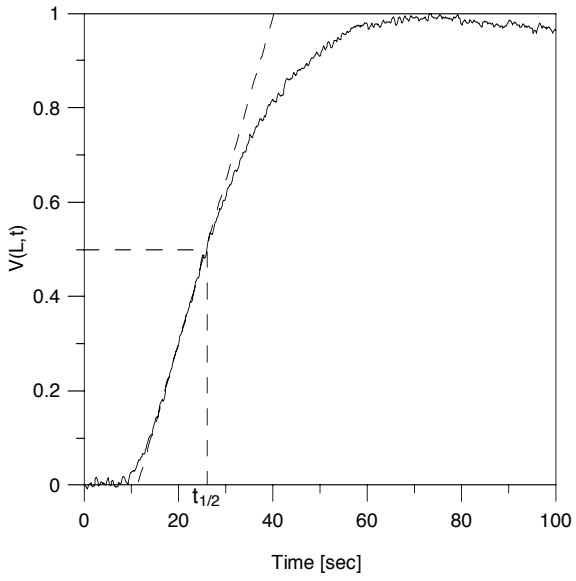


Fig. 14. Normalized temperature increase on the rear surface of 22.7vol.% specimen. Half maximum temperature rise time ($t_{1/2}$) is equal to 25.8 sec. (conditions B)

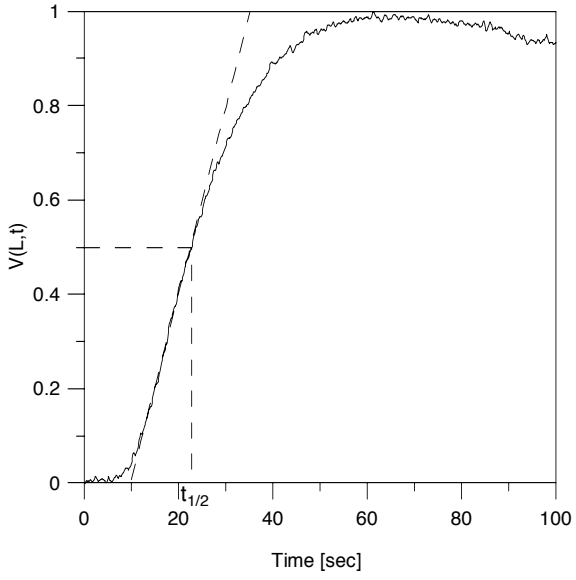


Fig. 15. Normalized temperature increase on the rear surface of 28.5vol.% specimen. Half maximum temperature rise time ($t_{1/2}$) is equal to 22.7 sec. (conditions B)

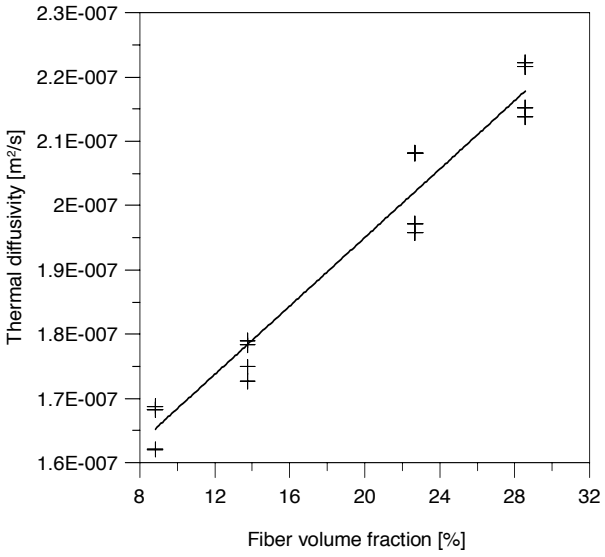


Fig. 16. Comparison of the thermal diffusivity values for carbon/epoxy specimens with different carbon fiber content

The developed empirical formula (expressed in vol.%) is given by:

$$V_f = 37.6 \cdot 10^7 \cdot \alpha - 53.4 \quad (7)$$

where:

V_f – fiber volume fraction,

α – thermal diffusivity value.

Formula (7) gives a quantitative first estimation of carbon fibre content in the considered CFRP composites. The relationship can be very useful in the local fiber content examination, but for any different composite materials, different formulas should be determined in order to obtain actual results.

5. Conclusions

In the present study, transient thermography was used to measure the thermal diffusivity of woven carbon fibre composites with different fiber content. The method initially proposed by Parker as “flash method” for the thermal diffusivity measurements of homogeneous solids was successfully applied to determine local fiber content by correlating thermal diffusivity with carbon volume fraction in CFRP composites. Relationship showed that the thermal diffusivity is linear function of carbon content in considered materials. The developed empirical formula can be very useful to obtain a first estimate of carbon fibre content in many industrial applications.

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