Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 31
ISSUE 2
December
2008

Transient thermography in the assessment of local fibre content in CFRP laminates

G. Wróbel [a], Z. Rdzawski [b,c], G. Muzia [b], 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] Institute of Non-Ferrous Metals, ul. Sowińskiego 5, 44-101 Gliwice, Poland
[c] 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
* Corresponding author: E-mail address: sebastian.pawlak@polsl.pl

Received 23.09.2008; published in revised form 01.12.2008

Properties

ABSTRACT

Purpose: The main objective of the present work was to find relationships between achieved results of the thermal non-destructive testing and the local fibre content in carbon/epoxy composite materials.
Design/methodology/approach: The experiments have been performed using thermography testing station designed and built specially for the purpose of the investigation. Each carbon/epoxy composite was prepared with different fiber content with the same total thickness of the specimens. Thermal non-destructive testing (TNDT) technique was employed to measure such parameters as threshold temperature rise, upper limit temperature and temperature growth rate on the specimen surface. The results achieved were then analysed and correlated with carbon fiber content.
Findings: The study has assessed the ability of transient thermography to carry out a testing of fiber content in carbon/epoxy composite materials. The experimental results revealed relationship between fiber content and temperature growth rate from which the empirical formula for predicting local fiber content has been developed.
Research limitations/implications: In order to obtain reliable results, there are many factors to be considered such as void content in composite matrix, type and quality of composite surface and others. Further work is needed in this area.
Practical implications: The results obtained would be of considerable importance in the industrial applications to achieve a first estimate of local fiber content in polymer composite materials.
Originality/value: A new approach to the problem of fibre content examination has been demonstrated by means of thermal non-destructive testing. The method developed should be of interest to the industrial quality control applications and has a great importance for the products with a high failure-free requirements.
Keywords: Non-destructive testing; Thermography; Carbon/epoxy laminates; Fiber content

1. Introduction

High-performance polymer composite materials, such as carbon fibre reinforced composites offer practical advantages over conventional materials in many applications in the modern aerospace, aircraft and automotive industry [1, 2]. It is also known that the mechanical properties of fiber reinforced composites are very sensitive to the local fiber content variations. The effect of fiber content on the selected characteristics of composites can be found in the literature [3-5]. Local reinforcement variations arising during production process decide about out-of-control variations of strength and stiffness in a given component, which is of a great importance for the products with a high failure-free requirements. Previous research results showed that the inhomogeneous distribution of glass fibers, which significantly affect the mechanical properties, is detectable by ultrasonic measurements [6-8]. To improve manufacturing quality it is necessary to develop a new reliable non-destructive testing (NDT) methods which are suitable for the purpose of reinforcement content evaluation. 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 [12].

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]. Thermography also seems to be the promising method for the purpose of fiber content evaluation because the total thermal conductivity of composite material highly depends on the thermal conductivity of constituent materials and their relative volume fraction. So far, no information is available on application of thermography for the fiber content evaluation in polymer composite materials.

Previously, the authors made an attempt to apply active IR-thermography using prototype testing station [15] for the purpose of fiber content evaluation in carbon/epoxy composites. The present study is the continuation of the prior investigations.

2. Experimental

2.1. Methodology

The thermal non-destructive testing (TNDT) was conducted to evaluate the local fiber content in carbon/epoxy composites. Each carbon fiber reinforced composite was prepared with different fiber content. The thermal images achieved from thermographic investigations were then analysed and compared for each composite.

2.2. Materials and specimen preparation

The composite specimens were made of cross - ply plain weave [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 [15].

Table 1.
The properties of constituent materials [15]

Parameter	Carbon fibre (* fabric)	Epoxy resin
Areal weight / Density	240 [g/m^2]*	1.15 [g/cm^3]
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. To eliminate a rough front surface after hand lay-up and to achieve high accuracy of the thickness (6 mm ±0.2), the specimens were covered with flat PMMA plate and pressed with load during curing process. The epoxy resin was cold-cured under ambient conditions (~20ºC) and after curing process was thermally hardened at 50ºC for 24 hours. The specimens were 100 mm by 100 mm square and 6.0 mm thick with 23, 30 and 37wt.% carbon content [15].

All specimens as well as close neighbourhood of the 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 human bodies and to ensure homogeneity in the specimen surface emissivity as was recommended in other study [9].

2.3. Transient thermography measurements

The measurement procedure consisted of heating the front side of each specimen using infrared radiator and observing the temperature response at back side with IR-camera.

The most important issue to be taken into account, when using active IR-thermography in the case of present purpose was to obtain the repeatability of the measurements. This reason caused the application of automatic testing station (Figs. 1 and 2) which was designed and built specially 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.

To provide a high accuracy and repeatability of all measurements an automatic testing station (Figs. 1 and 2) was used. 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.

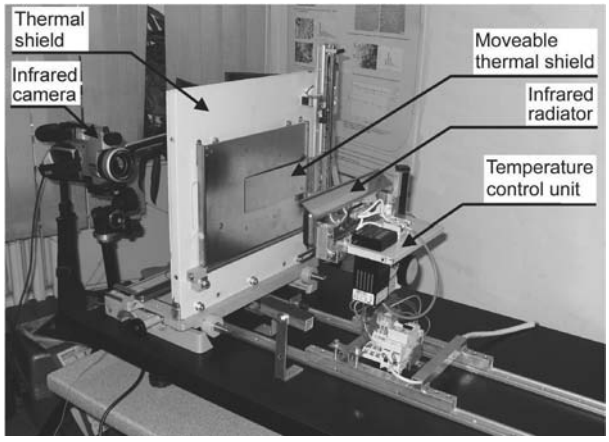


Fig. 1. Front view of the thermography testing station

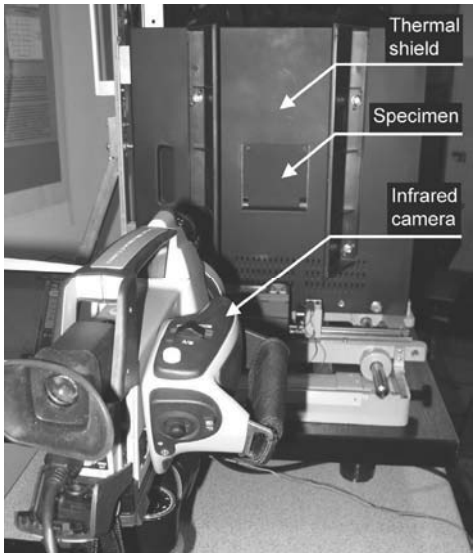


Fig. 2. Back view of the thermography testing station

It has been found in the literature [9] that good results can be obtained for slow thermal response materials, such as carbon/epoxy composites, using modest power illumination sources operating in the long-puls mode [9]. Due to the low conductivity of considered composites a long-pulse transient thermography approach was selected. The heating time of 2.0 seconds and distance between thermal wave source and specimen (30 mm) was determined experimentally using a neat resin specimen when the temperature difference between heated specimen surface and neighbourhood (~21ºC) was satisfactory for the investigations. The temperature variations on the opposite side of the heated specimen surface 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. The schematic view of the experimental configuration is shown in Fig. 3.

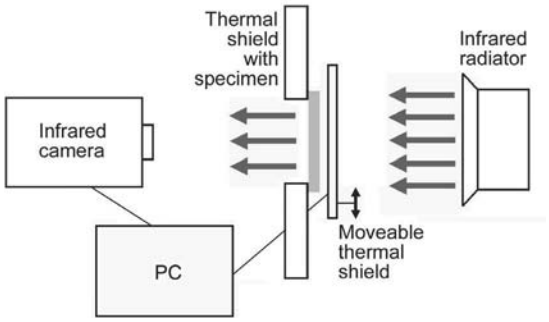
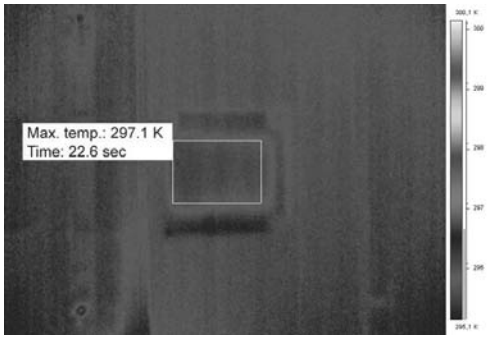


Fig. 3. Scheme of the experimental arrangement

3. Results and discussion

The thermal images of the investigated specimens obtained during transient thermographic inspection are presented in Figs. 4, 5 and 7. 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 is clearly seen from thermal images captured at the same time, that for each specimen, the higher is carbon content the higher is the temperature achieved. The highest temperature differences were obtained at times of about 22 seconds and 66 seconds counting from the beginning of heating process (Figs. 4, 5 and 7).

a)



b)

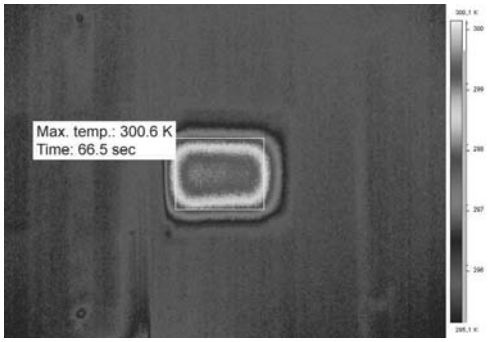
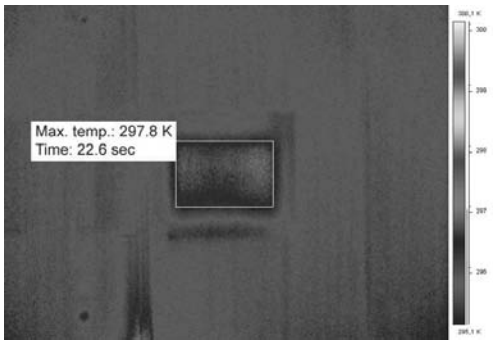


Fig. 4. Thermal images of 23wt.% carbon fiber specimen captured on the opposite side to the heated surface after: a) 22.6, b) 66.5 seconds counting from the beginning of the heating process

a)



b)

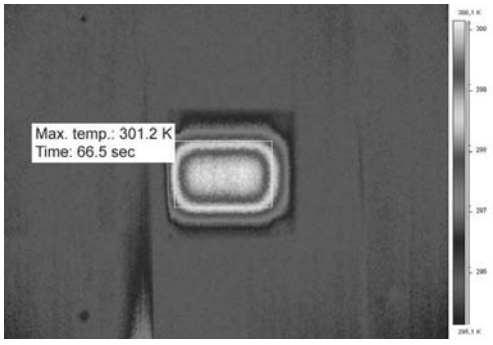


Fig. 5. Thermal images of 30wt.% carbon fiber specimen captured on the opposite side to the heated surface after: a) 22.6, b) 66.5 seconds counting from the beginning of the heating process

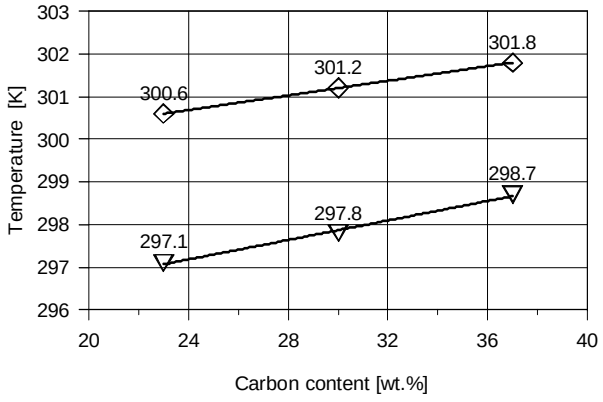
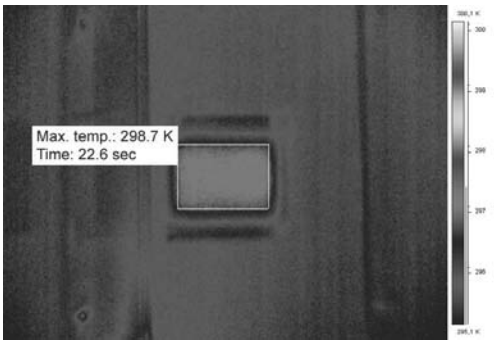


Fig. 6. Comparison of the temperatures taken from presented thermal images at the times of 22.6 and 66.5 seconds counting from the beginning of the heating process

Figure 6 compares the maximal temperatures taken from thermal images presented above.

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 image due to the same emissivity value of 0.95 for mat black coating.

a)



b)

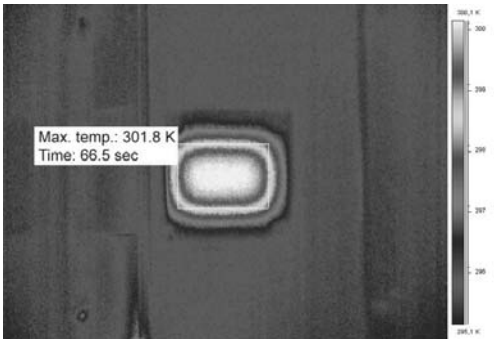


Fig. 7. Thermal images of 37wt.% carbon fiber specimen captured on the opposite side to the heated surface after: a) 22.6, b) 66.5 seconds counting from the beginning of the heating process

The infrared (IR) system recorded the temperature data at a rate of 7.5 measurements per second, so the time of 110 seconds on Figs. 8 and 10 represents 825 data points.

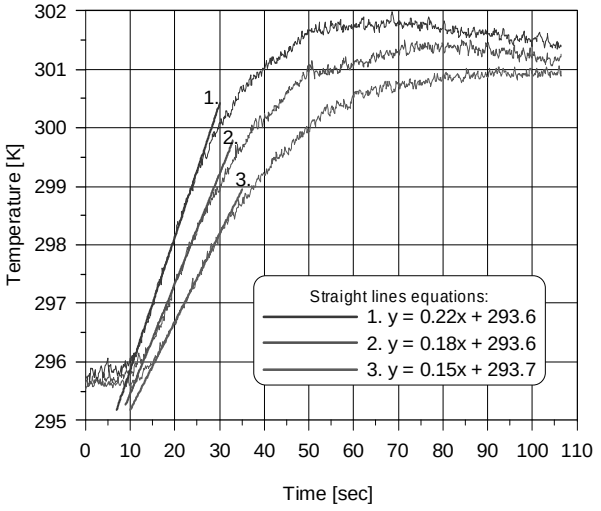


Fig. 8. Temperature variations versus time for carbon/epoxy specimens including: 1. 23wt.%, 2. 30wt.%, 3. 37wt.% carbon content (line profile plots for maximal temperatures)

Two different temperature values, maximal temperature and average temperature from thermal images were taken into consideration during analysis procedure.

Figure 8 shows the line profile plots of maximal temperature variation with time for all carbon/epoxy specimens including: 1. 37wt.%, 2. 30wt.%, 3. 23wt.% carbon content.

As can be seen in Fig. 8 the slopes of straight lines and also the highest achieved temperatures on the opposite side to the heated surfaces have different values. It is due to the different thermal conductivities for specimens including different carbon content.

The higher the carbon content the higher is slope of temperature increase (Fig. 9). The slope of straight line represents the temperature growth rate (K/sec) and is proportional to the fiber content (Fig. 9). The results from Fig. 9 have been further processed using standard regression technique to achieve empirical formula (1) able to predict the local fiber content. The developed empirical formula (expressed in wt%.) is given by:

$$V_f = 200.0 \cdot C - 6.6 \quad (1)$$

where:
V_f – fiber content [wt.%], C – temperature growth rate [K/sec].

The same analysis was also performed for the average achieved temperature on the examined area of the specimens. Figure 10 shows the line profile plots for average temperature variation with time for all investigated specimens. As can be seen in Fig. 10 the slopes of straight lines and also the highest achieved temperatures on the opposite side to the heated surfaces have different values. The similar situation could be seen in previously considered Figure 8 (above). It is also due to the different thermal conductivities for specimens including different carbon content.

Generally speaking, the temperature growth rate increases with an increase of fiber content in both considered cases namely for maximal and average temperatures (Fig. 11) taken from presented thermal images.

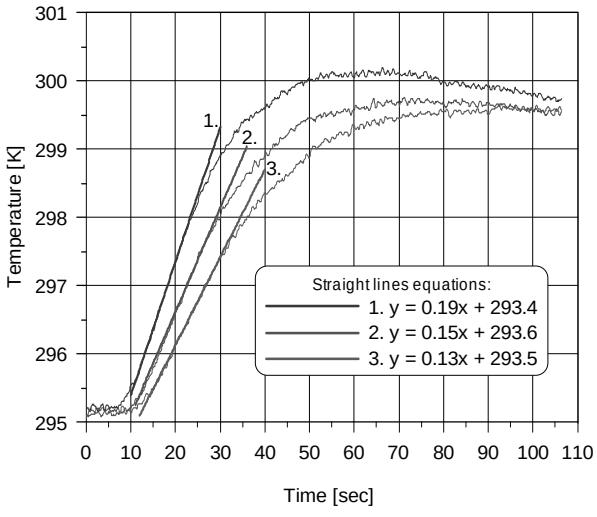


Fig. 10. Temperature variations versus time for carbon/epoxy specimens including: 1. 23wt.%, 2. 30wt.%, 3. 37wt.% carbon content (line profile plots for average temperatures)

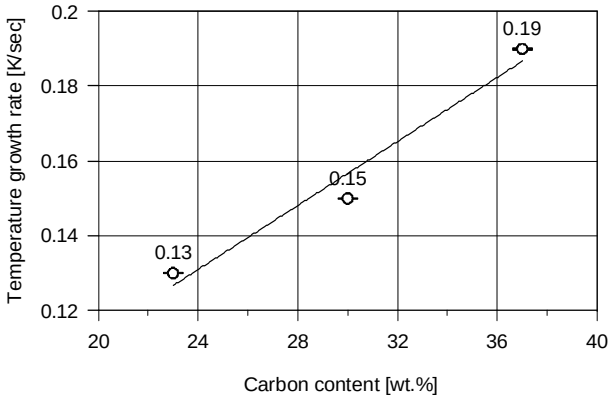


Fig. 11. Temperature growth rate vs fiber content for all three investigated specimens (for average temperature)

The developed empirical formula for average temperatures is given by:

$$V_f = 250.0 \cdot C - 7.0 \quad (2)$$

where:
V_f – fiber content [wt.%], C – temperature growth rate [K/sec].

From all considered empirical formulas 1 and 2, both can be applied in quality control procedures giving quantitative first estimation of carbon fiber content in polymer reinforced composites.

Relationships found may be useful for local fibre content examination, but for any different composite material, different relationships are required to be determined.

4. Conclusions

The main objective of this work was to examine the effectiveness of transient thermography to evaluate the local fiber content in carbon/epoxy composites. The investigation has assessed the ability of thermal non-destructive method to carry out such testing. The experimental results have shown relationship between fiber content and temperature growth rate. The developed empirical formula can be very useful to achieve first estimate of carbon fibre content in many industrial applications. Therefore, it is concluded that transient thermography can be used in the evaluation of local fiber content in polymer composite materials.

Acknowledgements

The authors would like to thank Mr Jerzy Miśków (MSc) from “Opticup” (Gliwice, Poland) for his helpful advices during preparation of composite specimens tested in the present study.

Special thanks also go to Mr Sebastian Nowak (Eng.) from “AMS-Systems” (Gliwice, Poland) for configuration the automatic devices in the thermography testing station used in the present investigations.

References

[1] L.A. Dobrzański, Engineering materials and material design. Principles of materials science and physical metallurgy, WNT, Warsaw, 2006 (in Polish).

[2] W. Hufenbach, L.A. Dobrzański, M. Gude, J. Konieczny, A. Czulak, Optimization of the rivet joints of the CFRP composite material and aluminium alloy, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 119-122.

[3] J.H. Chen, E. Schulz, J. Bohse, G. Hinrichsen, Effect of fibre content on the interlaminar fracture toughness of unidirectional glass-fibre/polyamide composite, Composites A 30 (1999) 747-755.

[4] O.I. Okoli, G.F. Smith, Failure modes of fibre reinforced composites: The effect o strain rate and fibre content, Journal of Materials Science 33 (1998) 5415-5422.

[5] S.B. Heru, J. Komotori, M. Shimizu, Y. Miyano, Effects of the fiber content on the longitudinal tensile fracture behavior of uni-directional carbon/epoxy composites, Journal of Materials Processing Technology 67 (1997) 89-93.

[6] G. Wróbel, S. Pawlak, Ultrasonic evaluation of the fiber content in glass/epoxy composites, Journal of Achievements in Materials and Manufacturing Engineering 18 (2006) 187-190.

[7] G. Wróbel, S. Pawlak, The effect of fiber content on the ultrasonic wave velocity in glass/polyester composites, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 295-298.

[8] G. Wróbel, S. Pawlak, A comparison study of the pulse-echo and through-transmission ultrasonics in glass/epoxy composites, Journal of Achievements in Materials and Manufacturing Engineering 22/2 (2007) 51-54.

[9] D. Bates, G. Smith, D. Lu, J. Hewitt, Rapid thermal non-destructive testing of aircraft components, Composites B 31 (2000) 175-185.

[10] M. Krishnapillai, R. Jones, I.H. Marshall, M. Bannister, N. Rajic, Thermography as a tool for damage assessment, Composite Structures 67 (2005) 149-155.

[11] C. Santulli, IR thermography study of the effect of moulding parameters on impact resistance in E-glass/PP commingled laminates, NDT&E International 35 (2002) 377-383.

[12] N.P. Avdelidis, B.C. Hawtin, D.P. Almond, Transient thermography in the assessment of defects of aircraft composites, NDT&E International 36 (2003) 433-439.

[13] C. Meola, G.M. Carlomagno, A. Squillance, A. Vitiello, Non-destructive evaluation of aerospace materials with lock-in thermography, Engineering Failure Analysis 13 (2006) 380-388.

[14] G. Muzia, Z.M. Rdzawski, M. Rojek, J. Stabik, G. Wróbel, Thermographic diagnosis of fatigue degradation of epoxy-glass composites, Journal of Achievements in Materials and Manufacturing Engineering 24/2 (2007) 123-126.

[15] G. Wróbel, G. Muzia, S. Pawlak, Active IR-thermography as a method of fiber content evaluation in carbon/epoxy composites, Archives of Materials Science and Engineering 30/2 (2008) 101-104.