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Thermographic diagnosis of fatigue degradation of epoxy-glass composites

G. Wróbel [a]
co-operating with
G. Muzia [b], Z.M. Rdzawski [a,b], M. Rojek [a], J. Stabik [a,*]
[a] 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
* Corresponding author: E-mail address: jozef.stabik@polsl.pl

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Materials

ABSTRACT

Purpose: The purpose of this paper was to describe results of application of thermography to evaluate the degree of fatigue degradation of epoxy-glass composites.
Design/methodology/approach: Samples of epoxy-glass composite were subjected to fatigue degradation. During fatigue test, after defined number of cycles, samples were heated using infra-red heater and at the opposite side temperature increase was evaluated with thermovision camera.
Findings: Analysis of achieved results allowed to elaborate relation between number of fatigue cycles and the degree of fatigue degradation. Such relation may be applied in diagnostic procedures.
Research limitations/implications: Performed tests were of preliminary character and results will be applied to prepare research programme on thermographic testing of composites.
Practical implications: Results of such tests may be applied in the future in diagnostic procedures to non-destructive evaluation of the degree of fatigue degradation of high performance polymer composites.
Originality/value: Thermographic methods are applied up till now to non-destructive flaws detection. Proposed in the paper method may be applied to evaluate the degree of thermal and fatigue degradation in composites without any macroscopic flaws.
Keywords: Engineering polymers; Non-destructive testing; Thermography; Composites; Fatigue

1. Introduction

In previous research ultrasonic methods were applied to non-destructive evaluation of fatigue and thermal degradation of composites [1,2].

The aim of the present research is to elaborate the evaluation methodology of the degree of polymer composites fatigue degradation using thermography. The research had a preliminary character. Epoxy-glass composite was used in described stage of experimental programme.

The basic idea of thermography is to apply infrared frequency range of electromagnetic radiation (Fig. 1) emitted by object under research to obtain information concerning its selected physical properties or processes taking place within this object.

The first known application of thermography methods took place at the beginning of twentieth century. In 1914 Parker patented the first infrared detector. In 1934 Barker proposed complete infrared system to detect forest's fires. In the next years many scientific and industrial applications of thermography appeared.

Thermography evaluates the distribution of infrared radiation emitted by body surface. Scientific and industrial methods apply basic knowledge concerning relations between infrared radiation and temperature distribution on body surface. Emissivity and other thermodynamic properties of body surface are also taken into account. Depending on experimental conditions, temperature distribution can also be an information source about other object properties.

In theory of radiation emission the key concept is the black body model. A black body is a theoretical object that absorbs 100% of the radiation that hits its surface. Therefore it reflects no radiation and appears perfectly black. The basic physical laws describing radiation emission are [3,4]:

- The Kirchoff law stating that the ratio of emission and absorption capability of given surface is constant;
- The Planck law describing radiation distribution of black body;
- The Wiena law describing the relation between wavelength of maximum emitance and surface temperature;
- The Stefan-Boltzman law describing the relation between total emitance and surface temperature.

These laws constitute experimental basis for evaluation of surface temperature distribution using thermographic images.

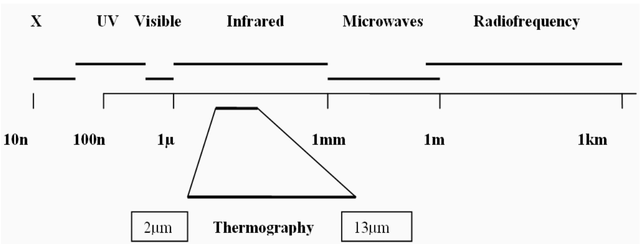

Fig. 1. Range of wave length of electromagnetic radiation applied in thermography

Knowing the surface temperature distribution one can formulate the inverse problem: What are the reasons of achieved surface temperature state or given process of surface temperature changes? Especially interesting is what material properties and structural characteristic of experimentally tested material can influence temperature distribution of scanned surface. In the described research relations between material changes caused by fatigue degradation and surface temperature distribution after short time heating were investigated.

There are many different thermographic methods classifications, depending on class of researched object, on factors chosen as essential for thermal processes in given experimental programme, on way of thermal activation of investigated object and on other criteria. Taking into account the way of thermal object activation thermography methods are divided into active and passive. Passive thermography is limited to recording of temperature states and processes on researched surfaces. Active thermography initializes thermal processes and records surface temperature distribution and its changes.

There are many different scientific and industrial fields of application of passive thermography. These methods are effectively applied in research programmes and in ordinary practice for such demanding spheres as cosmonautics, aviation, marine, fire service, military service, police, medicine, environment conservation and many other [5-16]. Because of different ways of thermal activation of objects, active thermography has even more interesting possibilities. The activation process can be static or dynamic in its nature. The most popular activation methods are: pulse activation (pulsed thermography), modulated heating (lock-in termography with modulated heating), pulse-phase heating (pulsed-phase termography). The most frequently used is radiation activation of observed surface. Information concerning surface or thin surface layer of tested material is subsequently gathered.

Dynamic thermography is another class of methods in which energy (mainly in form of mechanical vibrations) is transferred to tested object and response in the form of heat emission is observed (vibro-thermography). This technique is usually realized by forcing harmonic oscillations of object and simultaneous surface temperature measurement. The forced mechanical vibrations have in this case only a character of diagnostic tool. Temperature measurements are usually performed using very sensitive (with resolution up to 20mK) and quick (up to 25 000 images per second) thermovision cameras.

2. Experimental

2.1. Materials

Epoxy-glass composite TSE-6 produced by IZO-ERG Gliwice, Poland was used in the experimental part. Samples were cut from laminates produced by hot pressing. Samples with the following dimensions were applied: 250mmx 20mmx4mm. To achieve smooth cut surfaces, test samples were cut with diamond saw by composite producer. Basic properties of tested composites according to producer's data are given in Table 1 [17].

Table 1.
Basic properties of TSE-6 epoxy-glass composite

Property	Unit	Value
Density	g/cm^3	1,7 – 2,0
Flexural strength	MPa	340
Flexural modulus	GPa	24
Notched impact strength [a]	kJ/m^2	50
Temperature index $_b$	°C	180

a – tested according to Polish standard PN-81/C-89029
b – Maximum temperature of continuous exploitation

2.2. Methodology

The method used in the described research belongs to active thermography with static thermal activation [18]. Samples were activated by short time heating. Taking into account that the main aim of the research was to find relations between fatigue degradation and temperature changes, the surface opposite to heated surface were scanned by thermovision camera, so heat flux had to pass across the sample. Fatigue degradation has a dispersive character so no characteristic flaw images were expected but overall surface temperature changes. Fatigue degradation is expected to influence properties important for infrared emission process, especially thermal conductivity, and in this way for surface temperature distribution and surface temperature changes. Finally surface temperature monitored by thermographic methods is expected to be useful as diagnostic factor in evaluation of the degree of fatigue degradation.

Described research programme comprises two stages. In the first stage sets of samples were subjected to fatigue in double-sided three point bending with constant deflection amplitude (Fig. 2). Fatigue was performed using fatigue machine our own construction. To achieve mononomial stress distribution in sample's cross section, two samples ((a) and (b) in Fig. 2) were tested together with a interlayer of high density polyethylene between them (c). Samples and interlayer were mounted together by bolts (1) to avoid mutual sliding. Constant strain (deflection) type of fatigue with 3mm deflection was used. The frequency (0,8 Hz) was chosen in such a manner that testing specimens were not heated due to energy dissipation. Sets of samples were subjected to different number of fatigue cycles. Maximum 1 930 000 fatigue cycles were realized.

In the second stage of research programme thermographic experiment was performed. Sets of testing specimens after established number of fatigue cycles were heated individually during 40 seconds time. Infrared radiator was used as samples heater. To enhance heat absorption, heated side of specimen was painted using matt black paint. Testing specimens were placed at the constant distance of 78 mm from the source of heat. After 40 seconds of heating the heater was removed and temperature increase on the opposite side of testing sample was measured using precise thermovision camera INFRAMETRICS type 76B, USA. Schematic diagram of testing stand is presented in Fig. 3.

Thermographic images after different time were recorded. From this images temperature at the central point of the sample was automatically calculated with the help of the computer software.

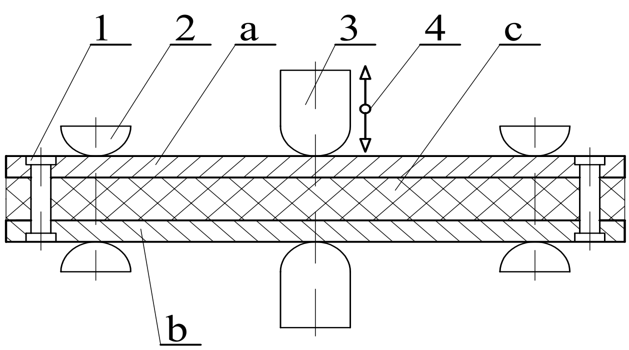

Fig. 2. Fatigue testing arrangement of samples and supports: a, b – samples, c – high density polyethylene interlayer, 1 – bolt, 2 – support, 3 – grip, 4 – direction of deflection

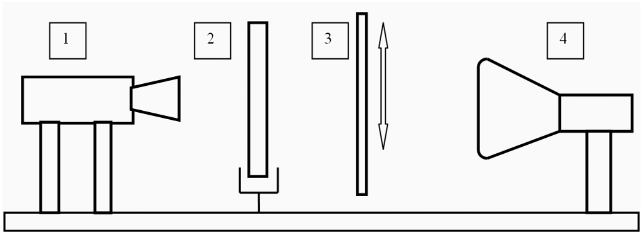

Fig. 3. Schematic draw of thermovision research stand. 1 – thermovision camera, 2 – sample, 3 – removable shield, 5 – infrared radiator

2.3. Results

It is not possible to present all thermographic images and temperature measurement results so only chosen examples will be shown. Fig. 4 presents temperature changes at one, central point on the side of the sample opposite to the heated one. This curve was prepared for sample not subjected to fatigue degradation. Next photographs (Fig. 5, 6, and 7) show termographic images taken 1 second, 10 seconds and 20 seconds after the beginning of temperature measurement for the same sample.

For the second example a sample after 1 190 000 fatigue cycles was chosen. Fig. 8 presents temperature changes at the same central point as in previous example. The subsequent photographs (Fig. 9, 10, and 11) show termographic images taken 1 second, 10 seconds and 20 seconds after the beginning of temperature measurement for the second example.

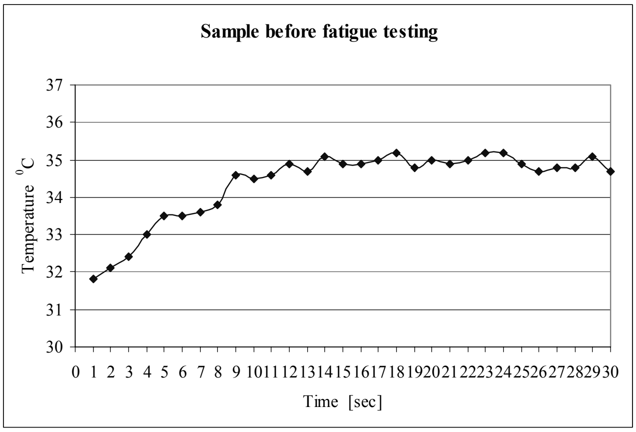

Fig. 4. Temperature changes with time after the end of heating for sample before fatigue testing

Curves presented in Fig. 4 and Fig. 8 and all other analogues dependences allowed to distinguish initial stage of temperature changes where temperature increases almost linearly with time. The rate of temperature increase is different for different number of fatigue cycles. Three such dependencies for the 10 initial seconds of temperature measurement are presented in Fig. 12.

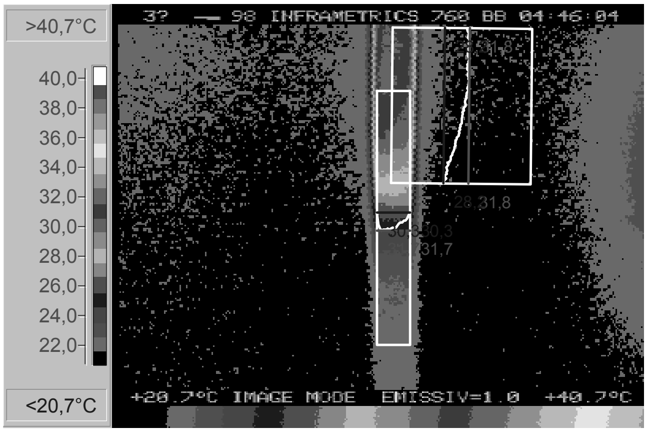

Fig. 5. Thermograph of sample before fatigue testing 1 second after the beginning of temperature measurement

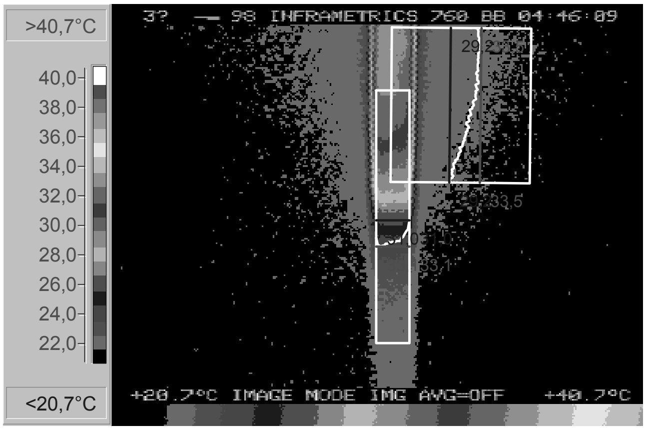

Fig. 6. Thermograph of sample before fatigue testing 10 seconds after the end of heating

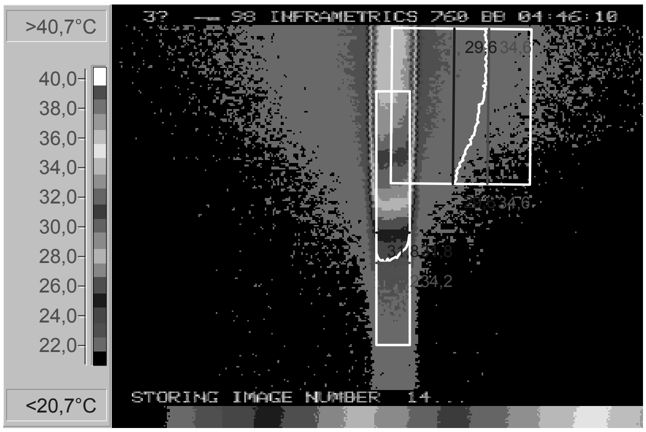

Fig. 7. Thermograph of sample before fatigue testing 20 seconds after the end of heating

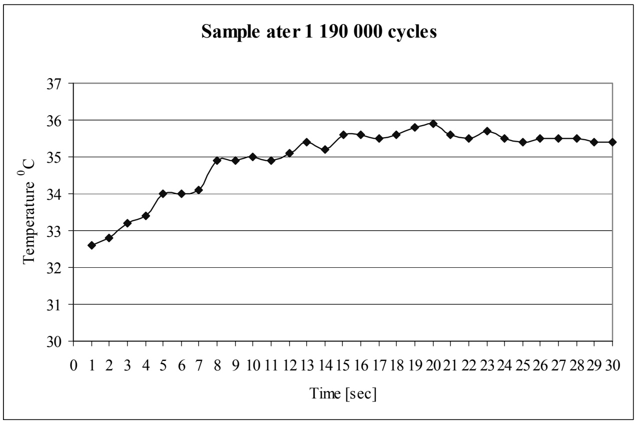

Fig. 8. Temperature changes with time after heating for sample subjected to 1 190 000 fatigue cycles

Fig. 9. Thermograph of sample subjected to 1 190 000 fatigue cycles 1 second after heating

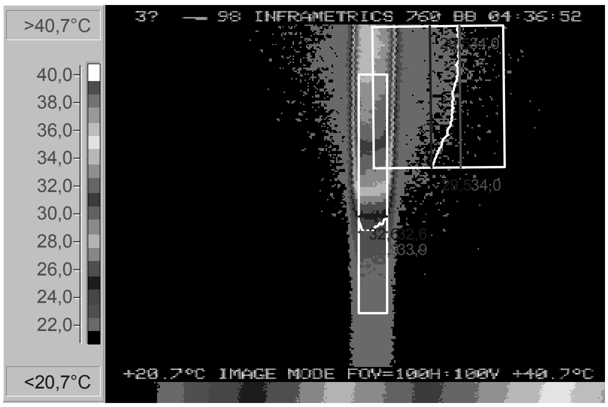

Fig. 10. Thermograph of sample subjected to 1 190 000 fatigue cycles 10 seconds after heating

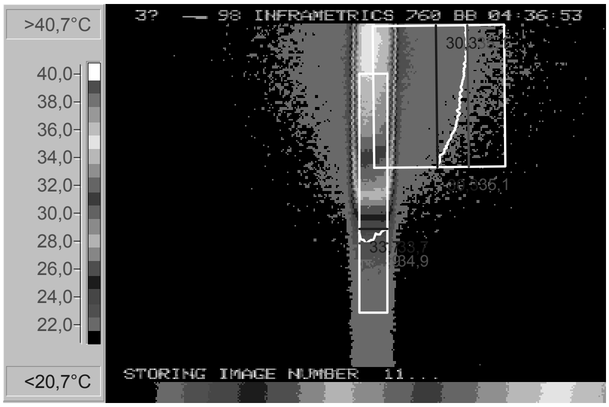

Fig. 11. Thermograph of sample subjected to 1 190 000 fatigue cycles 20 seconds after heating

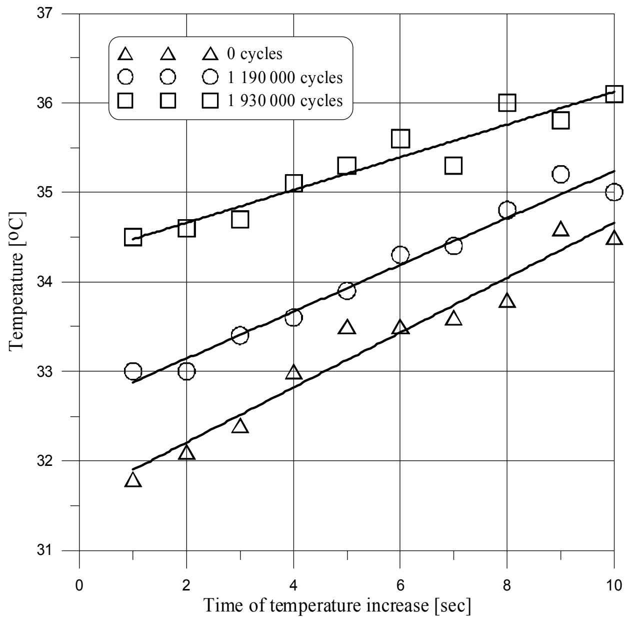

Fig. 12. Temperature increase in the first 10 seconds of temperature measuring procedure

Linear approximations for shown dependencies were the following:

- For 0 fatigue cycles: T = 0.307 x t + 31.59
- For 1 190 000 fatigue cycles: T = 0.262 x t + 32.62
- For 1 930 000 fatigue cycles: T = 0.183 x t + 34.29

where: T - temperature and t – time.

Very good correlation between temperature and time was achieved. Values of correlation coefficient were between 0,96 and 0,985.

The differences of curves inclination mean differences in rate of temperature increase what may be accepted as a measure of changes of composite thermal properties due to fatigue degradation. The dependence of rate of temperature increase on number of fatigue cycles is presented in Fig. 13.

Least square approximation gave the following relation:

rT = - 4.399E - 008 x N + 0.303

where: rT – rate of temperature increase, N – number of fatigue cycles.

Achieved coefficient of correlation was 0,765. It is satisfactory taking into account that the research had a preliminary character. Presented results will be utilized to elaborate full experimental and theoretical programme on application of thermography in diagnosis the degree of thermal and fatigue degradation of polymer composites.

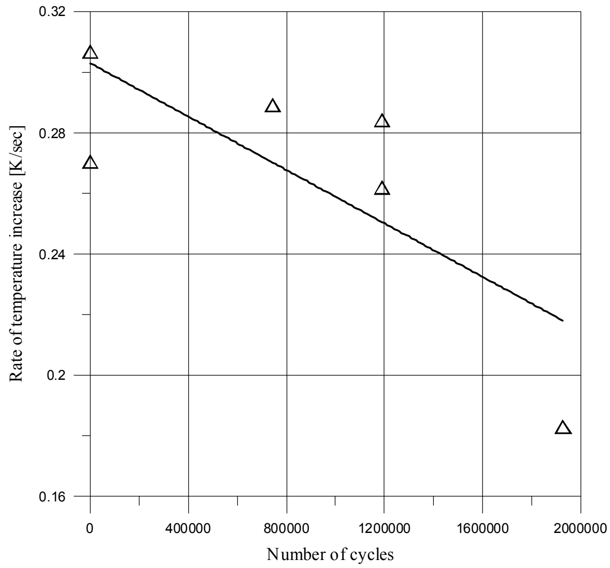

Fig. 13. Dependence of temperature increase rate on number of fatigue cycles for epoxy-glass composite TSE-6

4. Conclusions

1. Fatigue degradation of epoxy-glass composites caused decrease of its thermal conductivity. Changes of thermal conductivity can be indirectly determined with thermography help.
2. Analysis of the dependence between rate of temperature increase and the number of fatigue cycles allowed to establish correlation satisfactory in the view of diagnosis procedures.
3. Further research results are needed to elaborate more precise relations and diagnostic procedures for evaluation of polymer composites degradation degree.

References

[1] M. Rojek, J. Stabik, S. Sokół, Fatigue and ultrasonic testing of epoxy-glass composites, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 183-186.

[2] G. Wróbel, Ł. Wierzbicki, Ultrasonic methods in diagnostic of glass-polyester composites, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 203-206.
[3] S. Ochęduszko, Applied thermodynamics, .WNT, Warsaw 1970 (in Polish).
[4] E.H. Wichmann, Quantum Physics, PWN, Warsaw 1973 (in Polish).
[5] S. Poloszyk, Active thermovision in non-destructive testing, Proceedings of the Conference Manufacturing'01 Vol. 2 (2001) 221-228 (in Polish).
[6] W. Oliferuk, Active thermovision in non-destructive testing of materials, Proceedings of the XII Conference Non-destructive testing of materials Zakopane (2006), 10-25.
[7] D. Bates, G. Smith, D. Lu, J. Hewitt, Rapid thermal non destructive testing of aircraft components, Composites B 31 (2001) 75-185.
[8] N.P. Avdelidis, B.C. Hawtin, D.P. Almond, Transient thermography in the assessment of defects of aircraft composites. NDT and E International 36 (2003) 433-439.
[9] N.P. Avdelidis, C. Ibarra-Castanedo, X. Maldague, Z.P. Marioli-Riga, D.P. Almond, A thermographic comparison study for the assessment of composite patches, Infrared Physics and Technology 45 (2004) 291-299.
[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. Meola, G.M. Carlomagno, L. Giorleo, Geometrical limitations to detection of defects in comosite by means of infrared thermography, Journal of Nondestructive Evaluation 23 (2004) 4-8.
[12] N. Rajic, Principal component thermography for flaw contrast enhancement and flaw depth characterization in composites structures, Composite Structures 58 (2002) 521-528.
[13] C. Santulli, IR thermography study of the effect of moulding parameters on impact resistance in E-glass/polypropylene commingled laminates, NDT and E International 35 (2002) 377-383.
[14] D. Bates, G. Smith, D. Lu, J. Hewitt, Rapid thermal non destructive testing of aircraft components, Composites B 31 (2000) 175-185.
[15] C. Meola, G. M. Carlomagno, A. Squillace, A. Vitiello, Non-destructive evaluation of aerospace materials with lock-in thermography, Engineering Failure Analysis 13 (2006) 380-388.
[16] T. Uhl, Dynamic thermography as a construction diagnosis tool, Proceedings of the XLVI Conference Modelling in mechanics Wisła (2007) (in press).
[17] TSE-6 Product Data, Izo- Erg Gliwice, Poland (2006) – www.izoerg.com.pl .
[18] G. Muzia, Z. Rdzawski, M. Rojek, J. Stabik, G. Wróbel, Thermovision diagnosis of the degree of fatigue degradation of epoxy-glass composites, Proceedings of the XLVI Conference Modelling in mechanics, Wisła 2007 (in press).