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A model of heat transfer in composites subjected to thermographic testing

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ABSTRACT

Purpose: The aim of the paper is to present a model of heat transfer taking place during thermovision testing of polymer composites. The purpose of thermographic tests was to identify thermal properties of searched material and to correlate them with working characteristics.

Design/methodology/approach: Heat transfer model of composite samples mounted in thermographic test stand of our own design was elaborated. The model was applied as a tool of tested material characteristics identification and forming the basis of laminate degradation degree diagnosis.

Findings: The most essential result of the project is the physical and numerical heat transfer model. Good conformity between model predictions and exemplary experimental results was achieved.

Research limitations/implications: Experimental results of heat transfer through the composite mounted in thermographic testing stand proved the correctness of developed model. Results of physical properties identification showed the possibility of non-destructive diagnosis of wide class of materials.

Practical implications: Results of presented project together with results of planned experimental programme devoted to elaboration of diagnostic relations enable to apply thermography directly to the state of polymeric structural materials assessment.

Originality/value: Originality of the project is based on possibility of practical application of the model to simulate heat transfer through tested sample mounted in thermographic test stand. Proposed method of diagnostic tests was not interesting for scientists till now.

Keywords: Polymer composite; Thermovision; Diagnostics; Degradation

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Thermovision is widely used as non-destructive method of materials testing [1-9]. Thermovision diagnosis makes use of time and space characteristics of object surface temperature distribution. This temperature may be a result of thermal processes taking place in object in working conditions (passive thermography) or may be a result of thermal activation (active thermography). The purpose of all diagnosis techniques is to evaluate hazardous changes of object properties due to degrading processes [10-14]. In the present project samples of epoxy-glass composite were subjected to thermal ageing. Next physical model of heat transfer in sample heated and cooled in thermovision test stand was worked out. On the basis of physical model a numerical model was elaborated. Degraded composites were tested using thermography and finally experimental results were compared with numerical predictions.

2. The model of heat transfer process

The model of heat transfer in composite sample mounted in thermographic test stand and assumed boundary conditions are shown in Fig. 1. Because of sample symmetry only one half was modelled. The heat transfer process through test piece is non-stationary. Two characteristic phases of thermal process were: thermal activation by IR heating and cooling down stage.

Experimental schedule assumed the following possibilities: (a) Thermal activation of test piece in the constant and defined conditions; (b) Thermovision registration of surface temperature distribution; (c) Finding the temperature distribution properties highly correlated with functional characteristics of tested material; (d) Elaboration of empirical diagnostic functions relating temperature distribution characteristics and functional properties of searched materials. This characteristic will be called in the following text the ‘thermographic characteristic’.

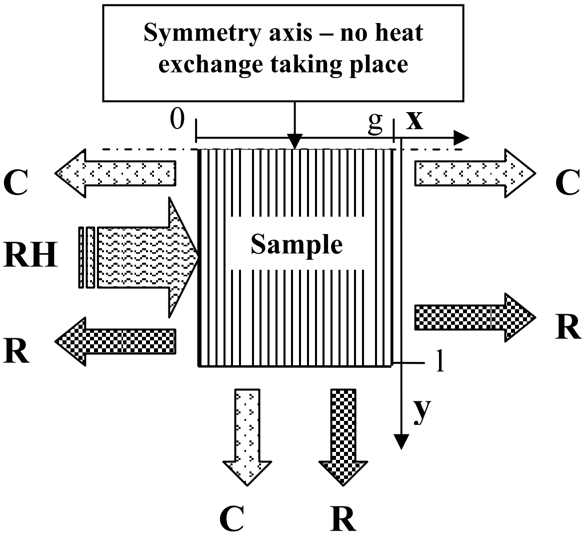

Fig. 1. The modelled half of sample cross section; RH – heater radiation flux, C – convection flux, R – sample radiation flux

Before activation the test piece is in thermal equilibrium with environment. Together with the test piece exposition to heater begins heat exchange with environment. The dominant form of heat exchange is radiation [15-17]. Instantaneous heat flux absorbed by the test piece is the result of thermal balance of the radiator heat flux reaching the surface of the test piece, Φ_H, and heat flux resulting from heat exchange with environment, Φ_E:

$$\Phi = \Phi_H + \Phi_E \tag{1}$$

Locally similar balance can be written for radiation in chosen point on the surface of the sample, P:

$$E(P) = E_H(P) + E_E(P) \tag{2}$$

Radiation intensity from point P to environment $E_E(P)$, assuming that surface is black body, according to Stefan – Boltzmann law, is equal:

$$E_E(P) = \varepsilon_1 \cdot \sigma_o \cdot T^4 \tag{3}$$

where $\sigma_0 = 5{,}7 \cdot 10^{-8}\,\mathrm{W/m^2K^4}$ is black body radiation constant, ε_1 is the surface emissivity at the point P and T is the thermodynamic temperature.

Radiation intensity $E_H(P)$ of energy going from the heater and reaching the point P determines the energy reaching this point relative to area dF_P around point P. Total energy radiated by heater surface with area, F, (Fig 2.) may be written as:

$$Q = E_R \cdot F \cdot \psi \tag{4}$$

where E_R is radiation intensity of heater surface in temperature, T_R, and characterized by surface emissivity, ε_2,

$$E_R = \varepsilon_2 \cdot \sigma_0 \cdot T_R^4 \tag{5}$$

The symbol Ψ in eq.4 denotes the configuration coefficient:

$$\psi = \frac{1}{F}\iint_{FF_P} \frac{\cos^2\varphi \, dF}{\pi r^2} dF_P \tag{6}$$

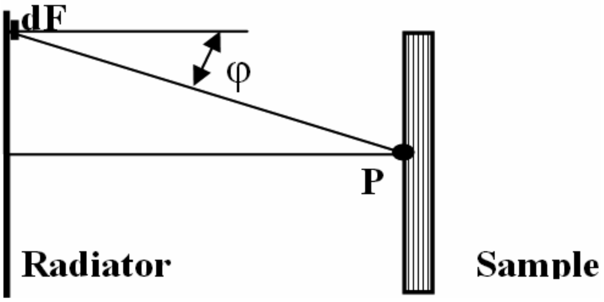

Fig. 2. Schema of heater and test piece arrangement

Radiation intensity $E_H(P)$ can now be written as

$$E_H(P) = \frac{dQ}{dF_P} = E_R \int_F \frac{\cos^2\varphi}{\pi r^2} dF \tag{7a}$$

$$E_H(P) = \varepsilon_2 \cdot \sigma_0 \cdot T_R^4 \int_F \frac{\cos^2\varphi}{\pi r^2} dF \tag{7b}$$

Resultant radiation intensity around point P, taking into account eq.(2) and (7), is equal:

$$E(P) = \varepsilon_1\varepsilon_2\sigma_0(T_R^4 - T^4)\int_F \frac{\cos^2\varphi}{\pi r^2} dF \; - \varepsilon_1\sigma_0 T^4 \tag{8}$$

Assuming that radiation is the only form of heat exchange at this stage, we can assume also that radiation with intensity E(P) on test piece surface transforms into heat flux q(P). The temperature of test piece surface, T, changes during activation process, so also q(P) and E(P) change with time, t:

$$q(P) = q(P,t) = E(P,t) \tag{9}$$

The heat flow within the test piece according to Fourier’s law is:

$$\nabla^T(k\nabla)T + (Q - c_P \cdot \rho \frac{\partial T}{\partial t}) = 0 \tag{10}$$

where: k – anisotropic thermal conductivities matrix, Q – thermal power of heat sources (the rate of heat generation within test piece volume), c_P – specific heat, ρ – material density.

Assuming that in the sufficient volume around the point P boundary conditions (9) are homogeneous (heating intensity , q, is the same), we may describe heat transfer in the test piece as unidirectional and proceeding in the direction normal to heated surface. In this case eq. (10) may be simplified to the form:

$$k\frac{\partial^2}{\partial x^2}T + (Q - c_P \cdot \rho\frac{\partial T}{\partial t}) = 0 \tag{11}$$

where x is coordinate as in Fig. 1. Convection flux density, q_k, at the sample surface is equal:

$$q_k = \alpha_k (T - T_e) \tag{12}$$

where α_k is the surface convection heat conductance and T_e is the environment temperature.

Equation (11) together with conditions (9) and (12) describe the activation stage. We designate the time of the activation as Δt_1. The end of this stage is the beginning of cooling down stage. For the second stage the boundary condition (9) must be changed. Rewriting eq. (8) for this stage, only radiation of test piece surface to environment have to be taken into consideration:

$$q(P,t) = E(P,t) = \varepsilon_1 \cdot \sigma_0 \cdot T(t)^4 \tag{13}$$

Thermal process taking place at this stage is described by eq.(11) together with (12) and (13) at x=0 and x=g (Fig. 1.).

3. Numerical procedure

Numerical calculations were conducted using finite differences method [18, 19]. A special computer programme was written in language C++. Using the programme the heat flow at the central cross section of the sample was modelled. Boundary conditions assumed for heating stage are shown in Fig. 1. At cooling stage radiation flux (RH) was turned off. At the beginning of calculations the following values of density, specific heat and conductivity were assumed (according to literature and producer data): $\rho=1{,}89\ g/cm^3$; c_P = 852,9 J/(kg K); k = 0,575 W/(m K). Taking into account differences in sample heating due to distance differences between point P and heater surface element dF (see Fig. 2.), it was assumed that this heat flux was distributed on the sample wideness according to the following distribution function:

$$q = q_0 + q_1 \cdot \frac{l^2 - y^2}{l^2} \tag{14}$$

where: $q_0 = -8{,}8\frac{kW}{m^2}$, $q_1 = -2{,}2\frac{kW}{m^2}$, l = 10mm,

y – coordinate as shown in Fig. 1.

Elaborated model allowed to determine the temperature distribution in arbitral point within sample volume and at its surfaces.

4. Application of the model to degradation process diagnosis

Epoxy-glass laminate (TSE-5, IZO-Erg, Poland) was subjected to thermal ageing at temperatures: 200, 220 and 240°C in time up to 2600 hours. Next aged samples were tested with thermovision camera (Fig. 3.). In termovision test stand samples were heated 20 sec. with 500W infrared radiator (Elstein HTS/2). Thermovision images were registered using Inframetrics 760 camera.

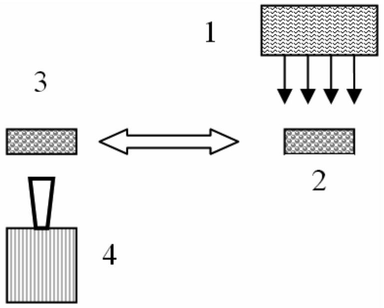

Fig. 3. Termovision test stand: 1 – IR heater, 2 – the sample in heating position, 3 – the sample in temperature scanning position, 4- thermovision camera

Presented model was applied to evaluate the influence of structural changes caused by degradation on chosen diagnostic thermographic characteristics [20-22]. Research project assumed possibility of determination the thermographic characteristic highly correlated with diagnosed material characteristics. The range of possible solutions is very wide. It is determined by all experimental conditions and also by type and parameters of searched characteristic. It confirms the necessity of searching described effective thermographic characteristic with the help of numerical model simulating heat transfer process.

The purpose of the project was to define experimental conditions for which searched diagnostic relation was the most explicit. It was assumed that diagnostically effective thermographic characteristic had to be defined for time dependent temperature distribution measured at surface opposite to heated one. This distribution was among others affected by material thermal properties. For the purpose of described research the temperatures at the central point of the sample were the most important. These temperatures allowed to plot curves describing temperature increase with time. Fulfilment repeatability conditions allows to expect that differences in thermal processes registered by thermovision camera were the result of changes of thermal properties of material so the hypothesis that thermographic characteristics are correlated with material characteristics seems to be justifiable.

All experimental parameters together with material data, test stand characteristics and geometry were introduced into the physical heat transfer model described in section 2 and numerical model presented in section 3. Described heat transfer model for test stand was verified for composite comparing numerical values with those achieved using thermography.

Example of measured and numerically calculated temperatures at the central point of the surface opposite to heated one for sample aged 1992 hours in 240°C are presented in Fig. 4. The following features of achieved dependences were analyzed: the moment of the beginning of temperature increase, the rate of temperature increase and the maximum value of temperature. The conformity of numerical with experimental results was achieved by selection of physical characteristics of material such as thermal conductivity, k, specific hest, c_P, and surface emissivity, ε_1.

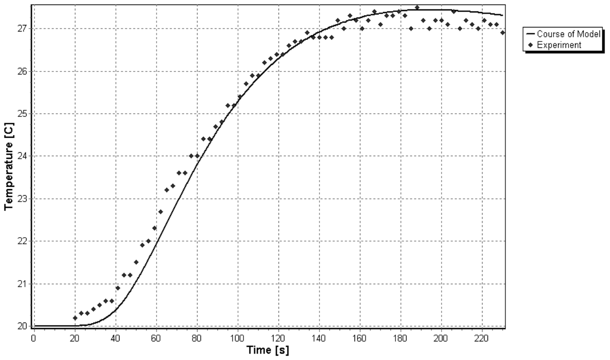

Fig. 4. Comparison of calculated (solid line) and measured (dots) temperatures of the sample aged 1992 hours at temperature 240°C

The main result of ageing was the thermal conductivity coefficient (k) change. For non-aged samples the best accordance between calculated and measured temperatures was achieved when k = 0,35 W/(m K), for samples aged at 200°C it was k = 0,31 W/(m K) and analogues value for sample aged at 240°C was k = 0,27 W/(m K). The results clearly showed that the higher is temperature of ageing the lower is thermal conductivity of epoxy-glass composite. It is in accordance with what was expected because thermal ageing is one of processes resulting in dispersed micro-defects formation in composite volume.

5. Conclusions

- Elaborated physical and numerical model allowed to determine the temperature distribution in arbitral point within sample volume and at sample's surface.
- Results of numerical simulation and results achieved using thermovision camera were in good conformity.
- The results showed that the higher was temperature of ageing the lower was thermal conductivity of epoxy-glass composite.
- The possibility of non-destructive thermovision evaluation of thermal properties of structural materials was proved.

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