INFLUENCE OF THE SELF-HEATING EFFECT ON FATIGUE OF POLYMERIC LAMINATES

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Abstract

The paper deals with investigation of influence of self-heating effect on the fatigue process of polymeric laminates. Depending on excitation parameters the self-heating temperature could rises following two scenarios and initiate mechanical fatigue or thermal fatigue. The experimental research was carried out in order to describe dependencies between self-heating temperature, excitation parameters and fatigue life of polymeric composites during cyclic excitation. Basing on experimental results the characteristic phases of thermal fatigue and parametric dependencies were discovered. The results of analyzes make possible development of new empirical models of fatigue and with some theoretical assumptions developed in previous studies – the new theoretical-empirical model of thermal fatigue of polymeric composites.

1 Introduction

High requirements to modern complex devices in engineering practice have recently compelled many researchers to pay attention to the maintenance and life prediction of polymeric composite materials applied in such devices. Many elements of machines made of polymeric composites have been subjected to the high-magnitude cyclic stresses, which could be a reason of heating-up of the structure and degradation intensification. The heating-up process is caused by out-of-phase oscillations between stress and strain amplitudes due to the viscoelastic nature of the most of polymers. During these oscillations the hysteresis phenomenon occurs and the most of dissipated energy is converted into heat. Depending on excitation parameters and thermomechanical properties of the structure the generated heat could be stored in the structure and initiate the self-heating effect when the self-heating temperature increases.

The heating-up process in such conditions always influence on structural characteristics and mechanical properties and thus on fatigue and life cycle of the structure. Depending on excitation parameters the fatigue process could progress following two scenarios. In the case when the self-heating temperature rise is inconsiderable and stabilizes in a short time the mechanical fatigue intensified by temperature is occurred. However, in the case when rapid heating-up is observed the self-heating effect dominates the fatigue process and thermal fatigue is occurred [1,2]. Research in this area shows, that in the case of thermal fatigue occurrence the life cycle of the structure drops rapidly and the self-heating effect may cause a breakdown in a short time. Therefore, it is necessary to investigate the character of self-heating temperature evolution, find potential physical aspects, which influence on the process of thermal fatigue and discover parametric dependencies between self-heating temperature and physical properties, excitation and environmental parameters and life cycle of the investigated structures.

In this paper, based on experimental results and previous theoretical studies [3,4], the description of thermal fatigue was presented. The experiments were carried out on glass/epoxy specimens subjected to cyclic bending loading with use of own designed laboratory setup. The parameters of empirical models developed basing on experimental results were used for analysis of parametric dependencies of self-heating temperature evolution. It was observed, that there is a critical self-heating temperature, which determines the initiation of damages in the structure and which is connected with characteristic temperatures of materials with a set of excitation parameters (e.g. glass-transition temperature). In additional experiments the nature of irreversible structural changes caused by self-heating effect was investigated and discussed. Obtained results allow to develop theoretical-empirical model, which consider the self-heating effect in all phases of fatigue of polymeric laminates.

2 Materials and experimental setup

The matrix of a laminate used for the tests was manufactured from a mixture of two commercial compounds: BPA and TBBA and reinforcement in the form of plane weave E-glass fibre. The laminated sheets were cut for specific dimensions of the specimens: width of 10 mm, thickness of 2.5 mm and four variants of effective length (i.e. the length of specimens without parts mounted in the holders) of 40, 45, 50 and 55 mm. The strength properties of manufactured specimens were as follows [5]: tensile strength of 415 MPa, flexural modulus of 24203.61 MPa and flexural strength of 633.2 MPa. The specimens were loaded cyclically in a cantilever bending mode on three excitation frequencies: 20, 25 and 30 Hz.

The experiments were carried out on own designed laboratory stand. The scheme and the picture of experimental setup were presented in Figure1.

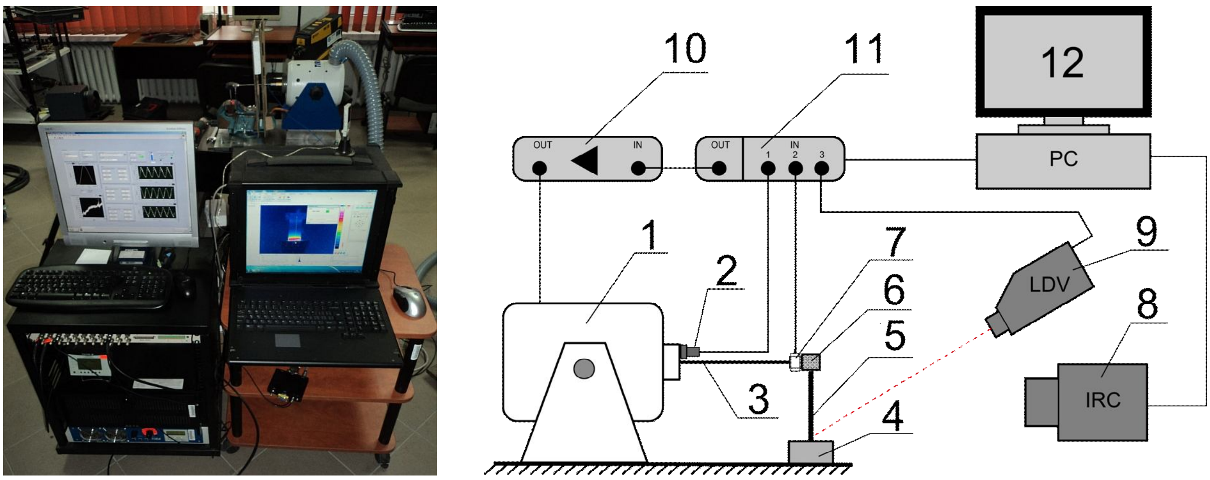

Figure 1. Picture and scheme of experimental setup.

The experimental stand consists of following devices. As it was shown on Figure 1, a tested specimen *5*, was clamped in a specimen holder *4* and excited by electrodynamic shaker *1* through the stinger *3* ended by holder *6*, connected with a stinger through the force sensor *7*. Specimen holder *4* was made of bakelite for ensuring thermal insulation of heat generated by the specimen during experiment. Each specimen was clamped with a constant torque of 20 Nm, which allowed mounting of the specimens with repeatable conditions. Excitation was measured by the accelerometer *2*. Additionally velocity of vibration near the clamp *4* was measured by single point laser Doppler vibrometer (LDV) *9*. The aim of vibration measurements in clamping point was the acquisition of signals for further elaboration of composite diagnostic method. Force and vibration sensors were connected through the conditioning modules to multi-channel data acquisition module *11*, connected to PC *12* and controlled by Labview® application. Signals were acquired with a sample rate of 8 kHz. The application allows to controlling excitation signal parameters through analog output of the multi-channel signal acquisition module and drives a shaker amplifier *10*. During each test, variations of temperature distribution on the specimens' surface were observed using of infrared camera (IRC) *8*. Sequences of infrared images were recorded for every specimen with a frame rate of 1 frame per second. On the basis of acquired images, it was possible to determine different temperature characteristics along observation time. The specimens before tests were painted black in case of increasing emissivity and reduce reflectivity. Specimen's emissivity was estimated experimentally and set to 0.9. Infrared observations were time-synchronized with other measured signals.

3 Analysis of experimental results

3.1 Determination of thermal fatigue phases

According to results of conducted experimental studies it was observed that fatigue and self-heating temperature evolution of polymeric composites may develop following two scenarios. In the first case the self-heating temperature grows until reaching the steady-state and after some time the breakdown of a specimen occurs due to the mechanical fatigue process without further growth of temperature. The self-heating temperature stabilization is caused by equalizing of amounts of dissipated energy resulted by hysteresis and energy convected to the environment. Such a scenario is called mechanical fatigue. In the second case the self-heating temperature grows exponentially, than the slight linear temperature growth could be observed and finally rapid temperature growth occurs until the breakdown of a specimen. Such a scenario is called thermal fatigue. A typical self-heating temperature evolution during thermal fatigue was presented in Figure 2.

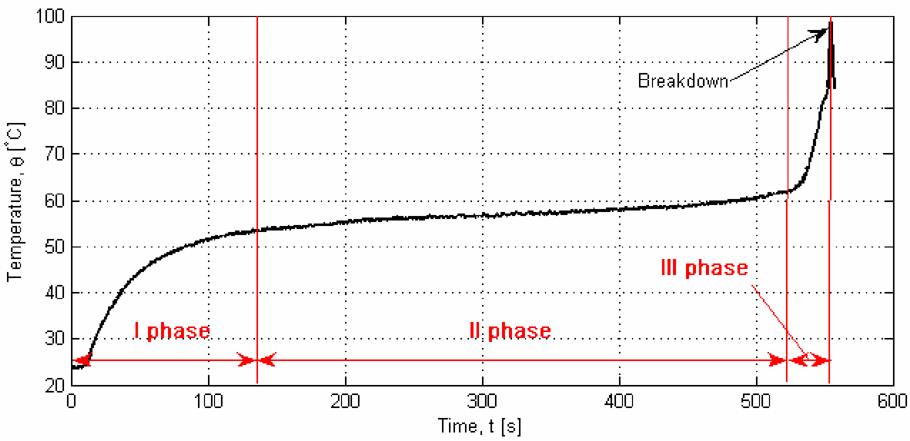

Figure 2. Typical self-heating temperature evolution during thermal fatigue.

Analyzing fatigue process by evolution of self-heating temperature it could be noticed that three phases of thermal fatigue are clearly detectable. These phases could be described in terms of temperature-dependent evolution of dynamic moduli. In the first phase the typical self-heating temperature growth was observed, which is accompanied with drop of storage modulus and increase of loss modulus. After equalizing of amounts of dissipated and convected energy at the beginning of a second phase the slight temperature growth, which has a linear character. In this phase the mechanical fatigue occurs and the temperature growth is resulted by mechanical degradation of a composite. In this phase both mechanical and thermal degradation occurs. In the third phase the self-heating temperature grows rapidly in a short time period until breakdown. Usually the third phase started due to initiation of cracks in the area of stress concentration and thus the highest temperature. The crack occurrence intensifies the temperature growth due to the additional heat from friction in a crack. The breakdown occurs, when the temperature in the specimen reaches the glass-transition temperature.

3.2 Parametric analysis of temperature evolution

In order to investigate the influence of excitation frequency and the specimens' length on values of self-heating temperature sequences of infrared images were analyzed. The analysis was performed basing on the evolution of maximal temperature in the point near the holder *4*. The double-exponential model, applied previously in [4], was used for approximation:

$$\theta(t) = C_1 \exp(F_1 t) + C_2 \exp(F_2 t) \tag{1}$$

where $\theta(t)$ is a self-heating temperature depended on time t, C_i and F_i are parameters of the model. This function was chosen due to physical statements of the phenomenon and the best fitting to the experimental data. An exemplary fitting result was shown in Figure 3.

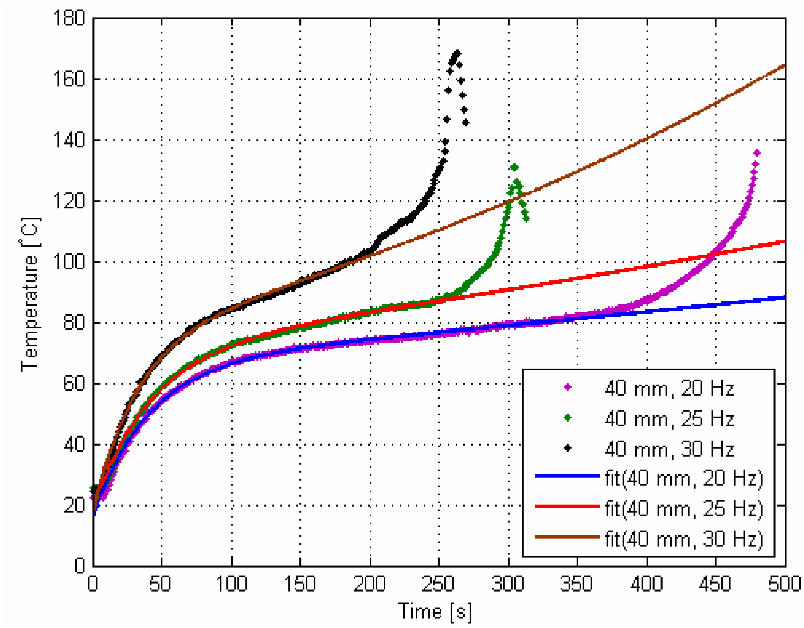

Figure 3. Exemplary results of fitting for different cases of excitation frequency.

Basing on model parameters (1) it was possible to describe dependencies of self-heating temperature evolution on specimens' length and excitation frequency. It was observed that during increase of excitation frequency parameters C_1 and F_1 increased, while parameters C_2 and F_2 decreased. In the case of increase of specimens' length all of the parameters reveal decay behaviour. The sum of C_1 and C_2 determines initial temperature of the self-heating process and parameters F_1 and F_2 determine the heating rate. Additionally, parameters C_1 and F_1 are responsible for temperature magnitude and heating rate in the second phase of fatigue, while parameters C_1 and F_1 influence on the temperature magnitude and heating rate in the first phase of fatigue. Moreover, it was observed that the moment of discrepancy between measurement data and fitting curves determines the end of second phase and beginning of the third phase of fatigue, which was also noticeable in infrared images by rapid concentration of isotherms in the area of crack occurrence.

3.3 Determination of critical self-heating temperatures

Basing on self-heating temperature evolution curves and results of approximation the characteristic temperatures were determined. It was observed, that the moment, when the approximation curve diverges with self-heating temperature evolution curve from measurements (at the end of second and beginning of third phase of fatigue) the crack is initiated, therefore this moment determines the critical self-heating temperature.

It was observed that there is a linear dependence between critical self-heating temperature and excitation frequency, which confirms previous experimental results [4] and theoretical models [3,4]. It should be noticed, that there is dependence between critical self-heating temperature and glass-transition temperature and following this values of critical self-heating temperatures were determined by excitation frequency and applied amplitude of stress/strain. In the case of temperature of breakdown the amount of temperature is determined by frictional heating of propagated crack, therefore the analysis of temperature evolution in the third phase of thermal fatigue is impossible based on presented data and needs performing of additional tests. However, it is possible to relate obtained values to the glass-transition temperatures determined in DMA experiments [5]. The glass-transition temperatures were determined from master curves of loss modulus for particular excitation frequencies and placed in the range 140÷150ºC. As it could be observed, the critical self-heating temperatures in some cases were about 2.5 times lower than glass-transition temperatures.

3.4 Theoretical-empirical model of thermal fatigue

The process of thermal fatigue consists of three phases, and every phase of fatigue is dominated by different physical phenomena, therefore every phase needs appropriate physical and mathematical description. In the first phase of fatigue the self-heating effect is dominated, therefore the temperature distribution could be described by heat transfer equation, where the dissipated energy could be presented as heat source function Q_d:

$$\lambda \nabla^2 \theta(X,t) = c\rho \frac{\partial \theta(X,t)}{\partial t}, \tag{2}$$

where λ is the heat conductivity coefficient, X is a quantity representing Cartesian coordinates, c is the heat capacity and ρ is the density of material. Using appropriate initial and boundary conditions the equation could be solved using the separation of variables method. Solving (2) with assumptions presented in [3] for non-stationary heat transfer the temperature distribution on the surface of rectangular specimen could be obtained in the form:

$$\theta(x,y,t) = \frac{4Q_d(x,y)}{\lambda} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\operatorname{sinc} \mu_m \operatorname{sinc} \gamma_n \cos \xi_m x \cos \xi_n y \left(1 - e^{-t\frac{c\rho}{\lambda}\left(\xi_m^2 + \xi_n^2\right)}\right)}{\mu_m \gamma_n \left(1 + \operatorname{sinc} 2\mu_m\right)\left(1 + \operatorname{sinc} 2\gamma_n\right)\left(\xi_m^2 + \xi_n^2\right)} + \theta_0, \tag{3}$$

where μ_m, γ_n, ξ_m, ξ_n are the coefficients depended on boundary conditions (see [3] for details), θ_0 is the ambient temperature and

$$Q_d = 3\pi f \varepsilon_{\max}^2 w^2(x,y) D''(f,\theta), \tag{4}$$

where f is an excitation frequency, $\varepsilon_{\max}$ is the maximal deflection, w is a deflection function and $D''(f,\theta)$ is the frequency- and temperature-dependent dynamic loss modulus, which could be determined from master curves presented in [5].

Basing on (4) the number of cycles of self-heating temperature stabilization n_a and its amount θ_a could be determined. From the experimental results it was determined that critical self-heating temperature θ_c depends on glass-transition temperature θ_g depended on excitation and environmental parameters. From the experimental results the function $\alpha(f)$, which represents slope of the self-heating temperature evolution curve in the second phase of fatigue was obtained. The number of cycles to achieving critical self-heating temperature could be determined as follows:

$$n_c = n_a + ctg\alpha(f)\theta_c(f)(\theta_a - \theta_0). \tag{5}$$

In the model (5) only two first phases of thermal fatigue were considered, because in the light of operation of composite elements in the moment of achieving the self-heating critical temperature the crack initiates, which discredited the element from the operation process.

4 Conclusions

Experimental study, which was carried out in order to investigate the influence of the self-heating process on fatigue of polymeric laminates makes possible to analyze the parametric dependencies of the self-heating temperature according to the sets of excitation and environmental conditions. It was observed, that the self-heating temperature evolution could be presented in three phases. Basing on the self-heating evolution curves the critical self-heating temperatures were determined and basing on theoretical assumptions and experimental data the new model for thermal fatigue was proposed. The model allows to predict the number of cycles of damage occurrence in the structure during cyclic loading and presence of the self-heating effect.

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