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COMPOSITES THEORY AND PRACTICE

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CRITICAL SELF-HEATING TEMPERATURE DURING FATIGUE OF POLYMERIC COMPOSITES UNDER CYCLIC LOADING

This paper deals with the results of an experimental study of the occurrence of the self-heating effect during cyclic fatigue loading of plates made of polymeric composites. The evolution of self-heating temperature distributions was registered by infrared camera from the beginning of loading till the breakdown of the specimens. During the experiments it was observed that the process of thermal fatigue of the composite elements could be divided to three phases. It was observed, that on the transition border of the second and third phases of thermal fatigue, a crack initiates, which is caused both by increasing the self-heating temperature and mechanical fatigue. This moment corresponds w to the value of self-heating temperature, which is critical for given loading parameters. The critical self-heating temperature is strongly dependent on the excitation frequency, which results from the tim-temperature superposition principle. The influence of the excitation frequency and length of the specimens on the value of critical self-heating temperature was investigated. Based on experimental data, the empirical model of thermal fatigue, which uses the master curve of dynamic storage modulus, was proposed. The obtained experimental results and proposed fatigue model could be used in operation and structural health monitoring problems for the prediction of critical loading parameters of elements made of polymeric composites.

Keywords: **polymeric layered composites, self-heating effect, critical self-heating temperature, thermal fatigue**

KRYTYCZNA TEMPERATURA SAMOROZGRZANIA PODCZAS ZMĘCZENIA KOMPOZYTÓW POLIMEROWYCH PODCZAS WYMUSZENIA CYKLICZNEGO

Artykuł przedstawia wyniki prac eksperymentalnych dotyczących obecności efektu samorozgrzania podczas cyklicznych obciążeń zmęczeniowych płyt wykonanych z kompozytów polimerowych. Zmienność rozkładów temperatury samorozgrzania była rejestrowana kamerą termowizyjną od początku obciążenia do zniszczenia próbek. Podczas eksperymentów zaobserwowano, że proces zmęczenia cieplnego kompozytów polimerowych może być podzielony na trzy fazy. Zaobserwowano, że na granicy drugiej i trzeciej fazy zmęczenia cieplnego inicjuje się pęknięcie, co jest spowodowane zarówno wzrostem temperatury samorozgrzania, jak i zmęczeniem mechanicznym. Ten moment odpowiada wartości temperatury samorozgrzania, która jest krytyczną dla danych parametrów obciążenia. Krytyczna temperaturura samorozgrzania wykazuje silną zależność od częstotliwości wymuszenia, co wynika z zasady superpozycji czasowo-temperaturowej. Zbadano wpływ częstotliwości wymuszenia i długości próbek na wartość krytycznej temperatury samorozgrzania. Na podstawie wyników eksperymentalnych zaproponowano model empiryczny zmęczenia cieplnego wykorzystujący krzywe wiodące dynamicznego modułu zachowawczego. Otrzymane wyniki eksperymentalne i zaproponowany model zmęczenia mogą być wykorzystane w zagadnieniach eksploatacji i monitoringu elementów wykonanych z kompozytów polimerowych w celu predykcji krytycznych parametrów obciążenia.

Słowa kluczowe: **polimerowe kompozyty warstwowe, efekt samorozgrzania, krytyczna temperatura samorozgrzania, zmęczenie cieplne**

INTRODUCTION

Dissipation processes in elements made of polymeric composites subjected to cyclic loading may have a great impact on their behavior and strength properties. Most of the dissipated energy during this process is transformed into heat. Considering the fact that most of the polymers used in engineering constructions are characterized by low thermal conductivity, the heat generated during prolonged cyclic deformations is stored inside the structure and the temperature grows, which initializes the self-heating effect. Previous experimental research [1] shows that the temperature during the cycle grows exponentially till it achieves a certain value and then stabilizes. In terms of the fatigue process, it could be considered as mechanical fatigue because the temperature does not grow after the stability point and only mechanical degradation of the structure is observed. However, in the case of some specific loading parameters, the self-heating temperature grows linearly after the first phase of exponential growth and influences the fatigue process as well. This phenomenon is called thermal fatigue [2, 3]. The temperature increase causes a decrease in the strength properties of a structure and intensifies the degradation process. During experiments it was observed that there is some critical value of the self-heating temperature after which crack occurrence and rapid heating-up until breakdown was noticed. The aim of the presented study is to investigate the influence of loading parameters on the amount of critical self-heating temperature and to determine other dependencies connected with this temperature.

The first experimental works on thermal fatigue were carried out by Ratner and Korobov [2, 4]. The authors describe the process by characteristic temperatures and empirical relationships based on self-heating curves. Then, the research on this phenomenon was continued by Oldyrev [5, 6] who proposed a kinetic approach based on the Zhurkov kinetic concept for evaluation of the fatigue life of composites considering the self-heating effect. Ferreira *et al.* [7] investigate the thermal fatigue phenomenon for glass-fiber reinforced polypropylene composites and evaluate fatigue life based on some kind of damage function from the ratio between the initial and actual stiffness. The same approach was used by the authors of [8]. They proposed a fatigue model based on stiffness reduction and analyzed the evolution of model material parameters regarding the self-heating temperature.

In this study, the problem of thermal fatigue was investigated experimentally in laboratory conditions. The evolution of self-heating temperature distributions was registered with the use of an infrared camera and based on obtained sequences of thermograms and then the analysis was performed. It was shown that the process of thermal fatigue could be divided into three characteristic phases, which coincides with the investigations presented in [5, 7, 8]. It was also noticed that the critical self-heating temperature coincides with fatigue crack initiation and the beginning of intensive degradation of a structure. For the evaluation of critical self-heating temperatures, the approximation model was proposed. Based on sets of model parameters, the influence of excitation frequency and specimen length was investigated. Finally, the empirical model of thermal fatigue was proposed with the use of data acquired in the experiment and the master curves of frequency-, temperature- and heating rate-dependent dynamic moduli presented in [9]. The proposed approach could be used for the prediction of fatigue life of polymeric composites and for determining critical loading parameters to prevent the occurrence of the self-heating effect.

EXPERIMENTAL SETUP AND SPECIMEN PREPARATION

Fatigue tests were carried out in order to identify the character of self-heating temperature evolution and determine the characteristic temperatures during the process. The specimens were made of the type TSE-2 epoxy E-glass laminate, which is characterized by a working temperature of 130ºC supplied by Izo-Erg S.A. in Gliwice. The laminate was made according to the requirements of European Standard EN 60893-3-2 and the results of the preliminary strength tests presented in [9] confirmed its strength properties. The dimensions of the prepared specimens were as follows: thickness of 2.5 mm, width of 10 mm and four variants of effective length (i.e. length of specimens without clamped parts) of 40, 45, 50 and 55 mm. The specimens were excited with three frequencies: 20, 25 and 30 Hz, which were selected in order to observe thermal fatigue. To ensure statistical repeatability, 20 specimens were tested for each set of parameters (effective length and excitation frequency), which gives a total of 240 specimens.

The experiments were carried out on a laboratory stand whose scheme is presented in Figure 1. The stand consisted of the following devices. A tested specimen - *5* was clamped in a specimen holder - *4* and excited by a electrodynamic shaker - *1* through a stinger - *3* with a specimen holder - *6* connected to a force sensor - *7* at the end. Specimen holder *4* was made of bakelite in order to provide thermal insulation of the heat generated during the tests. To ensure repeatable conditions, each specimen was clamped with a constant torque of 20 Nm. The excitation frequency was inspected by an accelerometer - *2*. The velocity of vibration of a specimen was measured near clamp *4* using a single point laser Doppler vibrometer (LDV) - *9*. The force sensor and LDV were connected through the conditioning modules to a multi-channel data acquisition module - *11*, connected to a PC - *12* and controlled by a LabView® application developed for this purpose. The force and vibration signals were acquired with a sample rate of 8 kHz. The application allows controlling of the excitation signal parameters through the analog output of multi-channel signal acquisition module *11* and drives a shaker amplifier - *10*. The temperature measurements were carried out using an infrared camera (IRC) - *8*, which was connected to a conditioning module through a break-out box for ensuring synchronization of all of the measured signals. The frame rate of the IRC was set to 1 frame per second.

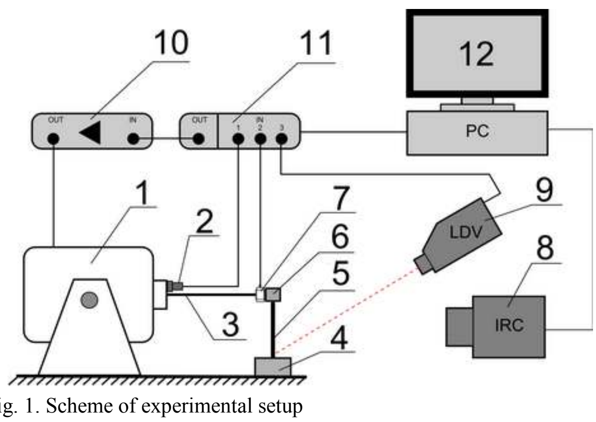

Fig. 1. Scheme of experimental setup

Rys. 1. Schemat stanowiska badawczego

The obtained signals were collected and converted to MATLAB® data files for further analysis. The sequences of thermograms were collected and analyzed using IRC-dedicated software - IRBIS®.

ANALYSIS OF EXPERIMENTAL RESULTS

According to the observation of self-heating temperature evolution during thermal fatigue, it was noticed that the process proceeds in three clearly separable phases. In the first phase an exponential temperature rise was observed, in the second phase the self-heating temperature grew linearly and in the third phase a rapid temperature growth was observed until the breakdown of the specimen. A typical temperature evolution during thermal fatigue is presented in Figure 2.

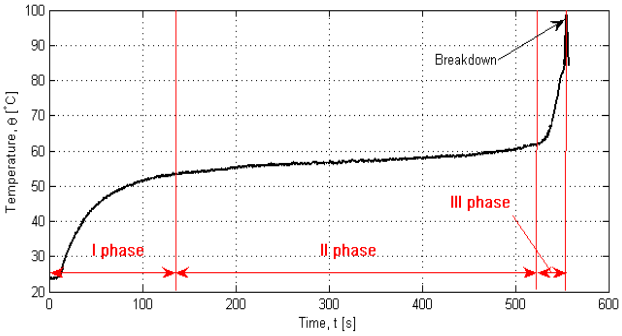

Fig. 2. Typical temperature evolution during thermal fatigue

Rys. 2. Typowa charakterystyka temperaturowa podczas zmęczenia cieplnego

The self-heating temperature evolution in particular phases of thermal fatigue could be described in terms of dynamic moduli. In the first phase, a typical exponential temperature growth is observed (for details see e.g. [1, 10]), which is connected with a drop in the storage modulus and an increase in the loss modulus caused mainly by the dissipation process. The second phase is characterized by a slight linear temperature growth caused by mechanical degradation of the structure intensified by the self-heating temperature. At the beginning of the third phase, rapid temperature growth is observed which is caused by crack occurrence in the hottest region. The temperature growth in this phase results from several phenomena: besides mechanical fatigue and the influence of the self-heating temperature, the friction in a crack intensifies the process as well. The breakdown occurs at a temperature which is near the glass-transition point. However, considering the effective operation properties of a composite, the critical self-heating temperature is always lower than the glass-transition temperature and could be assumed as the temperature at the end of the second phase of thermal fatigue at the moment of crack occurrence.

In order to investigate the influence of excitation frequency and the specimen length on the values of critical self-heating temperature, sequences of thermograms were analyzed. The analysis was performed based on the evolution of temperature at the point of intersection of temperature profiles *L1* and *L2*, as shown in Figure 3. The double-exponential model, applied previously in [1,10], was used for approximation:

$$\theta(t) = A_1 \exp(B_1 t) + A_2 \exp(B_2 t) \tag{1}$$

where t is time, A_i and B_i are the pre-exponential and exponential model parameters respectively. The acquired self-heating temperature evolution curves were fitted with a 95% confidence bounds based trust-region reflective Newton algorithm. Exemplary results for single length l_e of the specimens and various excitation frequencies f are presented in Figure 4. The model parameters were determined and tabulated in Table 1 together with the approximation accuracy σ for each case of parameters.

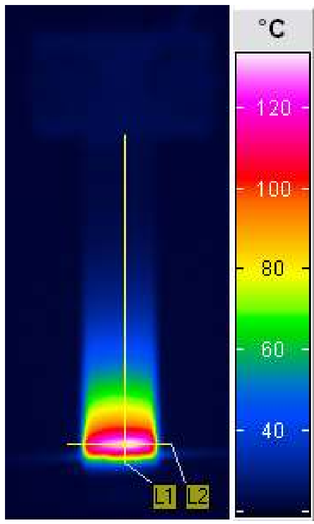

Fig. 3. Temperature profiles on specimen surface

Rys. 3. Profile temperaturowe na powierzchni próbek

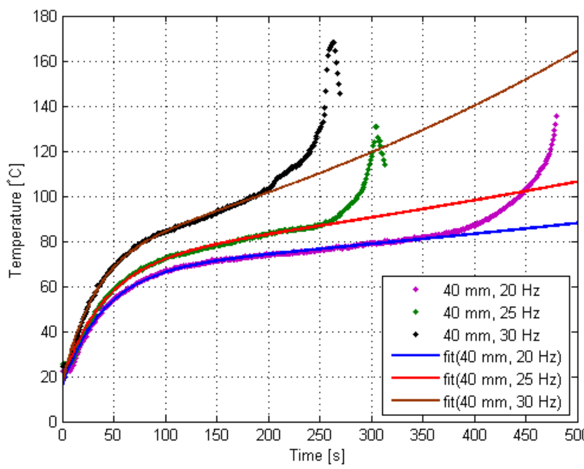

Fig. 4. Exemplary results of fitting for different cases of excitation frequency

Rys. 4. Przykładowe wyniki aproksymacji dla różnych przypadków częstotliwości wymuszenia

TABLE 1. **Model parameters**
TABELA 1. **Parametry modelu**

l_e [mm]	f [Hz]	A_1 [ºC]	B_1 [s^{-1}]	A_2 [ºC]	B_2 [s^{-1}]	σ [%]
40	20	66.75	0.0005517	–50.78	–0.02466	0.9971
	25	71.03	0.0008077	–52.32	–0.02354	0.9967
	30	73.91	0.001599	–56.9	–0.0315	0.9966
45	20	57.84	0.0004512	–39.96	–0.02842	0.9956
	25	62.56	0.0006852	–41.69	–0.02399	0.9983
	30	67.13	0.0007397	–48.94	–0.0277	0.9970
50	20	57.22	0.0001387	–37.15	–0.02348	0.9947
	25	59.32	0.0008112	–40.91	–0.02471	0.9983
	30	57.71	0.001166	–40.85	–0.02574	0.9985
55	20	55.30	0.0001808	–37.02	–0.02606	0.9926
	25	57.62	0.0004732	–38.59	–0.02582	0.9970
	30	59.13	0.0009015	–39.22	–0.02458	0.9983

Based on the parameters of model (1), the parametric dependencies were evaluated. It was noticed that during an increase in excitation frequency parameters, A_1 and B_1 increased, while parameters A_2 and B_2 decreased. In the case when the effective length increased, the entire model parameters reveal a decreasing tendency. The sum of parameters A_1 and A_2 determines the initial temperature of the process and parameters B_1 and B_2 determine the heating rate. Additionally, parameters A_1 and B_1 are responsible for the temperature value and heating rate in the second phase of thermal fatigue, while parameters A_2 and B_2 are responsible for the above-mentioned parameters in the first phase of fatigue. It was observed that the moment when the fitting curve diverges from the self-heating temperature evolution curve, this characterizes the end of the second phase of thermal fatigue and crack occurrence (which is also noticeable on thermograms in the form of concentration of isotherms in the area of crack occurrence). This moment determines the critical self-heating temperatures.

Following the observations made during the experiments, the critical self-heating temperatures θ_c and temperatures at the breakdown θ_b of the specimens with an accompanying numbers of cycles (n_c and n_b respectively) were determined and collected in Table 2.

Analyzing the results presented in Table 2, it was observed that there is a linear dependence of critical self-heating temperature on the excitation frequency, which confirms previous experimental results [1, 10] and theoretical models [10, 11]. It should be noticed that there is a dependence between the critical self-heating temperature and glass-transition temperature and following this, the values of critical self-heating temperatures were determined by the excitation frequency and applied amplitude of stress/strain. In the case of θ_b the amount of temperature is determined by the frictional heating of a propagated crack, therefore the analysis of temperature evolution in the third phase of thermal fatigue is impossible based on the presented data and needs additional testing . However, it is possible to relate the obtained values to the glass-transition temperatures determined in DMA experiments [9]. The glass-transition temperatures were determined from master curves of loss modulus for particular excitation frequencies and placed in the range 140÷150ºC. As could be observed, the critical self-heating temperatures in some cases were about 2.5 times lower than the glass-transition temperatures.

TABLE 2. **Characteristic temperatures and numbers of cycles during thermal fatigue**
TABELA 2. **Temperatury charakterystyczne i liczby cykli podczas zmęczenia cieplnego**

l_e [mm]	f [Hz]	θ_c [ºC]	n_c [-]	θ_b [ºC]	n_b [-]
40	20	80.06	6600	135.5	9602
	25	86.63	6200	130.9	7627
	30	98.69	5460	168.1	7923
45	20	68.53	7520	113.3	9762
	25	74.78	6550	121.3	8902
	30	77.07	5730	125.3	8283
50	20	59.93	6700	111.3	10222
	25	77.96	8425	108.2	10177
	30	78.56	7950	114.9	9513
55	20	59.21	7560	110.3	11400
	25	67.32	8225	121.0	11452
	30	75.03	7950	123.1	10500

For evaluation of the fatigue life of composites in thermal fatigue conditions, the damage function approach could be used. Such a concept in the light of stiffness degradation used for polymeric composites is often applied [8, 12-14] and could be classified as the Fitzgerald-Wang-type model [15]. The concept could be modified by replacing Young's modulus by dynamic storage modulus E', which makes it possible to take into account its functional dependencies on excitation frequency f, temperature θ and heating rate β following the time-temperature superposition principle and modified Arrhenius law presented in [9]. In the case when the dynamic material properties of a composite are known, e.g. in the form of master curves, the Fitzgerald-Wang model could be modified as follows:

$$S = 1 - \frac{E'(f,\theta,\beta)}{E'_0(f,\theta,\beta)} \tag{2}$$

where S is the damage function, which describes the degradation degree from 1 to 0 and E'_0 is the initial storage modulus. However, as experimental research shows, the breakdown occurs during $S(E'_0(f,\theta,\beta)) >> 0$, therefore equation (2) should take into account a critical value of storage modulus E'_c. This value could be determined from the storage modulus master curve for a given critical self-heating temperature. Equation (2) could be modified as follows:

$$S = 1 - \frac{E_0'(f,\theta,\beta) - E'(f,\theta,\beta)}{E_0'(f,\theta,\beta) - E_c'(f,\theta_c,\beta)} \quad (3)$$

Such a modification makes it possible to fit the bounds of the damage function to real conditions of thermal fatigue.

CONCLUSIONS

The experimental study on the thermal fatigue of polymeric composites was discussed in this paper. It was shown that the thermal fatigue process of such materials consists of three phases which are characterized by various phenomena occurring during each of them. The evolution of the self-heating temperature during thermal fatigue was analyzed with use of the double-exponential approximation model, which provides the best fit of the self-heating curves. Based on the results of approximation, a parametric analysis of the influence of the excitation frequency and specimen length on self-heating was carried out. The critical self-heating temperatures were determined based on the approximation results. It was noticed that the values of critical self-heating temperatures are related to the excitation frequency and glass-transition temperature. Based on the experimental results, an empirical model of thermal fatigue based on the damage function approach was proposed. Based on the parameter-dependent dynamic properties of the composite and appropriate values of the critical self-heating temperature, it is possible to evaluate and predict the fatigue life of polymeric composites during thermal fatigue.

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