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COMPOSITES THEORY AND PRACTICE

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# FATIGUE OF POLYMERIC COMPOSITES DURING STATIONARY AND NON-STATIONARY SELF-HEATING

**The self-heating effect occurring during the cyclic loading of materials that exhibit thermoviscoelastic properties, depending on the loading conditions, may develop according to two possible scenarios: stationary and non-stationary. Since stationary self-heating has not been not previously studied in terms of the criticality of the self-heating effect, it is essential to perform such a study to better understand the degradation processes in this scenario and to confront the results with the criticality of non-stationary self-heating. In the present study, the experimental results on fatigue testing following the stationary self-heating scenario are presented and discussed. In order to characterize the degradation process, both self-heating temperature distributions and their evolution as well as acoustic emission measured at various self-heating temperature ranges were analyzed. The obtained results allow the influence of the self-heating effect on the residual life of composite structures under the stationary self-heating scenario to be estimated.**

**Keywords: fatigue, self-heating effect, degradation of composite structures, acoustic emission**

## ZMĘCZENIE KOMPOZYTÓW POLIMEROWYCH PODCZAS USTALONEGO I NIEUSTALONEGO SAMOROZGRZANIA

**Efekt samorozgrzania, powstający podczas cyklicznych obciążeń materiałów, wykazujących właściwości termolepkosprężyste, w zależności od warunków obciążenia, może rozwinąć się według dwóch możliwych scenariuszy: ustalonego i nieustalonego. Ze względu na to, że samorozgrzanie ustalone nie było wcześniej badane pod względem krytyczności efektu samorozgrzania, istotne jest przeprowadzenie takich badań w celu lepszego zrozumienia procesów degradacji przy takim scenariuszu i skonfrontowania wyników z krytycznością dla nieustalonego samorozgrzania. W niniejszej pracy zostały przeanalizowane i opisane wyniki dotyczące badań eksperymentalnych zmęczenia według scenariusza ustalonego samorozgrzania. W celu scharakteryzowania procesu degradacji przeanalizowano zarówno rozkłady temperatury samorozgrzania i ich zmienność, jak i emisji akustycznej zmierzonej dla różnych zakresów temperatury samorozgrzania. Otrzymane wyniki pozwoliły na oszacowanie wpływu efektu samorozgrzania na trwałość resztkową struktur kompozytowych podczas występowania scenariusza ustalonego samorozgrzania.**

**Słowa kluczowe: zmęczenie, efekt samorozgrzania, degradacja struktur kompozytowych, emisja akustyczna**

## INTRODUCTION

The self-heating effect occurs in polymers and polymeric composites subjected to cyclic loading due to the viscoelastic nature of polymers. This causes hysteresis between the stress and strain amplitudes to occur, and in consequence, mechanical energy dissipation. Most of this energy dissipates in the form of heat, and, considering the low thermal conductivity of industrial polymers, the generated heat is stored in the structure, which causes temperature growth. Such a phenomenon may significantly intensify structural degradation, which is dangerous for polymeric and composite elements working in cyclic loading conditions or subjected to high-magnitude vibrations during their operational lifetime.

Depending on the loading conditions, the self-heating effect may develop following two scenarios: stationary and non-stationary self-heating. The first scenario assumes growth of the self-heating temperature until reaching a specific value, and then stabilization or very slow linear growth (caused by mechanical degradation), while the second scenario assumes domination of the self-heating effect in the fatigue process, which results in sudden degradation of the structure until reaching the strength limit and failure.

When the self-heating effect dominates the fatigue process, damage initiation and propagation occur at a much lower value of temperature than the temperature reached during failure, which intensifies this process [1]. Moreover, in the case of non-stationary self-heating, one can clearly observe three characteristic phases of temperature growth (confirmed in numerous studies - see e.g. [2-5]): the first one is heating following the exponential characteristic (according to thermodynamic laws), the second phase is connected with the temperature stabilization or monotonic linear growth resulting from progressive damage accumulation, and the third phase is connected with the initiation and development of a macrocrack in the location of the highest stress concentration, which in consequence leads to rapid self-heating temperature growth and failure of the structure. In the case of stationary self-heating, while a relatively low number of cycles (or a short loading time period) is considered, only the first and the second phase of temperature growth are observed, i.e. after reaching a certain value the self-heating temperature distribution stabilizes. Thus, it can be interpreted that the self-heating effect influences fatigue, though, does not dominate it.

Numerous studies on the influence of the self-heating effect on fatigue have been performed to-date. The mentioned duality of evolution of self-heating temperature, namely, stationary and non-stationary self-heating, has been observed in many studies (see e.g. [5-8]). For practical reasons, it is essential to investigate the criticality of the self-heating effect occurring during the fatigue of polymeric composites, i.e. the point (or temperature value) at which self-heating dominates the fatigue process, leading to sudden degradation and failure of the loaded structure. Recently, several attempts at evaluating the criticality of the self-heating effect have been made by the authors of [9, 10]. In their studies they analysed a temperature history curve together with the intensity of acoustic emission events in order to determine the criticality of self-heating. Previous studies of the author of the present paper focused on evaluation of the criticality of the self-heating effect covered the approximation of self-heating temperature history curves [11] in order to determine the difference between the measured temperature and the approximation model (this difference indicated the beginning of macrocrack development, and thus the critical value of the self-heating temperature).

All of the mentioned studies were performed under the assumption of the occurrence of non-stationary self-heating. The aim of this paper is to investigate the criticality of self-heating and the residual life of cyclically loaded composite structures in the stationary self-heating regime as well as determine the characteristic temperature at which the self-heating effect becomes non-stationary. Additionally, having the thermal response measurements and acoustic emission test results, it is possible to compare the obtained results and determine the criticality of self-heating using acoustic emission data as well as describe degradation processes using this data. Performing such studies allows both the influence of particular self-heating temperature values on the intensity of structural degradation as well as the critical self-heating temperature by comparison of the number of loading cycles to failure between particular cases to be determined. Such an analysis allows full qualitative and quantitative description of the influence of the self-heating effect on the fatigue of polymeric composites and development of the relation between the self-heating temperature values and the structural lifetime of polymeric composites in the stationary self-heating regime.

## MATERIALS AND FATIGUE TESTING PROCEDURE

The specimens used for the fatigue tests were manufactured from a 14-layered unidirectional glass/epoxy composite supplied by Izo-Erg S.A. (Gliwice, Poland). The composite sheet of the thickness of 2.5 mm was cut to specific dimensions for the specimens: width 10 mm and length 100 mm. The effective length, i.e. the length between the specimen holders which participated in loading, of each specimen equalled 40 mm. The specimens were loaded with a constant frequency of 30 Hz. Considering the loading frequency the glass transition temperature of this composite is ca. 130°C (see [11] for more information). The tests were performed on a laboratory test rig, which is presented in a diagram (Fig.1a) and a photograph (Fig.1b).

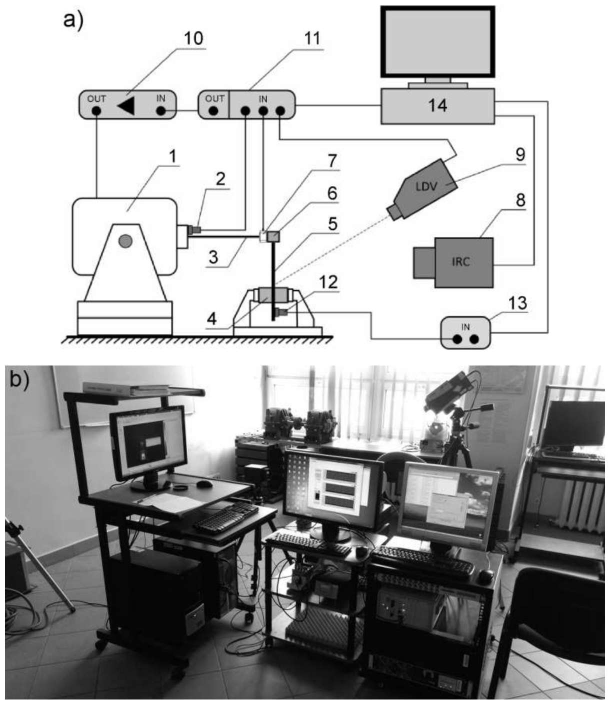


Fig. 1. Experimental test rig for performing fatigue tests: a) diagram, b) photograph

Rys. 1. Stanowisko badawcze do przeprowadzenia testów zmęczeniowych: a) schemat, b) fotografia

Tested specimen *5* was clamped in specimen holder *4* and excited by TIRA® TV-51120 electrodynamic shaker *1* through stinger *3* with specimen holder *6* connected to force sensor PCB Piezotronics® 208C03 *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 signal was measured by accelerometer PCB Piezotronics® T352C34 *2*. The velocity of vibration of the specimen was measured on its surface near clamp *4* using single point laser Doppler vibrometer (LDV) Polytec® PDV-100 *9*. In order to detect damage initiation in the structure due to the self-heating effect, besides measuring the surface temperature and excitation parameters, the acoustic emission (AE) was observed. The AE signal was measured by means of the Vallen® AMSY-5 system. In particular, AE sensor *12*, an AE signal preamplifier, dual channel AE signal processor board *13* and dedicated software for AE signal acquisition and processing were used. The force sensor and accelerometer were connected through a conditioning module to the multi-channel data acquisition card NI® DAQ Card 6062E, which was connected to PC *14* and controlled by an application developed in LabView®. The force and vibration signals were acquired at a sample rate of 2 kHz. The application allows controlling of the excitation signal parameters through the analogue output of multi-channel signal acquisition module *11* and controls shaker amplifier *10* TIRA® BAA 500. The temperature measurements were carried out using InfraTec® VarioCAM® hr infrared camera (IRC) *8*. The frame rate of the IRC was set to 2 frames per second.

The fatigue tests were performed as follows. The specimens were loaded in such a way that the maximal self-heating temperature on their surfaces reached a certain value in the range of 30÷55°C with a step of 5°C. The upper limit of 55°C was selected based on the results of previous tests, where the self-heating temperature growth became non-stationary in the second phase of its development. As a criterion of examining the non-stationarity of temperature growth, the following assumption was made: if the temperature growth in the second phase increases at a rate of less than 1°C per 3000 cycles (100 s), then the self-heating temperature growth is assumed to be stationary. After reaching the certain temperature the specimens were subjected to fatigue cyclic loading until failure. For each maximal self-heating temperature value 5 specimens were tested to obtain statistically valid results. During such a study all of the parameters available to be acquired using the above-described measurement equipment were collected. The collected data allow evaluation of the influence of the self-heating effect in the stationary regime on the fatigue lifetime of polymeric composites as well as the criticality of the self-heating effect in the stationary and non-stationary self-heating regimes.

## RESULTS AND DISCUSSION

### Analysis of self-heating temperature evolution curves

For the purpose of analysing the temperature evolution, the maximal self-heating surface temperature was taken from each registered thermogram during fatigue loading. Since the temperature distributions were non-uniform, these maximal values appeared at the maximal stress concentration, i.e. near the clamp. The results of the performed tests indicated that for the considered dimensions of specimens and loading parameters, the maximal self-heating temperature curves reveal stationarity up to 50°C (according the assumed criterion of temperature growth), which can be observed in Figure 2.

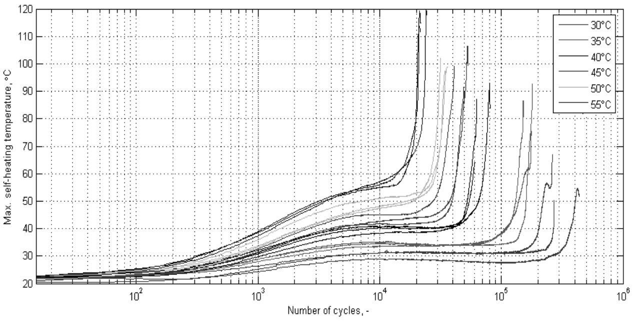


Fig. 2. Selected self-heating temperature history curves for various stabilization temperature values

Rys. 2. Wybrane krzywe temperaturowe procesu samorozgrzania dla różnych wartości temperatury stabilizacji

From direct observations of the self-heating temperature history curves, one can conclude that the increased temperature resulting from the self-heating effect significantly influences the residual life of the polymer-based composite structure. Comparing the results for the stabilization temperature close to 30°C, one can see that the increase of 3°C (cf. red lines in Fig. 3) may shorten the residual life of the structure two times or more. Assuming the case of a stabilization temperature at the level of 30°C and comparing the obtained temperature history curves with the results obtained for higher values of stabilization temperature, one can observe that the difference in residual life in these cases reaches even one order, which has a crucial meaning during the design and operation stages of composite structures subjected to cyclic loading or forced vibrations.

The results of the self-heating temperature growth during fatigue tests indicate a dependence between the residual life of a composite structure and the observed self-heating temperature, which allows modelling and prediction of the residual life based on the observed stabilized self-heating temperature, as well as evaluation of the criticality of the self-heating effect in the case of the appearance of stationary self-heating during the fatigue loading of polymer-based composite structures. For the purpose of comparison, the determined average critical self-heating temperature values based on the double-exponential approximation approach described in [12], together with the accompanying average number of cycles reaching the critical self-heating temperature values, as well as the average number of cycles at failure, are presented in Table 1.

 

TABLE 1. **Critical self-heating temperature values and accompanying number of cycles of tested specimens**
TABELA 1. **Wartości krytyczne temperatury samorozgrzania i odpowiadające im liczby cykli badanych próbek**

| $T_{stab}$ [°C] | $\bar{T}_c$ [°C] | $\bar{N}_c$ [–] | $\bar{N}_f$ [–] | $T_{stab}$ [°C] | $\bar{T}_c$ [°C] | $\bar{N}_c$ [–] | $\bar{N}_f$ [–] |
|---|---|---|---|---|---|---|---|
| 30 | 29.82 | 233033 | 317767 | 45 | 44.73 | 16077 | 47683 |
| 35 | 34.62 | 73200 | 169233 | 50 | 51.00 | 19000 | 34017 |
| 40 | 39.71 | 26243 | 67807 | 55 | 56.46 | 11552 | 22227 |

From the presented results one can observe that in the cases of a low stabilization temperature the critical self-heating temperature is even lower than the stabilization temperature. This can also be observed in Figure 2, especially for the cases of stabilization temperatures of 30 and 35°C. This phenomenon is probably caused by the relaxation mechanisms in viscoelastic specimens, and thus, the small temperature drop. Contrary to the above-mentioned cases, the last two cases reveal a higher critical self-heating temperature with respect to the stabilization temperature, and the previously discussed temperature drop does not occur in these cases. This can be considered as an additional indicator of the non-stationarity of self-heating. The relation of the numbers of cycles at the critical self-heating temperature and at failure with respect to the stabilization temperature behaves following the power law, which is in agreement with the fundamental concepts of fracture mechanics. Following this, the structural degradation during occurrence of the self-heating effect in a stationary regime can be described by fundamental power laws of fracture mechanics.

One can also observe that the lower the stationary self-heating temperature during fatigue, the lower the temperature at failure of a structure, which is clearly observable in Figure 2. These observations prove that the criticality of the self-heating effect described in previous studies [5, 12, 13] depends on the loading conditions, which is directly connected with the generated heat. However, this dependence is very noticeable for the stationary regime of self-heating, while in the case of non-stationary self-heating and domination of the self-heating effect, the influence of loading conditions on the residual life is much less, and in many cases can be neglected due to intensive degradation of the composite structure in such conditions, which was also stated by the authors of [14].

## Analysis of self-heating temperature distribution

The maximal values of self-heating temperature for non-stationary self-heating at failure usually reach the range of 110÷130°C (see [5, 12, 13]), which is similar to the results for the stabilization temperature of 55°C obtained in the present study. This additionally proves that the loading parameters in the case of non-stationary self-heating have little influence on the resulting critical self-heating temperature. In the case of stationary self-heating, i.e. when the self-heating effect does not dominate the fatigue processes, the self-heating effect accelerates the degradation processes, but the main factor which influences the final failure of a structure is the mechanical degradation with accompanying macrocrack formation. Previous studies [14] showed that the critical self-heating temperature during non-stationary self-heating is in the range of 65÷70°C, which is connected with cracking of the polymeric matrix of a composite, while the formation of a macrocrack in the case of stationary self-heating appears at much lower temperature values (see Fig. 3).

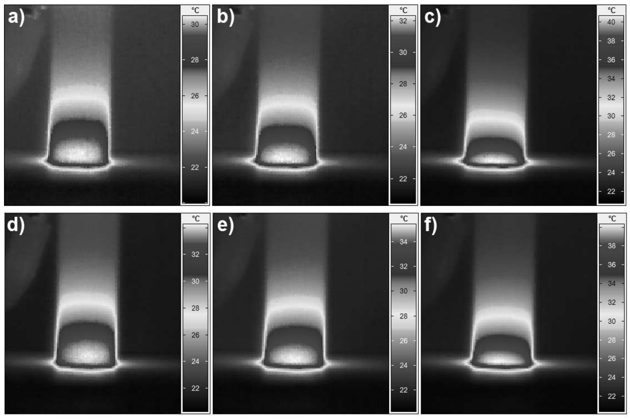


Fig. 3. Thermograms of tested specimens after various numbers of cycles: with self-heating stabilization temperature of 30°C after: a) 103455, b) 275355, c) 386835 cycles and stabilization temperature 35°C after d) 16380, e) 147570, f) 187095 cycles

Rys. 3. Termogramy badanych próbek po różnej liczbie cykli: ze stabilizacją na poziomie 30°C po: a) 103455, b) 275355, c) 386835 cyklach oraz ze stabilizacją na poziomie 35°C po: d) 16380, e) 147570, f) 187095 cyklach

## Acoustic emission analysis

Having obtained the results of critical self-heating temperature from the approximation of the maximal self-heating temperature evolution curves for the stationary self-heating regime, it is essential to analyze the AE response of the tested composite structures to qualitatively and quantitatively evaluate their structural degradation in such conditions. From the variety of measures of AE activity available in the dedicated post-processing software of the applied AE measurement system and collected during fatigue testing of the specimens, one of them was selected as one of the most sensitive to damage initiation - the energy ratio (ETE). This selection was based on the results of previous studies focused on the sensitivity of these measures [13, 15]. The selected results for the considered values of stabilization temperature are presented in Figure 4. In the obtained results, the beginning of a rapid increase in ETE is considered as increased AE activity connected with structural degradation, and as a consequence, damage initiation. Based on this assumption the average number of cycles to reach the critical self-heating temperature values, and accompanying this value, the averaged critical self-heating temperature values were determined and are presented in Table 2.

 

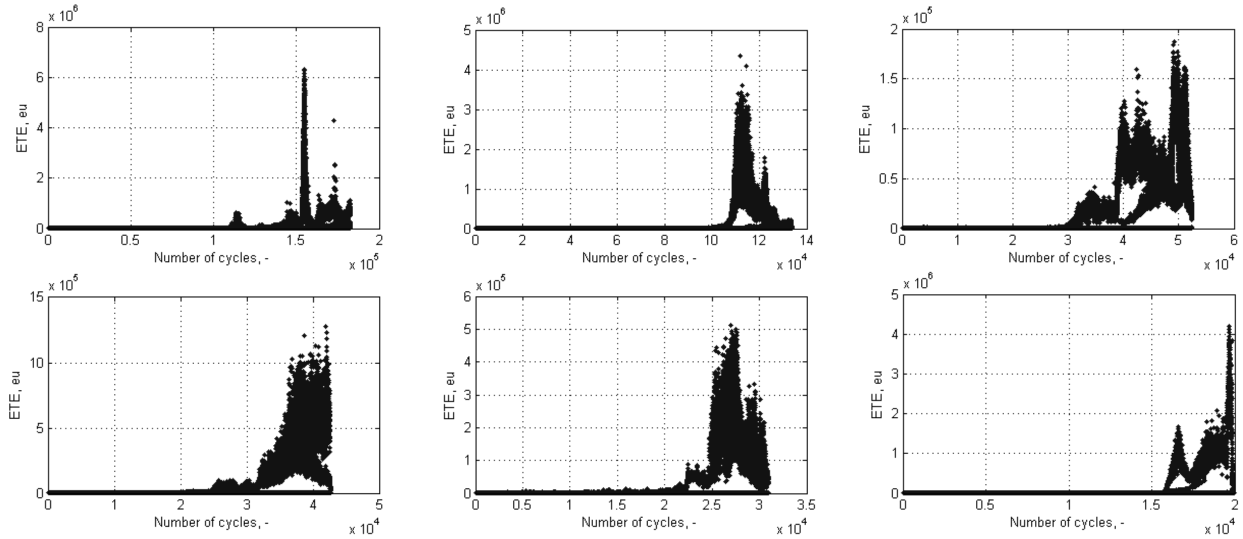


Fig. 4. AE energy ratios for selected fatigue tests for considered values of stabilization temperature

Rys. 4. Miara energii emisji akustycznej dla wybranych badań zmęczeniowych dla rozpatrywanych wartości temperatury ustalenia

TABLE 2. **AE-based critical self-heating temperature values and accompanying number of cycles of tested specimens**

TABELA 2. **Wartości krytyczne temperatury samorozgrzania i odpowiadające im liczby cykli badanych próbek oparte na miarze energii akustycznej**

| $T_{stab}$ [°C] | $\bar{T}_c$ [°C] | $\bar{N}_c$ [–] | $T_{stab}$ [°C] | $\bar{T}_c$ [°C] | $\bar{N}_c$ [–] |
|---|---|---|---|---|---|
| 30 | 29.27 | 229150 | 45 | 44.05 | 15540 |
| 35 | 34.23 | 53507 | 50 | 51.13 | 16040 |
| 40 | 40.64 | 25420 | 55 | 57.91 | 11979 |

Comparing the results presented in Tables 1 and 2, one can conclude that the obtained values, both for the critical self-heating temperature and number of cycles to reach this temperature are slightly lower in general for the AE-based approach, which confirms the previous observations of the higher sensitivity of AE to damage initiation [13]. All of the obtained values of the critical self-heating temperature using both presented approaches indicated that in the case of stationary self-heating, the stabilization temperature is practically equal to the critical self-heating temperature. This constitutes an additional danger from the operational point of view, since none of the signs of degradation in this case can be distinguished before starting damage initiation.

## CONCLUSIONS

The performed studies focused on determining the influence of the self-heating effect in the stationary regime on the fatigue processes of polymeric composites allows the evaluation of structural degradation. Based on the obtained results estimation of the residual life of composite structures subjected to such a type of loading and the accompanying values of the critical self-heating temperature (at which structural degradation begins) was possible. The obtained results show that the degradation initiation in the case of stationary self-heating, in contrast to non-stationary self-heating, depends on the loading parameters, and the resulting self-heating stabilization temperature significantly influences the residual life of a composite structure. Moreover, it was observed that the degradation initiation during stationary self-heating takes place at much lower temperature values than the critical self-heating temperature range determined in the author's previous studies for non-stationary self-heating, and practically equal to the stabilization temperature values. However, the formation of a macrocrack in the polymeric matrix occurs after a large number of cycles, which points to domination of the mechanical character of degradation. It was observed that the increase in the stabilization temperature causes a rapid decrease in the residual life of polymeric composite structures, which can be described by the classic power laws applicable in problems of damage mechanics. Considering the significant decrease in residual life with an increase in stabilization temperature and the fact that no signs of degradation can be observed before damage initiation for the case of stationary self-heating, it can be considered as a serious danger for such structures being in operation. These problems will be the topics of further studies of the author's team.


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