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Andrzej Katunin[1]*, Angelika Wronkowicz[1], Marcin Bilewicz[2]

[1]Silesian University of Technology, Institute of Fundamentals of Machinery Design, ul. Konarskiego 18A, 44-100 Gliwice, Poland
[2]Silesian University of Technology, Institute of Engineering Materials and Biomaterials, ul. Konarskiego 18A, 44-100 Gliwice, Poland
**Corresponding author. E-mail: andrzej.katunin@polsl.pl*

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EVALUATION OF CRITICAL SELF-HEATING TEMPERATURE OF COMPOSITE STRUCTURES BASED ON ANALYSIS OF MICROCRACK DEVELOPMENT

The self-heating effect occurring during the cyclic loading of polymers and polymeric composites may initiate accelerated thermally induced fatigue processes, which causes a rapid increase in the self-heating temperature at a location of stress concentration and, as a consequence, sudden structural degradation. Therefore, it is essential to investigate this process and determine the criticality of the self-heating effect, i.e. the critical value of temperature which initiates accelerated degradation processes. In this paper, an aspect of microcrack formation and development was considered as an indicator which reflects the degradation degree of a structure. Microscopic observation of microcrack development at progressive temperature values was chosen due to its high sensitivity to the initiation of fracture processes among applied measurement techniques to evaluate structural degradation during fatigue tests. Appropriate image processing techniques as well as quantitative measures to describe microcrack development enable evaluation of the criticality of the self-heating effect using this approach and comparison of the obtained results with those obtained by other measurement techniques. The specified critical value of self-heating temperature allows determination of a safe temperature range for heavily loaded structures made of polymeric composites, which can be helpful both during the design stage as well as at the operating stage of composite structures.

Keywords: **self-heating effect, microcracks development, crack density, degradation of composite structures**

OCENA KRYTYCZNEJ TEMPERATURY SAMOROZGRZANIA STRUKTUR KOMPOZYTOWYCH NA PODSTAWIE ANALIZY ROZWOJU MIKROPĘKNIĘĆ

Efekt samorozgrzania, powstający podczas cyklicznych obciążeń polimerów i kompozytów polimerowych, może zainicjować przyspieszone indukowane termicznie procesy zmęczeniowe, co powoduje szybki wzrost temperatury samorozgrzania w miejscu koncentracji naprężeń i w konsekwencji nagłą degradację strukturalną. Dlatego istotne jest zbadanie tego procesu i określenie krytyczności efektu samorozgrzania, tj. krytycznej wartości temperatury, która inicjuje przyspieszone procesy degradacji. W artykule aspekt formowania i rozwoju mikropęknięć uwzględniono jako czynnik, który odzwierciedla stopień degradacji struktury. Obserwacja mikroskopowa rozwoju mikropęknięć przy narastających wartościach temperatury została wybrana dzięki wysokiej wrażliwości na inicjację procesów zniszczenia spośród technik pomiarowych stosowanych do oceny degradacji strukturalnej podczas testów zmęczeniowych. Odpowiednie techniki przetwarzania obrazów oraz miary ilościowe do opisu rozwoju mikropęknięć pozwoliły na ocenę krytyczności efektu samorozgrzania, wykorzystując takie podejście, oraz na porównanie otrzymanych wyników z wynikami uzyskanymi z wykorzystaniem innych technik pomiarowych. Wyznaczona wartość krytyczna temperatury samorozgrzania pozwoliła na określenie bezpiecznego przedziału temperaturowego dla silnie obciążanych struktur wykonanych z kompozytów polimerowych, co może być pomocne zarówno na etapie projektowania, jak i podczas eksploatacji struktur kompozytowych.

Słowa kluczowe: **efekt samorozgrzania, rozwój mikropęknięć, gęstość pęknięć, degradacja struktur kompozytowych**

INTRODUCTION

The self-heating effect resulting from mechanical energy dissipation during the cyclic loading of structures made of polymers and polymeric composites is a dangerous phenomenon for these structures since a growing self-heating temperature intensifies structural degradation. Following the results of previous studies [1], the self-heating effect may manifest itself following two scenarios. During the first scenario, the self-heating temperature grows until reaching a certain value at which the temperature as well as its distribution stabilizes. In this state, the energy supplied by mechanical loading is in equilibrium with the dissipated energy and heating-up of the structure has an insignificant effect on the fatigue process. In contrast to this scenario, when mechanical loading is high enough to exceed a certain critical value of self-heating temperature, development of the self-heating effect can be described by a three-phase model [1-3]. In the first phase, a typical exponential-like, non-stationary temperature growth occurs until reaching a certain self-heating temperature. Due to the fact that this temperature is high enough to influence fatigue processes, it initiates the second phase during which a linear temperature growth is observed. This phase ends when the fatigue damage accumulation becomes critical, which starts the formation of a macrocrack and initiates the third phase. During the third phase, a rapid self-heating temperature growth occurs which leads to failure of the structure. As one can expect, the second scenario is much more critical for the operation of a structure since the self-heating effect significantly accelerates structural degradation, and therefore it is essential to investigate the degradation process and evaluate the critical value of self-heating temperature that initiates degradation processes.

The criticality of structural degradation of composites subjected to self-heating has been investigated by several authors using various approaches. Most often the criticality of the described phenomenon was evaluated based on the value of self-heating temperature. Rittel [4] connected failure processes in polymers with their glass-transition temperature, while the first author of the present paper used an approximation model to identify the critical self-heating temperature [5]. A similar approach based on temperature observation was presented by the authors of [2, 6] as well as the authors of [7], who described the criticality of self-heating in terms of stiffness reduction. This approach, however, indicated the development of macrocracks, which leads to a sudden structural failure. In order to detect degradation processes at earlier stages, Kahirdeh et al. used acoustic emission monitoring during fatigue tests, which enables indication of the appearance of microcracks (see [2, 3] for instance). These authors validated the described measurements by scanning electron microscope (SEM) observations [2, 3, 8], which indicated various types of damage occurring during the fatigue of composites induced by the self-heating effect.

Since the appearance of microcracks affects degradation of the considered composite structures, which is indirectly reflected in temperature and acoustic measurements, it is essential to observe the formation and evolution of these microcracks as a source of information about the degradation degree. In this study, the authors considered crack density as a measure of structural degradation, which allows comparison of the obtained results of damage evolution of composite structures subjected to self-heating of various temperature values with a self-heating temperature history curve as well as acoustic emission measures. The evaluation of crack density using image processing techniques makes it possible to obtain information about the evolution of structural degradation depending on the self-heating temperature and determine its critical value by analyzing an increase in crack density. The performed studies allow the evaluation of a safe temperature range in which composite structures may be loaded and not subjected to accelerated degradation, which has a practical importance both in terms of the design of composite structures and their loading conditions as well as at their operation stage.

SPECIMEN PREPARATION AND EXPERIMENTAL SETUP

The tested specimens with the dimensions of 100×10×2.5 mm made of epoxy resin reinforced by a glass fabric were subjected to fatigue loading on the authors' own-designed test rig. A detailed description of the tested composite can be found in [1]. The specimens were clamped in such a way that the working length (i.e. the length subjected to deflection) was equal to 50 mm and loaded in a constant deflection mode at a frequency of 30 Hz and with an initial loading force of 90 N. During the fatigue process the surface temperature distribution was monitored by an infrared camera and loading parameters (acceleration and vibration velocity) were monitored by an accelerometer and laser Doppler vibrometer, respectively. Additionally, acoustic emission was measured during the tests by sensors glued to a non-deflected part of the specimen. Using the described experimental setup, the specimens were loaded until reaching the defined values of self-heating temperature. During the tests a self-heating temperature range of 40÷100°C with a step of 5°C was assumed. Due to the non-uniform temperature distribution, the observed maximal self-heating temperature was considered the temperature of heating. The tests were repeated 5 times for each temperature of heating.

After performing the fatigue tests with monitoring of the surface temperature and acoustic emission, the specimens were subjected to microscopic observations. The observations were performed using a stereoscopic microscope at 8x magnification.

ANALYSIS OF CRACK DENSITY AND COMPARATIVE STUDIES

The acquired pictures during microscopic observations were processed in order to enhance cracks resulting from loading. Examples of crack distributions observable at various stages of fatigue are presented in Figure 1. The microscopic side views of fatigue cracks appearing during fatigue with the accompanying self-heating effect can be found in [9]. By analyzing these representative cases, one can observe characteristic regularly distributed damage sites in each case. These damage sites resulted from debonding at the interface of the glass fabric and the polymeric matrix, thus, degradation processes occur even at low self-heating temperature values.

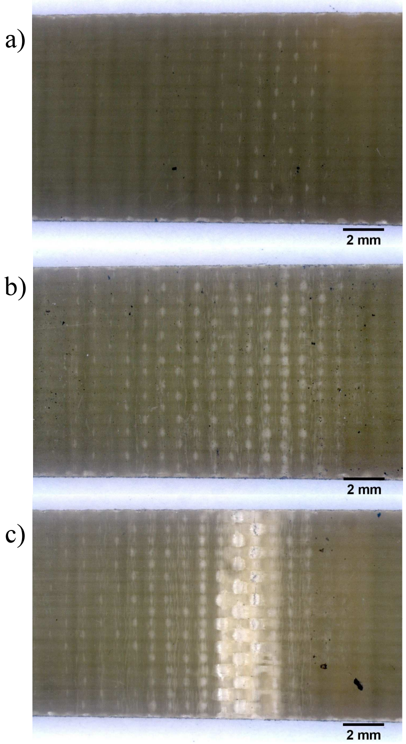

Fig. 1. Fatigue crack distribution after loading to maximal self-heating temperatures of: a) 40°C, b) 70°C, c) 100°C

Rys. 1. Rozkład pęknięć zmęczeniowych po obciążeniu do maksymalnej temperatury samorozgrzania: a) 40°C, b) 70°C, c) 100°C

The interface debonding is a result of high-stress cyclic loading, however, its appearance does not necessarily directly influence structural degradation. In this case, the analysis is limited only to surface observations, therefore the evaluation of degradation is possible based on surface cracks only. Nevertheless, one can observe the appearance of a net of cracks oriented transverse to the longer edges of the specimens. Initial visual analysis of these cracks allows one to hypothesize that the development and evolution of these cracks have a direct connection with structural degradation. One can observe that these cracks have a tendency to connect to through-the-width cracks (as is visible in Fig. 1b and 1c), which justifies the physical fundamentals of the observed degradation phenomena.

In order to evaluate the accumulation of cracks during the increase in self-heating temperature, it is necessary to consider a quantitative measure that enables representation and further evaluation of crack density growth. One adequate measure is crack density calculated as the number of cracks per unit of area or sometimes its variation calculated as the total length of cracks per unit of area [10]. This measure is often used to characterize the evolution of the cracking process of composite materials, primarily when describing fatigue test results [11-13]. Nonetheless, considering the character of the observed damage sites and their wide extent, especially at higher self-heating temperature values when macrocrack formation can be observed, it was decided to adapt a classical crack density measure for the analyzed photographs, as described below.

Firstly, the acquired photographs were pre-processed, namely the areas of the background not belonging to the specimens were cut and the remaining black paint, visible in Figure 1, was removed. Next, the images were converted to the grayscale and then sharpened using an unsharp masking method in order to obtain an appropriate contrast. Subsequently, the obtained images were binarized using global image thresholding in order to separate the cracks from the images of the specimens. Finally, the crack density was calculated as the ratio of regions classified as cracks to the whole visible area of the specimen. This allows one to obtain a dimensionless measure, which represents the averaged crack density. The microscopic pictures contain only a limited (the damaged) region of the specimens, though, considering that the obtained values of this measure have less importance with respect to their trend in the function of self-heating temperature, such an analysis gave reliable results. The resulting binary images corresponding to those presented in Figure 1 are presented in Figure 2.

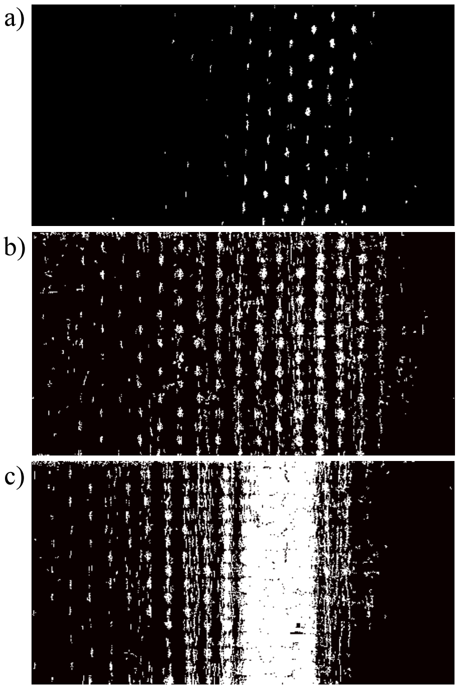

Fig. 2. Processed photographs with separated cracks for maximal self-heating temperatures of: a) 40°C, b) 70°C, c) 100°C

Rys.2. Przetworzone fotografie z wydzielonymi pęknięciami dla maksymalnej temperatury samorozgrzania: a) 40°C, b) 70°C, c) 100°C

The performed analysis allowed the construction of a characteristic which describes the growth of crack density during increasing self-heating temperature (see Fig. 3). From these results one can notice two sharp increases in crack density: the first one is between the self-heating temperature of 60 and 65°C and the second one occurred above the temperature of 85°C. Based on these observations as well as the previously analysed microscopic images, it can be assumed that during the first stage of self-heating (up to 60°C) debonding at the interface of the glass fabric and the polymeric matrix appear, afterwards - during the second stage (in the range of 65÷85°C) - through-the-width cracks occur, thus initiation of structural degradation starts, and finally, clearly visible macrocrack formation can be observed after reaching a temperature of above 85°C.

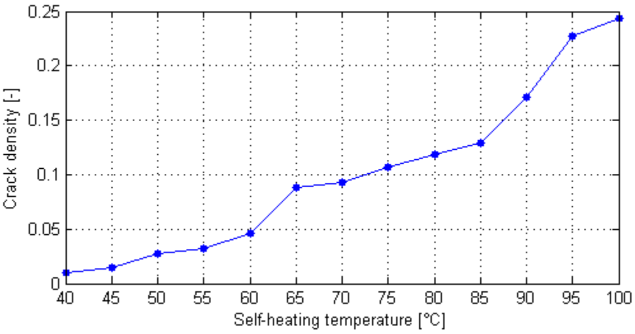

Fig. 3. Crack density for different values of self-heating temperature

Rys. 3. Gęstość pęknięć dla różnych wartości temperatury samorozgrzania

The above discussed results were compared with those from the analysis of other parameters measured during testing, namely the self-heating temperature and acoustic emission. Such exemplary results are presented in Figure 4, where the acoustic emission measure (total energy of hit-cascade) is the sum of the energies of the first-hit and all subsequent hits in a hit-cascade.

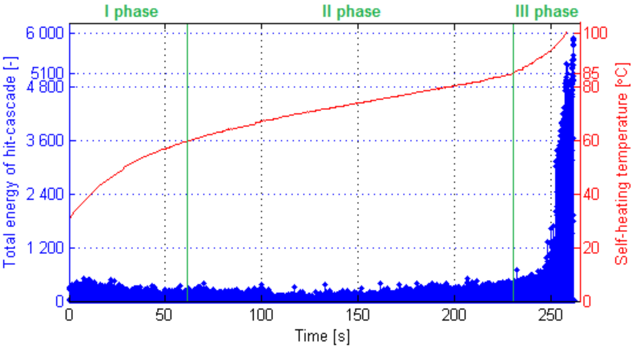

Fig. 4. Evolution of acoustic emission and self-heating temperature during thermal fatigue

Rys. 4. Postęp emisji akustycznej i temperatury samorozgrzania podczas zmęczenia cieplnego

Additionally, three phases of self-heating were highlighted on this graph at critical points of temperature values determined based on microscopic observations. Comparing the results based on analysis of microscopic images with the self-heating temperature history curve, one can notice a convergence of the critical values of temperature with the three-phase model of the self-heating effect [1-3]. Analysis of the acoustic emission measurements returned less evident results since only transition from the second to the third phase is well visible, however, a critical temperature value between the first two phases cannot be noticed or identified.

CONCLUSIONS

The performed microscopic observations of GFRP specimens subjected to fatigue processes induced by the self-heating effect allow evaluation of the criticality of the self-heating effect phenomenon with respect to crack density evolution at progressive self-heating temperature values. The performed analysis was possible due to the application of appropriate image processing techniques which enable the extraction of information about cracks visible on the surface of the specimens from the acquired images. Moreover, by comparing the obtained results of damage accumulation and its criticality with those obtained during performing fatigue tests, namely measurements of self-heating temperature and acoustic emission, it was found that the obtained results reflect the sudden changes in a more evident way than the mentioned measured quantities. The coincidence of the three-phase model typical for the appearance of the self-heating effect during fatigue additionally justifies the obtained results.

The obtained results do not fully reflect the fracture progress during fatigue due to the fact that only surface cracks were considered during the analysis. To enhance the obtained results in this study additional analysis will be performed with use of X-ray computed tomography. This method makes analysis of the fracture mechanisms in a whole cross section of specimens possible. Due to the occurrence of the self-heating effect, in many cases when the fatigue processes of elements made of polymers and polymeric composites occur, the observations and results obtained in this study may be very helpful during the design and operation of such elements.

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