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VARIABLE SURFACE TEMPERATURE DISTRIBUTION AS A CRITICALITY INDICATOR OF THE SELF-HEATING EFFECT IN COMPOSITES

ABSTRACT

Since self-heating effect may significantly intensify structural degradation, it is essential to investigate its criticality, i.e. the temperature value at which fatigue fracture is initiated. In this paper, a new and sensitive criticality indicator based on evaluation of evolution of surface temperature distribution was proposed and experimentally validated. It was shown that comparing to other measurement techniques the presented approach allows for precise evaluation of the critical value of the self-heating temperature. The properly determined critical value may be helpful both during design and operation of elements made of polymers and polymeric composite.

Keywords: *self-heating effect, surface temperature distribution, fatigue fracture*

INTRODUCTION

A self-heating effect, caused by cyclic loading or vibrations of polymeric or polymer-based composite structures, is a very dangerous phenomenon accompanying fatigue processes due to dissipation of mechanical energy in a form of heat and its significant influence on the structural residual life. Considering that thermal conductivity of most industrial polymers used as a matrix in composites is low, the generated heat is stored in the structure, which leads to intensification of structural degradation and its failure in critical cases. However, the influence of the self-heating effect is not always dominant in the fatigue process: depending on a loading rate and the resulting stress field the self-heating effect may appear in a stationary or non-stationary regime. The stationary regime appears in a case when the self-heating temperature grows up to a certain value and then stabilizes on this level, which means that a loaded structure reaches a thermal equilibrium, i.e. the amount of generated heat equilibrates with the amount of heat released from the structure by means of convection, radiation and conduction. In the case of exceeding the critical loading value the self-heating effect becomes dominant, and during loading the amount of generated heat is higher than capabilities of its release to environment. This causes a rapid increase of the self-heating temperature, which leads to sudden degradation and structural failure. The self-heating temperature growth characteristic has three phases, which coincide with stages of structural degradation (see [1] for instance): in the first phase rapid exponential self-heating temperature growth is observed; in the second phase the temperature increase is linear and slow, which is a result of mechanical degradation induced by self-heating effect; finally, in the third phase, after development of damage on macro-level, a rapid temperature growth with quite low duration is observed. The third phase ends by failure of a structure. This characteristic has its reflection both in mechanical properties [2,3] as well as in evolution of the self-heating temperature, which was confirmed in numerous studies (see e.g. [4,5]). Taking into consideration a fact that the appearance of the self-heating effect in polymeric and composite structures is unwanted in general, and cannot be completely removed, it is essential to investigate its criticality, i.e. the characteristic self-heating temperature value at which the intensive structural degradation, influencing on mechanical properties of a structure, begins.

The criticality of the self-heating effect is a subject of numerous research studies. The early author's studies [6] were based on approximation of self-heating temperature history curves by a double-exponential functions in order to find specific temperature value where the approximation and the experimental temperature curve start diverging. Recent studies of the authors of [7,8] reported another approach, which was based on estimation of structural degradation by means of acoustic emission measured during the loading process. Based on these measurements it was possible to determine the moment of intensification of a fracture energy release and compare it with appropriate self-heating temperature values. Recent studies of the author's team have been focused on determination of the critical self-heating temperature value, at which structural damage initiation begins. For this purpose, several approaches to determination of the criticality of the self-heating effect were examined. In [9] the authors studied surface cracks accumulation using optical microscopy and further image processing of the acquired microscopic images of specimens subjected to fatigue loading accompanied with self-heating. The specimens were cyclically loaded until reaching maximal self-heating temperature of a certain value in a range of 40-100°C with a step of 5°C. After reaching the certain temperature value the loading was stopped and the specimen was subjected to observations. Results of application of another approaches were reported in [10], where the criticality of the self-heating effect was studied by means of acoustic emission during the loading process, and tensile quasi-static testing for determination of residual strength of a material subjected to self-heating after the loading process. The specimens for tensile testing were prepared in the same way as for the prior-described microscopic studies.

In this paper, another approach of determination of the criticality of the self-heating effect is presented. During experimental studies characteristic temperature distributions were observed for various phases of structural degradation, i.e. in the case of formation of a macrocrack the temperature isolines are concentrated close to this crack, while in the cases where the degradation process is not critical, i.e. no damage appears, the temperature isolines are more widespread in the heated region. Similar observations were reported by the authors of [11,12]. This phenomenon was highlighted and initially studied by the author in [13], where the relation between the self-heating temperature distribution and formation of a macrocrack was shown. Later, the authors of [14, 15] confirmed the relation of damage formation and evolution with changes in the self-heating temperature distribution.

Since the obvious relation between the self-heating temperature distribution and damage initiation and propagation comes from stress redistribution it was decided to use the observed phenomenon as an indicator of damage initiation. The aim of this paper is to evaluate of the criticality of the self-heating effect by means of the above-described self-heating temperature distribution-based indicator and comparison of its effectiveness with the previously tested approaches. The determination of critical self-heating temperature values allows for establishment of safe temperature ranges of polymeric and polymer-based composite structures reached during their operation in cyclic loading or vibration regimes, which, in turn, will allow for extending their residual life and preventing their sudden failure.

SPECIMENS AND EXPERIMENTAL STUDIES

The tested specimens made of glass/epoxy 12-layered laminate reinforced by a E-glass fabric with a trade symbol EP GC 201 were manufactured and supplied by Izo-Erg S.A. (Gliwice, Poland). The matrix of a composite was made from a mixture of epoxy resin of Epidian 6 type, phenol formaldehyde resin of a medium molecular weight as a curing agent and 2-methylimidazole as a catalyzer. A molar ratio of the epoxy groups of the epoxy resin to the phenolic hydroxyl groups of the novolac was equal to 1:1. The reinforcement of a composite was impregnated into the matrix by the prepolymer acetone solution (with above-mentioned composition) and dried in a hot air. The dimensions of the manufactured specimens were as follows: the length of 80 mm, the width of 10 mm, and the thickness of 2.5 mm. Note that the effective length, i.e. the length between specimen holders, was 50 mm. In order to ensure statistical validity, 36 specimens were selected for the experimental studies. The specimens were loaded with an excitation frequency of 30 Hz and initial loading force of ca. 90 N. The loading was performed until occurrence of a total failure of each specimen. Before testing, the specimens were covered with a black matt heat-resisting silicone enamel produced by Dragon Poland Sp. z o.o. (Cracow, Poland) in order to ensure appropriate thermal emissivity for infrared measurements and reduce surface reflectivity.

The experiments were performed on the own-designed test rig, which allowed for a fully reversed cyclic mechanical excitation of the specimens in a stress relaxation mode. A scheme of the experimental setup is presented in Fig. 1. The cyclic loading was performed by the TIRA® TV-51120 electrodynamic shaker *1* controlled by analogue output of a multi-channel signal acquisition module *11*, which controls the TIRA® BAA 500 shaker amplifier *10*. The excitation signal is generated and controlled through the own-developed application from the PC *12*.

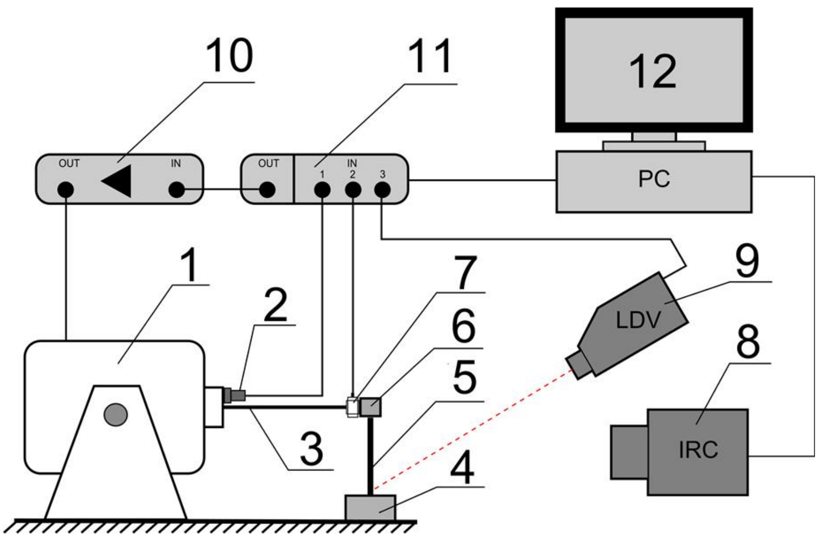

Fig. 1. A scheme of the experimental setup

A specimen *5* was clamped in a bakelite fixed holder *4*, which ensures appropriate thermal isolation of a specimen, and connected with the shaker *1* through a stinger *3* ended by the PCB Piezotronics® 208C03 force sensor *7* and a specimen holder *6* connected with a force sensor *7* on the screw joint. For ensuring repeatable conditions, each specimen was clamped with a constant torque of 20 Nm. The PCB Piezotronics® T352C34 accelerometer *2* was mounted directly on the shaker *1* and connected with the signal acquisition module *11* in order to control an excitation signal. A vibration velocity of a specimen was measured using the Polytec® PDV-100 laser Doppler vibrometer *9*, while the thermal response was registered using InfraTec® VarioCAM® hr infrared camera *8* with a resolution of 640×480 px and a framerate of 2 pictures per second.

ANALYSIS OF EXPERIMENTAL RESULTS

As it was mentioned, the temperature distribution varies depending on the fatigue phase of a tested structure. In order to evaluate this variation quantitatively, the acquired sequences of infrared images for the tested specimens were subjected to image processing in order to determine a total area of a heated region up to the defined temperature value. It should be noticed that the defined temperature value was not constant but variable with an increase of the maximal self-heating temperature value. In the selected colormap, the colorful region (non-grayscale) was assumed as a basis for determination of a heated region. The limit temperature value (i.e. the threshold between the colorful and the grayscale regions) was exactly in the middle of a temperature scale between minimal and maximal temperature values observed at a certain moment. The growth of the limit temperature value was proportional to the growth of a maximal self-heating temperature value. Following this, and neglecting small fluctuations of the ambient temperature, it can be assumed that the limit temperature is driven by the maximal self-heating temperature value. The exemplary infrared images are presented in Figs. 2a, 2c, 2e.

The thermal images were cropped in order to obtain the region of interest and lower the computational time during image processing, and imported to MATLAB® environment. The images were subjected to a squeezing operation on the red color channel, and the resulting images were transformed into a binary mode using adaptive thresholding algorithm. Then, using morphological operations, the region of heating was identified and the area in pixels was calculated. One pixel on the acquired thermal images has the dimensions of ca. 0.15×0.15 mm. The exemplary resulting images after processing are presented in Figs. 2b, 2d, 2f, and correspond to the infrared images presented on the top of Fig. 2. Additionally, Fig. 2 represents the observed phenomenon, i.e. variation of the temperature distribution at different phases of fatigue.

Following the observed phenomenon and having calculated the total areas of the heated regions visible on the thermal images in each sequence the evolution of the area in a function of time was determined. For a comparison purpose an exemplary total area evolution curve was presented together with a maximal self-heating temperature history curve observed for the selected case in Fig. 3.

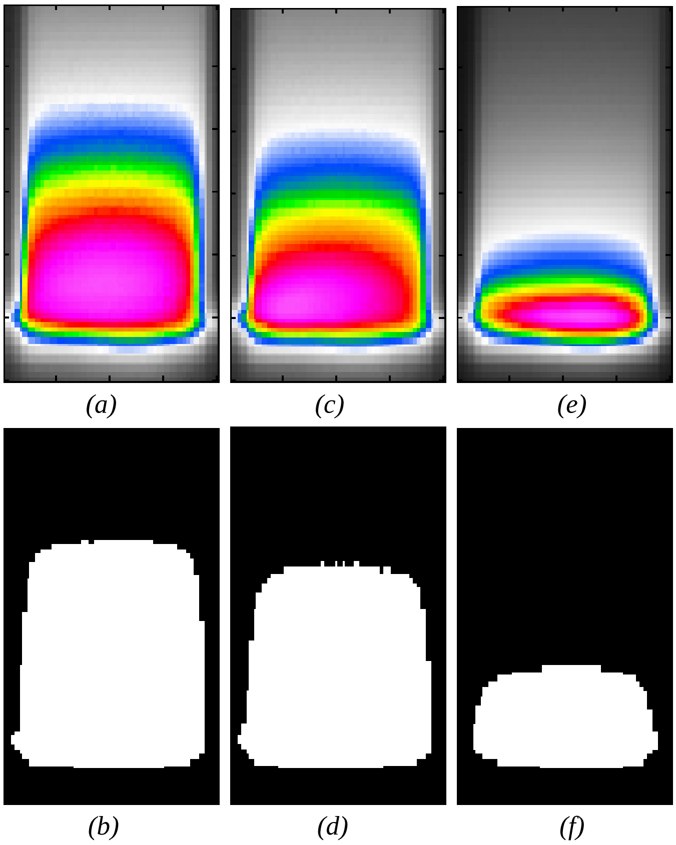

Fig. 2. Infrared images and corresponding processed images: (a), (b) before starting of structural degradation; (c), (d) after initiation of structural degradation, (e), (f) at structural failure

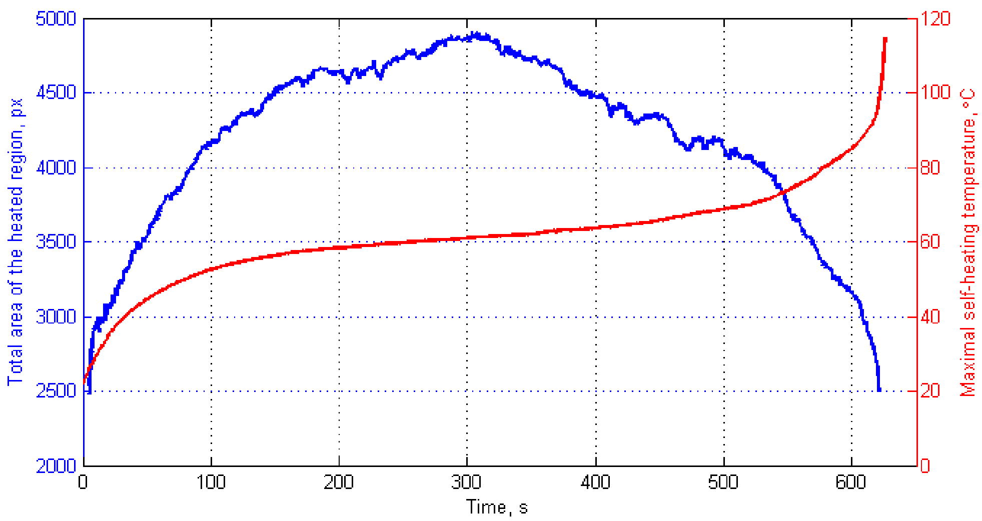

Fig. 3. Evolution of a total area of heated region with the maximal self-heating temperature history

One can observe that a total area of the heated region grows with an exponential increase observable in the maximal self-heating temperature history curve, which is a direct consequence of the second law of thermodynamics and coincides with the first phase of self-heating. However, the growth of the total area of the heated region can be also observed during the second phase of self-heating, when the maximal self-heating temperature slowly increases. In this case, the growth of the total area of the heated region is a result of a thermal imbalance between the amount of generated heat and heat released to environment. As one can observe, the total area of the heated region grows up to a certain value (in 303.5 s in the case presented in Fig. 3), and after reaching it, this quantity starts decreasing. Excluding the thermodynamic reasons (if the thermal equilibrium is not reached, then the growth of the heated region should continue), the reason of decreasing temperature is the stress redistribution in the loaded specimen caused by initiation of damage. In the next time steps a total area of the heated region decreases in almost monotonic way, which confirms propagation of initiated damage, including coupling of microcracks and formation of a macrocrack (cf. results of X-ray computed tomographic tests [16]). Following this, a selection of the last peak value before the beginning of a total area of heated region decrease was assumed to be a criterion for determination of the criticality of the self-heating effect.

The analysis of all the tested specimens was performed using the above-described criterion. The resulting critical values were determined by getting a moment of time at which a global peak of the total area of the heated region is observed and reading the maximal self-heating temperature at this time. The results of the performed analysis are presented in Fig. 4 in a form of a 12-bins histogram.

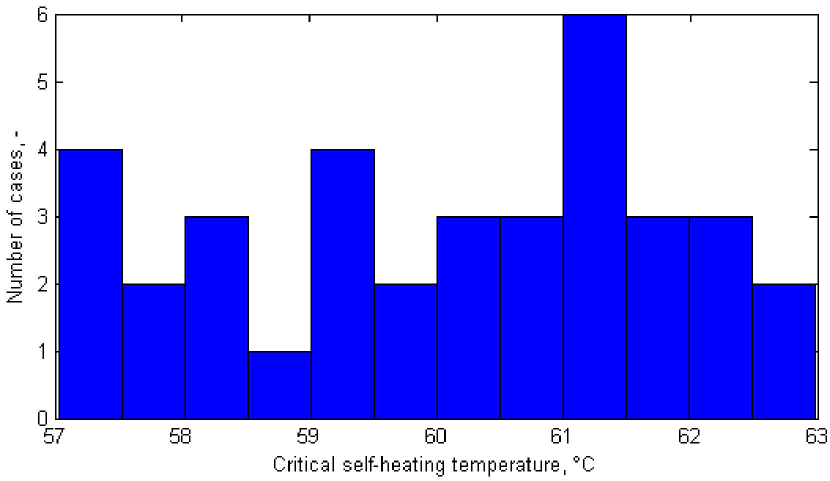

Fig. 4. Histogram of a distribution of resulting critical self-heating temperature values obtained following the proposed criterion

The number of bins was intentionally increased with respect to the commonly known statistical rules (e.g. Sturges' rule or Rice rule) in order to visualize the temperature intervals better. One can observe a multimodal histogram in the temperature range of 57÷63°C with the most frequent value of 61°C, while the average value from all the cases equals 60.06°C.

Comparing the obtained critical values to the previously obtained results using different measurement techniques, which were as follows: ~80°C for approximation of self-heating temperature history curves, ~70°C for acoustic emission measurements, ~65°C for quasi-static tensile tests [10], ~65°C for microscopic analysis [9], and ~60°C for X-ray computed tomography tests [16], one can conclude that the approach proposed in this paper is characterized by a very high sensitivity to structural changes, comparable to X-ray computed tomography. This confirms that the degradation processes during fatigue of composite structures accompanied by the self-heating effect starts when the maximal self-heating temperature in a distribution reaches 60°C. This value can be considered as the critical in further studies. Additionally, the observed changes of slopes of particular fragments of the total area curves can be assigned to the phases of fatigue, which is clearly visible comparing both curves in Fig. 3.

CONCLUSIONS

The proposed approach in this paper, which was based on evolution of the heated area on the surface temperature distribution during fatigue accompanied by the self-heating effect, was found to be an effective indicator of the criticality of the self-heating effect. Based on evolution of this indicator an accurate determination of irreversible structural changes, which lead to the structural failure, is possible. Comparing the obtained results to the critical values obtained using other measurement techniques, it was concluded that the proposed approach is one of the most sensitive. Following this approach the critical self-heating temperature for the tested composite structures was reevaluated and equals 60°C. It is possible to apply the obtained knowledge during design of polymeric and polymer-based composite elements subjected to cyclic loading or vibration in such a way that the generated heat should be controlled not to reach the critical value. The same rules are applicable to already maintained composite elements, which should work in safe temperature ranges in order to preserve their residual life.

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REFERENCES

1. Katunin A., Fidali M.: Fatigue and thermal failure of polymeric composites subjected to cyclic loading, Advanced Composites Letters 21 (2012) 64-69.
2. Talreja R.: Fatigue of Composite Materials, Technomic Publishing Company Inc., Lancaster, PA, 1987.
3. Toubal L., Karama M., Lorrain B.: Damage evolution and infrared thermography in woven composite laminates under fatigue loading, International Journal of Fatigue 28 (2006) 1867-1872.
4. Ferreira J.A.M., Costa J.D.M., Reis P.N.B., Richardson M.O.W.: Analysis of fatigue and damage in glass-fibre-reinforced polypropylene composite materials, Composites Science and Technology 59 (1999) 1461-1467.
5. Pegoretti A., Riccò T.: Fatigue crack propagation in polypropylene reinforced with short glass fibres, Composites Science and Technology 59 (1999) 1055-1062.
6. Katunin A.: Critical self-heating temperature during fatigue of polymeric composites under cyclic loading, Composites Theory and Practice 12 (2012) 72-76.
7. Naderi M., Kahirdeh A., Khonsari M.M.: Dissipated thermal energy and damage evolution of glass/epoxy using infrared thermography and acoustic emission, Composites: Part B 43 (2012) 1613-1620.
8. Kahirdeh A., Khonsari M.M.: Criticality of degradation in composite materials subjected to cyclic loading, Composites: Part B 61 (2014) 375-382.

9. Katunin A., Wronkowicz A., Bilewicz M.: Evaluation of critical self-heating temperature of composite structures based on analysis of microcrack development, Composites Theory and Practice 17 (2017) 9-13.
10. Katunin A., Wronkowicz A., Bilewicz M., Wachla D.: Criticality of self-heating in degradation processes of polymeric composites subjected to cyclic loading: A multiphysical approach, Archives of Civil and Mechanical Engineering 17 (2017) 806-815.
11. Facchini M., Botsis J., Sorensen L.: Measurements of temperature during fatigue of a thermoplastic polymer composite using FBG sensors, Smart Materials and Structures 16 (2007) 391-398.
12. Goidescu C., Welemane H., Garnier C., Fazzini M., Brault R., Péronnet E., Mistou S.: Damage investigation in CFRP composites using full-field measurement techniques: Combination of digital image stereo-correlation, infrared thermography and X-ray tomography, Composites: Part B 48 (2013) 95-105.
13. Katunin A.: Analysis of temperature distribution in composite plates during thermal fatigue, Modelling in Engineering 16 (2013) 99-105.
14. Backe D., Balle F., Eifler D.: Fatigue testing of CFRP in the Very High Cycle Fatigue (VHCF) regime at ultrasonic frequencies, Composites Science and Technology 106 (2015) 93-99.
15. Magi F., Di Maio D., Sever I.: Damage initiation and structural degradation through resonance vibration: Application to composite laminates in fatigue, Composites Science and Technology 132 (2016) 47-56.
16. Katunin A., Wronkowicz A.: Evolution of a fracture mechanism in a polymeric composite subjected to fatigue with self-heating effect, Procedia Structural Integrity 5 (2017) 416-421.