PHENOMENOLOGICAL ANALYSIS OF SELF-HEATING EFFECT IN GLASS AND CARBON FABRIC REINFORCED POLYMERIC COMPOSITES

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Summary
The self-heating effect occurring in polymeric composites during cyclic loading or vibrations is a dangerous phenomenon which affects intensification of mechanical degradation processes and shortening of structural residual life. During this process, heat is generated due to hysteretic behavior of a polymeric matrix, and the growing surface temperature may initiate the most dangerous mode of self-heating effect – the non-stationary one. During non-stationary self-heating the heating-up process dominates mechanical degradation and causes its significant intensification and sudden failure. Besides the loading conditions, several other factors influence the self-heating process. In this paper, the influence of reinforcing material as well as its content in the composite is analyzed in the light of self-heating effect. The results of the performed experimental studies show that these material properties have a great impact on intensity of self-heating effect. This observation allows for better understanding the mechanics of structural degradation of fabric-reinforced composites subjected to cyclic loading with self-heating effect occurrence. The obtained results might be helpful in development of new industrial composites, which will be characterized by high thermal conductivity and effectively release generated heat to the environment, increasing the operational safety of composite elements working in mentioned loading conditions.

Keywords: self-heating effect, polymeric composites, thermal conductivity, glass fabric, carbon fabric

ANALIZA FENOMENOLOGICZNA EFEKTU SAMOROZGRZANIA W KOMPOZYTACH POLIMEROWYCH WZMACNIANYCH TKAÑINĄ SZKLANĄ I WĘGLOWĄ

Streszczenie
Efekt samorozgrzania, powstający w kompozytach polimerowych podczas obciążeń cyklicznych lub drgań, jest niebezpiecznym zjawiskiem, które powoduje intensyfikację procesów mechanicznej degradacji oraz skrócenie żywotności struktur. Podczas tego procesu ciepło jest generowane wskutek histerezowego zachowania osnowy polimerowej, a wzrastająca temperatura na powierzchni może inicjować najbardziej niebezpieczną postać efektu samorozgrzania – niestacjonarną. Podczas samorozgrzania niestacjonarnego proces nagrzewania się staje się dominujący w stosunku do degradacji mechanicznej i powoduje jego znaczną intensyfikację oraz szybkie zniszczenie. Oprócz warunków obciążeń, niektóre inne czynniki wpływają na proces samorozgrzania. W niniejszym artykule wpływ materiału wzmacnienia oraz jego zawartości w kompozycji został przeanalizowany w świetle efektu samorozgrzania. Wyniki przeprowadzonych badań eksperymentalnych wskazują na znaczący wpływ właściwości materiałów umocnienia na intensywność efektu samorozgrzania. Taka obserwacja pozwala na lepsze zrozumienie mechaniki degradacji strukturalnej kompozytów wzmacnianych tkaninami poddanych obciążeniom cyklicznym z występowaniem efektu samorozgrzania. Otrzymane wyniki mogą być pomocne przy opracowaniu nowych kompozytów kon-
1. INTRODUCTION

Polymeric composites are widely used in engineering constructions due to their superior strength and operational properties, and low mass. Due to their outstanding properties, they often substitute metallic structures with significant improvement of a strength-to-mass ratio, resistance to corrosion and several aggressive chemicals, etc. However, a serious and still unsolved problem of applied composite materials is the predictability of fatigue processes occurring in them during operation. In particular, the fracture mechanisms appeared in these structures during loading are very complex, due to many factors, such as anisotropy, non-linearities of material properties and physical interactions occurring during fatigue processes, etc. Therefore, the prediction of a structural residual life of polymeric reinforced composites is still extremely difficult.

One of the most influencing phenomena on fatigue processes of polymeric composites is a thermal effect, known as the self-heating effect. This effect appears due to the out-of-phase oscillations between stress and strain amplitudes in a cyclically loaded polymeric composite, which leads to a mechanical hysteresis. The hysteretic behavior is due to viscoelastic nature of a matrix of a composite. During such behavior, mechanical energy dissipates, mostly in the form of heat, which, in consequence, causes non-uniform heating-up of a structure in regions of stress concentrations. Generated heat may stabilize at a certain temperature value due to thermal equilibrium between generated heat and heat released to the environment by convection, conduction, and radiation, which is less dangerous for the structural integrity, i.e., the stationary self-heating influence on the fatigue processes is minor. In the case, when the amount of generated heat is higher than the amount to be released by a structure, the self-heating effect dominates the fatigue process, and self-heating becomes non-stationary. In this case, a continuous surface temperature growth is observed, which significantly intensifies degradation processes, and finally leads to the thermal failure. During non-stationary self-heating, the maximal self-heating temperature may reach values even higher than glass-transition temperature for a loaded polymer (see e.g. [7]).

The self-heating effect occurring in polymers and polymeric composites is a subject of intensive studies since 60s of XX century [15-18]. The authors of mentioned studies performed first experiments connected with the self-heating evolution for various polymers and polymeric composites as well as proposed empirical equations for fatigue of these materials accompanied by the self-heating effect. Further, the character of heat generation in polymeric materials during cyclic loading was deeply investigated in terms of both theoretical modelling [2,4,5,13,22] and experimental investigations [14,19-21]. Previous author’s studies were focused on evaluation of influence of loading parameters on the resulting intensity of the self-heating effect. In particular, in [6,7] the influence of loading frequency and geometry were investigated, while in [12] the influence of mechanical reloading was analyzed. However, besides the influence of loading parameters, a crucial impact on the self-heating effect intensity have material properties of a loaded structure, which was experimentally proven in [10] during performing dynamic tests on glass- and carbon-reinforced composites. Following the obtained results, it was decided to analyze a phenomenology of self-heating effect in terms of materials used for reinforcement as well as an amount of polymer in a composite.

In this paper, a comparative study of experimentally determined thermal responses of glass- and carbon-reinforced polymers subjected to cyclic loading was performed. In order to compare a behavior of these two materials, the loading was performed in a stress relaxation mode. An evaluation of thermomechanical behavior of these two most widespread materials in structural elements during occurrence of the self-heating effect allows for better understanding the physics of the process, which may help in modelling and prediction of structural behavior of composites being loaded in such conditions. Additionally, the results of this investigations allow for limiting the influence of the self-heating effect on structural degradation and increase structural safety of composite elements subjected to such types of mechanical loading.

2. SPECIMENS

AND EXPERIMENTS

The 12-layered unidirectional glass fabric-reinforced polymeric (GFRP) composite specimens were manufactured and supplied by Izo-Erg S.A. (Gliwice), while carbon fabric-reinforced polymeric (CFRP) composite
specimens with the same internal architecture were manufactured and supplied by Dexcraft S.C. (Wolomin). The reinforcement of GFRP composite has a plain weave, while the reinforcement of CFRP has a double twill weave (see Fig. 1). For experimental studies 3 specimens of every kind of composite were selected. The dimensions of all specimens were as follows: the length of 100 mm, the width of 10 mm, and the thickness of 2.5 mm.

The experiments are performed on the own-designed test rig (see Fig. 2), which allows for excitation of specimens in a fully reversed stress relaxation mode with a constant frequency. The stress relaxation mode assumes that the excitation is performed with a constant strain, which is necessary to perform comparison of thermal responses of CFRP and GFRP specimens, since their stiffness significantly differs.

The excitation was performed by the electrodynamic shaker through the steel stinger ended with the force sensor (in order to control excitation force) and a holder which holds a loaded specimen. From the other side a specimen was clamped in a bakelite clamp in order to ensure its thermal insulation. In order to ensure repeatable conditions clamping was performed with a constant torque of 20 Nm. The excitation signal of harmonic type with a frequency of 30 Hz was generated in own-developed software, amplified by the power amplifier and delivered to the shaker. Additionally, the displacements were measured and controlled by the laser Doppler vibrometer focused on the bottom region of a specimen above the clamp. The signals of loading force and displacements were collected with a sample rate of 2 kHz. The self-heating surface temperature measurements were performed by the infrared camera focused on a specimen with a framerate of 2 Hz. Prior testing each specimen was covered by the black matt heat-resisting enamel in order to increase surface emissivity and reduce reflectivity during thermographic measurements. The duration of each test was set to 5 minutes in order to achieve stabilization of a surface temperature distribution.

3. ANALYSIS OF RESULTS

The collected sets of signals and thermograms were imported to Matlab® environment for further processing. The signals of displacements and force amplitudes were processed in order to determine their envelopes. The resulting envelopes (of positive values) of displacements and force amplitudes are presented in Figs. 3 and 4, respectively.

The results presented in Figs. 3 and 4 indicated that the loading force values significantly differ for CFRP and GFRP specimens, which is a result of much higher stiffness of carbon fabric comparing to the glass one.
However, the displacements were almost similar due to the assumed stress relaxation mode of loading. The vibration velocity was assumed on the level of $8.5 \times 10^{-3}$ m/s on average. The observed differences in force and vibration velocity measurements are resulting from manual regulation of the power amplifier voltage. Considering these loading conditions it is essential to analyze temperature history curves for the considered specimens, which are presented in Fig. 5 for the tested specimens.

![Maximal self-heating temperature history curves for tested specimens.](image)

**Fig. 5.** Maximal self-heating temperature history curves for tested specimens.

Analyzing the obtained temperature history curves it can be observed that in spite of similar loading amplitude of displacements for CFRP and GFRP specimens, the self-heating curves differ. This difference is a result of multiple phenomena influencing the self-heating process. Taking into consideration that in both cases the matrix of composites was made of epoxy resin, the reinforcing fabric plays here a crucial role. Analyzing thermal conductivity of CFRP and GFRP it can be stated that the value of a thermal conductivity of CFRP is much higher both in longitudinal and transverse directions [1]. This fact causes that in spite of similar level of loading displacements, and thus, similar amount of delivered mechanical energy, the amount of released energy is different (due to the differences in thermal conductivity), which reflects in registered temperature fields. Similar observations are reported in literature: Goel et al. [3] observed that the polypropylene reinforced by E-glass fiber reveals lower self-heating temperature increase in comparison to an unreinforced polypropylene. This is a direct consequence of a difference in thermal conductivity of tested materials, and thus, faster releasing of generated heat to the surrounding in the case of reinforced polypropylene. Similar results were obtained by Shukla et al. [23] during comparing thermal responses of specimens made of pure polypropylene, carbon nanotube-reinforced polypropylene, and glass fiber-reinforced polypropylene. The lowest temperature increase was observed in this case for carbon nanotube-reinforced polypropylene specimens due to their highest thermal conductivity among the tested types of materials.

Another material factor, which may have an influence on the self-heating effect intensity is an amount of a polymer in a composite. Since self-heating effect is driven by viscoelastic properties of a polymer, which constitutes a matrix of a composite, it is obvious that the more polymer content in a resulting composite, the more intensive self-heating effect occurs. However, considering the currently used manufacturing techniques of composite elements in underpressure conditions (e.g. vacuum bagging, autoclave manufacturing), which is beneficial from the point of view of operational properties as well as lowering the content of manufacturing flaws, the amount of a polymer in composite structures and elements seems to be negligible.

### 3. DISCUSSION AND CONCLUSIONS

The specimens of CFRP and GFRP subjected to cyclic loading in the stress relaxation mode in order to investigate the influence of material properties of reinforcement on the intensity of the self-heating effect are tested. Based on the results of preformed studies it was observed that the specimens with carbon fabric reinforcement reveal lower increase of self-heating temperature, which can be explained by much higher thermal conductivity of carbon fiber with respect to the glass one. Obviously, the conductivity of reinforcement significantly influences on an overall conductivity of a composite, and may sufficiently minimize the negative consequences of the self-heating effect and extend the residual life of a structure subjected to such a type of loading. Considering this fact, it is possible to modify the component content in industrial composites used for elements subjected to cyclic loading and vibrations in such a way, that the self-heating effect will be sufficiently lowered by increasing a thermal conductivity of a composite. Such results can be achieved by adding low amounts of low-cost highly conductive particles, such as carbon dust, into a polymeric matrix, which may additionally increase a thermal conductivity. Moreover, in the case of increasing of thermal conductivity of composite structures, the intensification of fatigue structural degradation of composites may be sufficiently limited. As the previous results show [8,9,11], reaching the critical value of a self-heating temperature leads to the formation of irreversible chemical and structural changes, e.g. matrix cracks and residual cross-linking processes in a polymeric matrix. Increasing a thermal conductivity of a composite may prevent a structure from reaching the critical temperature value, which increases an operation safety of composite structures being operated in such loading conditions.
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References


