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Original Research Article

Criticality of self-heating in degradation processes of polymeric composites subjected to cyclic loading: A multiphysical approach

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ABSTRACT

In this paper, the criticality of the self-heating effect accompanying the fatigue process of polymeric composites is studied by monitoring various physical parameters, which reflects degradation progress in a direct or indirect way. The occurring self-heating effect, resulted from the mechanical energy dissipation due to the viscoelastic nature of a polymeric matrix of composites, under certain loading conditions, may dominate the fatigue process, causing significant intensification of degradation and thermal failure at temperature often higher than the glass-transition temperature. The aim of this study is to determine the critical values of the self-heating temperature, which exceeding results in damage initiation and, in consequence, intensive degradation and failure. Additionally, performed tests enable evaluation of sensitivity of particular techniques as well as obtaining more accurate results with physical justification. Following the obtained results, the critical value of a self-heating temperature, at which domination of the fatigue process by the self-heating effect is observed, is at a level of 65–70 °C. Information about the obtained critical values has a great importance both during the design stage of composite structures subjected to cyclic loading as well as their further operation.

1. Introduction

Fatigue is one of the most important failure mechanisms occurring in composite structures being in operation. Due to their heterogeneity, anisotropy of material properties and specific rheological properties the fatigue processes of polymeric composites are very complex. Therefore, the resulting structural degradation is a consequence of many physical phenomena occurring during the fatigue process and interacting with each other. In case of cyclic loading of polymeric composite structures the fatigue process is accompanied by

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mechanical energy dissipative processes. Some small amount of this energy dissipates due to microcracking of a polymeric matrix and at an interface of composite components (see e.g. [1]), another small amount of this energy dissipates due to plastic mechanisms developing during loading [2], however, an overwhelming majority of the dissipated energy is generated due to the viscoelastic nature of a polymeric matrix of a composite [3]. During cyclic loading the mechanical energy resulting from out-of-phase oscillations between stress and strain magnitudes dissipates in a form of heat and, considering low thermal conductivity of most industrial polymers used for manufacturing of composites, the generated heat is stored in the structure causing temperature growth. This temperature is known in the literature as the self-heating temperature or the hysteretic heating temperature.

In general, the process of fatigue degradation of polymeric composites consists of three stages: at the first stage initial damage accumulation in a form of microckracks of a polymeric matrix can be observed; further, at the second stage, monotonically growing damage accumulation in the matrix as well as at the fiber/matrix interface occurs; and finally, at the third stage, macroscopic cracks development in the matrix, and immediately after that, fiber breakage occurs which leads to failure of the structure. This three-stage model was observed by numerous researchers studying fatigue and fracture of polymeric composites, and what is interesting, a similar model can be observed during analysis of various operational parameters during fatigue. One can observe that both the three-stage degradation model as well as a history curve is similar for stiffness reduction (or damage index) [4,5] and temperature growth [5–8]. Moreover, recent studies of Kahirdeh and Naderi have shown that a similar character is observed in the cumulative acoustic emission (AE) energy [9] and the acoustic entropy [10]. Considering the mentioned experimental results one can conclude that the mechanical, thermal and acoustic phenomena occurred during structural degradation of cyclically loaded polymeric composites are coupled. Similar observations have been made by Mortazavian and Fatemi in their literature survey [11], where the self-heating effect is broadly discussed.

Depending on the stress magnitudes of a cyclically loaded structure (which are directly connected with the amount of dissipated mechanical energy), the fatigue process may evolve following two scenarios with respect to occurrence of the self-heating effect. If the stress magnitudes are below a certain critical value the self-heating temperature increases to the value equivalent to the resulting stress value and then stabilizes at a certain value. This stabilization occurs since the structure reaches thermal equilibrium between the generated thermal energy and the thermal energy convected to the environment. In such case the stationary self-heating occurs, which is characterized by a small temperature increase, and thus, does not influence on the fatigue process significantly. Examples of such the self-heating temperature evolution can be found in [12–15]. In the second case the stress values are high enough to generate heat which dominates the fatigue process and significantly intensifies it. In this case the temperature value tends to a certain critical value, which results in development of fracture mechanisms at the micro level. This, in turn, causes stiffness decrease and ability of increasing the generated heat. As a result, the self-heating temperature does not reach the thermal equilibrium – the temperature history curve in the second stage of degradation is characterized by a slope, which depends on the applied loading. In this case the non-stationary self-heating can be observed. Such a behavior has been confirmed in numerous experimental studies (see e.g. [16,17,8]). Similar observations on duality of the self-heating effect have been made by different research groups, see e.g. [18–20].

Considering the duality of the self-heating effect it is essential to determine the criticality of this phenomenon in terms of fatigue processes, in particular to determine the critical self-heating temperature or a temperature range within which the non-stationary self-heating occurs. Several attempts have been done to-date by different research groups. One of the first studies on criticality of the self-heating effect during fatigue of polymeric composites was performed in a previous research [21], where the critical self-heating temperature was determined based on differences between an experimental self-heating temperature history curve and an approximating double-exponential model. It was stated that the self-heating temperature is critical when the measured temperature curve and the approximating model starts diverging. However, further Raman spectroscopy tests of the loaded specimens of a polymeric composite [22] indicated that the degradation processes may occur at lower temperature values. In the same period, the problem of criticality of the self-heating phenomenon was deeply investigated by Kahirdeh, Khonsari and Naderi [17,9]. The authors have come to the same conclusions by analyzing the degradation process of composites induced by the self-heating effect based on temperature and AE measurements. Similar studies on structural degradation of composites were performed by Magi et al. [23]. The authors investigated influence of low-frequency and resonant vibrations on damage initiation intensified by the self-heating effect and observed the moment of initiation of delamination in the composite. Such delamination can be considered as macroscopic damage. The problem of heat generation in polymeric and composite elements subjected to cyclic loading is of a great importance from a practical point of view. Several studies indicate negative influence of the self-heating effect, e.g. in viscoelastic dampers [24], composite driveshafts [25] or in polymer adhesively bonded composite joints [26], thus studying the criticality of this phenomenon is of crucial importance in modern fatigue studies of polymeric composite structures.

All of the above-discussed studies were focused on dominating influence of the self-heating effect on fatigue and structural degradation. However, analyzing the obtained results one can conclude that they differ significantly. There are several factors that have a crucial influence on such differences: the degradation process depends on excitation parameters, which was proven in the previous studies [8,15], another important factor is sensitivity of the applied measurement techniques. Therefore, a multiphysical approach is needed to evaluate the sensitivity of particular experimental methods as well as to determine the critical self-heating temperature value that initiates the non-stationary self-heating in polymeric composites.