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Analysis of defect detectability in polymeric composites using self-heating based vibrothermography

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ABSTRACT

The self-heating based vibrothermography (SHVT) is a new non-destructive testing method dedicated for testing of polymer matrix composite structures, where the excitation is performed by externally applied mechanical vibrations in a low frequency range. Exciting a structure with several resonant frequencies, the heating up of this structure is possible due to the occurrence of the thermoviscoleastic effect called the self-heating, whose nature originates from the mechanical energy dissipation. In order to examine an efficiency of the SHVT an analysis of defect detectability on composite specimens with milled artificial defects was performed. The post-processing of the series of resulting thermograms was performed in order to enhance defect detectability. The obtained results allow to conclude about high efficiency of SHVT NDT technique, which can be used especially in cases when a direct access to the testing structure in order to excite it externally is difficult or impossible.

1. Introduction

Active infrared thermography (IRT) is a widespread non-destructive testing (NDT) method applied for testing and inspection of structural elements in various industrial branches. A special attention in IRT testing is paid to structures made of polymer matrix composites (PMCs) due to their wide applicability for manufacturing of elements of transport means. IRT NDT methods, considering its various modifications, allow for fast and non-contact inspection of such structures and detection of surface and subsurface manufacturing and operational defects and propagating damage resulting e.g. from fatigue processes. Numerous research studies prove the efficiency of application of IRT NDT for aircraft [1–3], aerospace [4–6], automotive [7,8], and other composite structures to detect and identify internal defects and damage.

The difficulty in inspection of such structures with respect to homogeneous ones, is, first of all, its anisotropy, which influences on thermal wave speeds in various directions, and the directionality of thermomechanical properties of tested composite structures [9]. Moreover, the crucial influence on the defect detectability in such structures has an applied IRT method and the parameters of thermal excitation of a tested structure. Following this, it is essential to classify the methods and discuss possible excitation procedures.

The classical IRT methods used for structural damage identification (SDI) in composites can be classified, in general, to pulsed IRT methods, transient IRT methods, and the methods with frequency-modulated excitation (lock-in IRT). The pulsed IRT methods are the simplest ones, and are based on excitation by a thermal pulse and observation of a tested structure using infrared (IR) camera, while the delivered heat diffuses through the tested structure. A comprehensive review with the historical overview and theoretical background on the pulsed IRT methods is presented in [10]. The transient IRT methods are very similar to the pulsed ones with one significant difference: the duration of excitation in the case of transient IRT is much bigger, which allows using less powerful heating sources with respect to the pulsed IRT. The SDI ability of this group of methods is comparable with those of pulsed IRT. More details on this approach can be found in [11]. The application of lock-in IRT, where the excitation thermal wave is modulated at a fixed frequency and the thermal response is observed by IR camera, allows for significant improvement of defect detectability with respect to previously discussed methods (see [12,13] for more details). In all of the aforementioned types of IRT optical or external heating source excitation is used, usually in the form of flashes, halogen or IR lamps, lasers, fluid jets, heating blankets, etc. [14,15].

An alternative IRT approach with respect to already presented methods is vibrothermography (VT) – a group of methods which use mechanical or internal excitation, classified by the authors of [15] as an another group of methods with respect to all aforementioned IRT methods. The main difference of VT with respect to other IRT methods is a lack of external heating source, which is substituted by heating resulting from mechanical excitation of a tested structure. The concept of VT was proposed by the authors of [16,17] in the early 1980s. The heating of a tested specimen is usually performed in the form of

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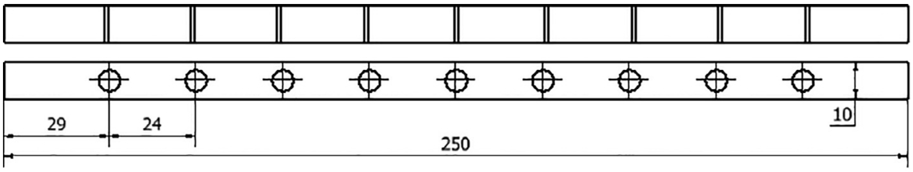

Fig. 1. The schemes of milled defects with characteristic dimensions.

mechanical excitation by an elastic wave in a sonic or ultrasonic [18–20] frequency range, which results in energy dissipation in a tested structure. In the case of existence of a defect the bigger energy dissipation is observed due to the friction between the faces of a defect or stress concentration in the surrounding area of a defect [20]. The physics of this phenomenon is widely discussed in [21,22]. This leads to the situation, where an increase of temperature is observed only at the location of a defect, which can be captured by IR camera. The excitation is usually performed in the contact way using ultrasonic boosters or actuators placed on the surface or integrated with a tested structure.

Besides of sonic and ultrasonic heating sources used in VT, other types of excitation are successfully developed. The authors of [23] based their approach of the thermal excitation on electromagnetic induction applied to the carbon fibre of a tested composite structure, which allows for local heating. Another approach of thermal excitation of a tested composite structure is using the thermoviscoelastic effect, known in a literature as the self-heating effect, accompanied by mechanical vibrations of such a structure. The nature of internal heat generation is different than for classical ultrasonic VT, since the heating in this case is coming from hysteresis resulting from phase lag of stress and strain amplitudes during mechanical vibrations, and originating from an internal structure of a polymeric matrix of a tested composite instead of frictional heating phenomena occurring during ultrasonic excitation of a tested structure [21]. The ability of heat generation of polymeric composites subjected to vibrations was successfully used in several previous studies. In particular, the self-heating effect was used by the authors of [24], where they presented results of investigation on viscoelastic response of flat-bottom holes (FBHs) filled with a viscous material, while the specimen was subjected to mechanical vibrations in the ultrasonic frequency range. The authors of [25,26] used mechanical excitation on resonant frequencies to localize the crack and monitor its propagation. The idea on excitation of tested structures with resonant frequencies was also used by the authors of [27], where they used absorptive viscoelastic coatings on the tested metallic specimens in order to observe the self-heating effect during excitation of specimens with resonant frequencies in the ultrasonic frequency range.

Previous experimental studies of the authors' team on a self-heating temperature distribution during mechanical excitation with resonant frequencies starting from the fundamental frequency of vibrations [28] as well as initial studies on application of the self-heating effect to damage identification in composite structures [29] show the potential of this approach in NDT practice. The preliminary studies presented in [29] allow for definition of a testing procedure based on the performed experiments, i.e. it was observed that the reasonable and the most effective approach is an excitation of a composite structure with a multi-harmonic signal composed of several harmonics corresponding to the resonant frequencies of vibrations of a tested structure. An excitation with multiple resonant frequencies allows to excite the corresponding modal shapes, and thus, the regions of the highest stress for each modal shapes are different. Since in viscoelastic materials mechanical stress is directly related with the amount of energy dissipation (see [28] for instance), these regions correspond with regions of maximal heating up. This justifies the mechanical excitation with multiple resonant frequencies, assuming that the presence and location of eventual defect is not a priori known.

The main goal of this paper is to investigate defect detectability efficiency, i.e. an estimation of depth at which a defect is still detectable. For this purpose the tests were performed on specimens with FBHs of various depths and shapes. It was shown that taking into consideration a series of thermograms instead of a single thermogram, and their further common analysis allow to enhance defect detectability. Additionally, the post-processing of thermograms in order to enhance defect detectability is discussed. The efficiency of the proposed approach is confirmed by the promising results obtained from self-heating based vibrothermography (SHVT) NDT experiments.

2. Specimens preparation

The specimens made of the glass E-fabric-reinforced 14-layered epoxy composite material purchased from Izo-Erg S.A. (Gliwice, Poland) were cut from a sheet with the thickness of 2.5 mm into strips with the length of 250 mm and the width of 10 mm. For the investigation of defect detectability efficiency FBHs were milled in the specimens according to the schemes presented in Fig. 1.

The milling was performed on the two-axis milling machine Roland Modela MDX-20 (Hamamatsu, Japan) using ø1 diamond milling cutter (see Fig. 2) with the following milling parameters: milling speed in the planar directions of specimens' surface was of 10 mm/s, milling speed in the thickness direction was of 0.5 mm/s, and a spindle speed was of 6500 rpm.

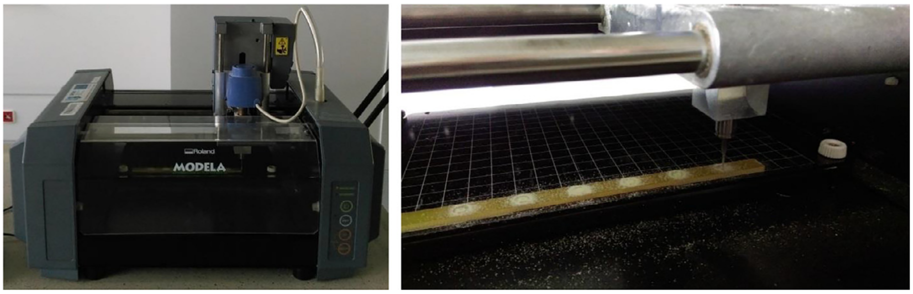

Fig. 2. Milling process of artificial defects in specimens.