Infrared Thermographic Testing of Composite Materials with Adhesive Joints

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Abstract
Active infrared thermography is a relatively new NDT method, used in many applications. In this method the external energy source is used to induce thermal differences between the background and the region of interest in examined materials. The type of energy source is chosen for a specific application. In this paper the active infrared thermography with both: microwave and eddy current excitation is used to examine composite materials with adhesive bounded joints. Typical defects such as lack of adhesive or delaminations can be detected due to dielectric (in case of microwave excitation) and thermal differences between the defect and the background. The result of the experiments conducted in the regime of pulse thermography, as well as the outcome of obtained thermograms image processing will be presented in this article.

Keywords: Active thermography, microwave heating, eddy current excitation, composite materials testing

1. Introduction

The studies on polymer composites, due to their growing popularity and high diversity of industrial applications, are becoming an increasingly popular branch of the non-destructive testing. One of the most important applications are hulls of ships and aircrafts, piping systems of liquid fuels and wind turbine blades. All the mentioned structures are exposed to various environmental conditions. In case of composite materials, adhesive joints are commonly used, the over-all quality of element made from composite is often dependent on the quality of the adhesive joint. Any damage which may be found in these joints, such as, for example, lack of adhesive, should be evaluated using an appropriate technique. The ultrasonic testing, radiography and shearography are common methods of composite materials non-destructive evaluation [1]. In this paper the basics of active thermography with convection heating excitation and with microwave excitation will be presented. Then the pulse phase thermography with discrete Fourier transform of thermogram sequences [5] will be applied to examine the polymer composite specimens with adhesive joints. Some image processing of obtained amplitude images and phaseograms will be shown as well.

The specially prepared samples with adhesive joints defects were tested and evaluated. Two samples of a plexiglas plates with joints made with use of chloroform and epoxy glue with a few defects in the form of lack of adhesive spots. The third sample is a two plates of composite with adhesive joint made with epoxy glue, whit the spot of lack of adhesive. Described samples are presented in Figure 1.
Figure 1. Photos of examined samples: a) P1 - plexiglas plates glued with epoxy glue, b) P2 - plexiglas plates glued with chloroform, c) composite plates glued with epoxy glue. 1 - indicate the adhesive joint areas, 2 - indicates the spots with lack of adhesive.

2. Active thermography with convection and microwave excitation

Composite samples with adhesive joints defects were investigated using active infrared thermography. As the excitation we propose two energy sources: convective heat flow from inductively heated steel plate (contact method) and microwave heating (contactless method). In the convective heating the composite sample is placed on the inductively heated steel plate (Fig. 2a). The free flow of heat through the examined specimen can be then observed using thermovision camera. Defects are detected as (depending on the damage type) under- or overheated spots. The main disadvantage of this method is the requirement that the sample should be in contact with the heated steel plate, which can make problems for practical applications.

The active thermography with microwave excitation is the contactless method. In this technique, examined sample is heated by high power microwaves (500 W, working at the frequency 2.45 GHz). Heating phase is observed by the properly secured thermovision camera. A schematic drawing of the method is shown in Fig. 2b whereas Fig. 3 shows the designed laboratory setup.
Fig. 3 Experimental setup for active thermography with microwave excitation. 1) thermovision camera in protective housing, 2) magnetron, 3) absorbers, 4) rectangular waveguide, 5) examined sample, 6) magnetron’s cooling system

Since the heating phase can be observed, the Pulsed Phase Thermography (PPT) could be applied. This method combines the experimental procedure used in Pulsed Thermography (PT), with signal analysis used in Modulated Thermography (MT) [2, 4]. The thermograms’ sequence is recorded, while the heat pulse is applied to examined specimen. The analysis of obtained sequence is based on Discrete Fourier Transform (DFT), which allow to evaluate the output as the combination of phase and amplitude. The procedure scheme is presented in Fig. 4.

![Fig. 4 The Discrete Fourier Transform for thermogram sequence scheme](image)

The well known Fourier Transform of each pixel in the thermogram sequence may be written as follows [3]:

$$F_n = \sum_{k=0}^{N-1} T(k)e^{-j2\pi nk / N} = \text{Re}_n + \text{Im}_n$$  \hspace{1cm} (1)

where $n$ denotes the frequency increment, and Re and Im indicate the real and imaginary parts of transform. The amplitude ($A_n$) and phase ($\phi_n$) are computed using following formulas:

$$A_n = \sqrt{\text{Re}_n^2 + \text{Im}_n^2} \quad \text{and} \quad \Phi_n = \arctan \frac{\text{Im}_n}{\text{Re}_n}$$  \hspace{1cm} (2)

Both: amplitude images and phaseograms were used to obtain reliable results of specimens' evaluation in case of active thermography with conductive heating.
In the case of active thermography with microwave excitation, image analysis is difficult because the camera is protected by the influence of a strong electromagnetic field, therefore the lens is covered with special metallic mesh. In this case the image is heavily distorted, which makes use of phase analysis impossible. We propose to use dedicated image processing algorithm based on normalized or standardized contrast, described respectively by equations (3) and (4) [3].

\[
C_n(t) = \frac{T_{\text{def}}(t)}{T_{\text{def}}(t_0)} - \frac{T_{\text{sound}}(t)}{T_{\text{sound}}(t_0)},
\]

\[
C_s(t) = \frac{T_{\text{def}}(t)}{T_{\text{sound}}(t)} - \frac{T_{\text{def}}(t_0)}{T_{\text{sound}}(t_0)},
\]

where \(T_{\text{def}}(t)\) indicate the thermal image (at time \(t\)) to which the thermal contrast is computed, \(T_{\text{def}}(t_0)\) is the thermal image at time \(t_0\) (first image in the sequence), \(T_{\text{sound}}(t)\) is the defect-free zone in considered image (defined as the average temperature in the selected area of image), \(T_{\text{def}}(t_0)\) is the defect-free zone in the image at time \(t_0\).

Diagram of the algorithm is presented in Figure.

Proposed algorithm has been also applied for the thermograms’ sequences obtained in experiments using convective heating, to compare its effectiveness with method based on Fourier transform.

3. Convection heating experiment’s regime and results

In case of convection heating two plexiglas samples were tested using the same heating time and recording frequency: the observation time was set to 20 seconds, and recording frequency was 30 Hz, which allowed us to obtain 600 thermograms in one sequence. In case of sample made of composite, the time of observation was extended to 60 second with the same recording frequency as previously, therefore the total number of thermograms in one sequence was 1800. For every sample the same procedure of signal processing was used: the DFT of thermograms sequence was performed, chosen amplitude images and phaseograms were then processed using median filter, to enhance the contrast between the background and defect. The results (chosen phaseograms, and image processing of selected amplitude images and phaseograms) are shown in Fig. 6-8.
Figure 6. The results of P1 sample evaluation using active thermography with convective excitation. a) the original thermogram (the last one in sequence), b) the chosen maximum amplitude image, c) chosen phaseogram (0.05 Hz), d) Phaseogram after median filtration, e) the resulting image obtained by applying the dedicated algorithm (vide Fig. 5)

Figure 7. The results of P2 sample evaluation using active thermography with convective excitation. a) the original thermogram (the last one in sequence), b) the chosen maximum amplitude image, c) chosen phaseogram (0.05 Hz), d) Phaseogram after median filtration, e) the resulting image obtained by applying the dedicated algorithm (vide Fig. 5)
Figure 8. The results of C1 sample evaluation using active thermography with convective excitation. a) the original thermogram (the last one in sequence), b) the chosen maximum amplitude image, c) chosen phaseogram (0.016 Hz), d) Phaseogram after median filtration, e) the resulting image obtained by applying the dedicated algorithm (vide Fig. 5)

It can be noticed that defects (which can be observed in each case as darker spots at the sample surface) are visible in most distinguishable way in the phaseograms (samples P1, P2) and the phaseograms after median filtering (in case of sample C1). The results are also reliable for each sample in the case of the proposed algorithm using the cosine transform and standardized and normalized contrast.

4. Microwave heating experiment's regime and results

Microwave enhanced infrared thermography is a relatively new NDT method. Using microwaves as the energy source gives a possibility of volumetric heating of the material, what can significantly speed-up the heat process. Moreover this method is contactless. Unfortunately the high power microwaves, needed to obtain visible temperature differences between the defect and the background, may cause damage to the thermovision camera. Therefore additional protective housing is needed in this case. Special metallic mesh, used as camera lens protection, increases the noise level in obtained thermograms. The image processing of thermogram sequence is then more demanding and time consuming.

In case of microwave heating the observation time was set to 180 seconds, and recording frequency was set to 1 Hz, which allowed to obtain 180 thermograms in one sequence. The dedicated image processing algorithm using normalized or standardized contrast and cosine transform was used to obtain resulting images. The results (only for samples made of plexiglas (P1 and P2)) are promising (Figures 9-10), but obviously future work is needed to obtain more accurately outcome. Heating of sample made of composite (C1) and obtained thermogram sequence analysis did not allow for damage detection, therefore it was omitted in
the presentation of the resulting images. For each sample the steps of image processing and resulting images are presented.

Figure 9. The results of P1 sample evaluation using active thermography with microwave excitation. a) the original thermogram (the last one in sequence), b) chosen thermogram after filtration based on cosine transformation, c) the contrast computed for chosen thermogram d) the resulting image obtained by applying the contrast enhancement

Figure 10. The results of P2 sample evaluation using active thermography with microwave excitation. a) the original thermogram (the last one in sequence), b) chosen thermogram after filtration based on cosine transformation, c) the contrast computed for chosen thermogram d) the resulting image obtained by applying the contrast enhancement
The image processing obtained thermograms sequence give the defect approximate location, and the information about flaws' size. Due to high noise level in the output thermograms, the research on improving the methodology of measurement should be continued.

5. Conclusions

Active Infrared thermography is a fast (sometimes it allows real time monitoring of structures) and giving tangible results method. The convection excitation allows obtaining information about the location and size of the defect, however, due to the fact that it requires contact with the heat source, the application of this method in practice can be sometimes difficult. The microwave excitation, on the other hand, is a contactless method. However, requires additional thermovision camera protection, which causes significant increment of obtained thermograms noise level. Therefore the received thermogram sequence image processing is much more difficult. Moreover, obtained results allow only to an approximate localization of the defect. The further development of the active infrared thermography with microwave excitation method, however, is highly warranted because of the ease of its industrial application, high speed and the ability to simultaneous study of materials' large surfaces.

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References