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Detection of Defects in CFRP by Ultrasonic IR Thermographic Method

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***Abstract*—In the paper introduced the diagnostic technique making possible the research of internal structures in composite materials reinforced fibres using in different applications. The main reason of damages in structures of these materials is the changing distribution of load in constructions in the lifetime. Appearing defect is largely complicated because of the appearance of disturbing of continuity of reinforced fibres, binder cracks and loss of fibres adhesiveness from binders. Defect in composite materials is usually more complicated than in metals. At present, infrared thermography is the most effective method in non-destructive testing composite. One of IR thermography methods used in non-destructive evaluation is vibrothermography. The vibrothermography is not a new non-destructive method, but the new solution in this test is use ultrasonic waves to thermal stimulation of materials. In this paper, both modelling and experimental results which illustrate the advantages and limitations of ultrasonic IR thermography in inspecting composite materials will be presented. The ThermoSon computer program for computing 3D dynamic temperature distribuions in anisotropic layered solids with subsurface defects subject to ulrasonic stimulation was used to optimise heating parameters in the detection of subsurface defects in composite materials. The program allows for the analysis of transient heat conduction and ultrasonic wave propagation phenomena in solids. The experiments at MIAT were fulfilled by means of FLIR SC 7600 IR camera. Ultrasonic stimulation was performed with the frequency from 15 kHz to 30 kHz with maximum power up to 2 kW.

***Keywords*—**Composite material, ultrasonic, infrared thermography, non-destructive testing.

I. Introduction

COMPOSITES are a group of many modern construction materials with special properties thanks to which they are increasingly used in various technical fields. As a result, there is a growing interest in non-destructive testing of materials whose purpose is to detect defects occurring both in production and exploitation. The first of them arises from the imperfection of the technological process of their implementation, and the second is the result of operating conditions. In the case of multilayer composites of reinforced fibres, the damage to their individual layers is particularly affected by their properties. They generally have the nature of transverse cracks of individual layers or delaminations. Damage of this type leads to destruction of the composite [1]. Non-destructive testing methods for real-time damage disclosure include infrared thermography. Especially active infrared thermography methods have been widely used in composite materials testing. In active thermography it is necessary to deliver some energy to the tested sample in order to obtain significant temperature differences affirming the presence of subsurface anomalies [2]. Vibrotermography is one of these methods in which mechanical, ultrasonic or sound waves are used to thermal stimulate the material during the test. The phenomenon of mechanical hysteresis seems to be vanishing in the range of typically-used ultrasonic frequencies and electrical power [3] (from 15 to 30 kHz and up to a few kW, respectively); therefore, the sound composite remains 'cold' during stimulation, while noticeable temperature signals appear in defective areas due to internal friction [4], [5]. The ultrasonic wave transmission by the material is thermo-elastic damping and scattering depending on structure of this material. Therefore, in order to detect the defect in the test material by ultrasonic thermography, it is very important to select the correct frequency of the ultrasound source. This paper shows these relationships for testing a sample of CFRP. The composite material is increasingly becoming commonly used due to its characteristics [6].

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II. Modeling Thermal NDT

A. ThermoSon Computer Program

The ThermoSon computer program [7] was used to optimise heating parameters in the detection of defects in CFRP. ThermoSon introduces the solution to a 3D Cartesian-coordinate transient heat conduction problem for a six-layer parallel piped-shaped body that contains up to nine infinitely thin defects. The defects generate thermal energy due to friction of their edges. The heat power generated by a defect perpendicular to the axis X is calculated by the formula [8]:

$$P = \frac{\mu \sigma_x S_{mp}}{T} \int_0^T \left| \frac{\partial U}{\partial t} \right| \partial t \quad (1)$$

where μ is the friction coefficient between defect surfaces, S_{mp} is the defect area, σ_x is the stress normal to the defect surface, U is the displacement projection by the coordinate X, t is time, T is temperature.
The calculation formulas are analogous for the defects which are perpendicular to other axes.

The modelling of heat conduction will be done by using a method of splitting [9]. In order to obtain finite difference equations, one has to derive an equation of heat balance for each area which surrounds any node of the numerical mesh (this area is Dirihle's cell). Mesh nodes are to be chosen in such way that the boundary surfaces between the host material and the defect will slip by mesh boundaries.

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Both the front and rear surfaces are cooled down according to Newton's Law. The determination of spatial thermal properties of samples and defects in three directions allows modeling of fully anisotropic material [10]. The specimen side surfaces are adiabatic. The temperature and heat flux continuity conditions occur on the boundaries between the specimen layers and between the host materials and the defects. ThermoSon programming makes it possible to implement the concept of so-called capacitive defects. This is not taken into account by other NDT models in which only resistive defects are considered. This solution, arranged in the ThermoSon program model, provides a correct description of the phenomena occurring in damaged materials [11].

B. Modelling Results

The multi-layered structure to be tested consists of three layers of carbon fibre joined with formaldehyde resin glue. The analysed model composite has a thickness of 3.2 mm and lateral size 100 mm. Two defects (of a lateral size of 10 mm and a thickness of 0.1 mm) in a thin Teflon were placed at various depths (1 mm and 2.1 mm) below the surface of the model of the composite specimen (Fig. 1).

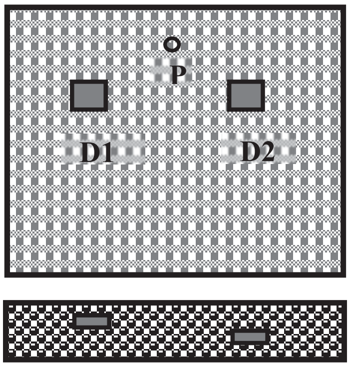

Fig. 1 Model of composite included defects (P - the central source point of vibration)

The thermal properties of defects (Teflon) and CFRP are taken from the literature (Tables I and II) [12], [13].

TABLE I
THERMAL AND STRENGTH PROPERTIES OF CFRP COMPOSITE

Parameter	Value	Unite
Specific heat	406	J·kg^{-1}·K^{-1}
Density	1500	kg·m^{-3}
*Thermal conductivity**	0 .55(⊥) 2.33 (‖)	W·m^{-1}·K^{-1}
Poisson's coefficient	0.46	
Young's modulus	150	GPa

*Values depend are supplied for orientation

Numerically-simulated modelling involved an ultrasound of different frequencies (25 kHz, 20 kHz and 15 kHz) and amplitude of 8·e-06 m. The central source point of vibration (P) during the simulation is shown in Fig. 1. The vibration time was 3 seconds, and the total simulation time was 10 seconds. The obtained results are shown in Tables III-V. The tables show data such as the maximum temperature rise over the *ΔT* defect and the running temperature contrast *C*:

$$C = \Delta T(\tau) / T(\tau) \tag{2}$$

and the time at which the best conditions exist to detect defects τ_m.

TABLE II
THERMAL AND STRENGTH PROPERTIES OF TEFLON

Parameter	Value	Unite
Specific heat	1050	J·kg^{-1}·K^{-1}
Density	2210	kg·m^{-3}
Thermal conductivity	0 .23	W·m^{-1}·K^{-1}
Poisson's coefficient	0.46	
Young's modulus	0.4	GPa

TABLE III
EXPECTED DETECTION PARAMETERS IN THE FRONT-SURFACE ULTRASONIC TEST (15 KHZ)

Defect	ΔT, °C	τ_m, s	C, %
D1	1.21	3.0	9
D2	0.55	3.1	5.2

TABLE IV
EXPECTED DETECTION PARAMETERS IN THE FRONT-SURFACE ULTRASONIC TEST (20 KHZ)

Defect	ΔT, °C	τ_m, s	C, %
D1	0.75	3.0	7.3
D2	0.27	3.1	4.1

TABLE V
EXPECTED DETECTION PARAMETERS IN THE FRONT-SURFACE ULTRASONIC TEST (25 KHZ)

Defect	ΔT, °C	τ_m, s	C, %
D1	0.21	3.0	3.9
D2	0.12	3.1	2.1

III. EXPERIMENTAL TESTING

A. Experimental Setup

The experiments at the Military Institute of Armament Technology (MIAT) was made using a FLIR SC 7600 IR imager (image format 640×512) in a sequence of 300 thermograms. Ultrasonic stimulation was performed with an ultrasound generator at the frequency from 15 kHz to 25 kHz. Output power was 300 W (the maximum allowed power was 2 kW). The ultrasonic signal was generated for 3 sec. While the registration time was 5 sec. Fig. 2 presents the set-up used for the thermographic tests containing an ultrasonic thermal stimulation.

Tests were carried out on a sample composite plate made of three carbon fibre bonded with epoxy resin. The carbon fibre plate had dimensions of 350x150x1 mm (Fig. 3). Teflon square shaped defects and dimensions of 10x10 mm (0.1 mm thin) were placed at different depths D1 - 1 mm and D2 - 2.1 mm below the surface of the test sample just as in the case of the model (Fig. 1).

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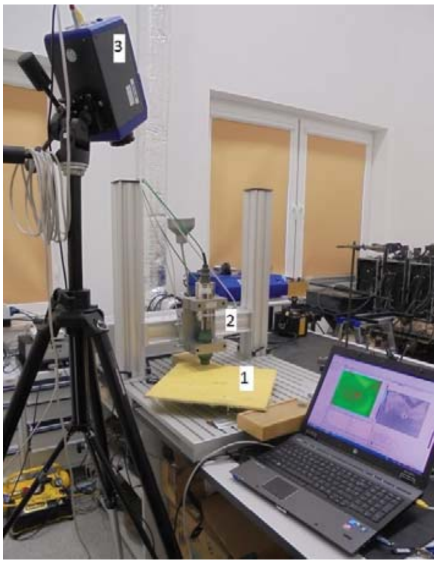

Fig. 2 Experimental set-up (1- sample, 2- ultrasound generator, 3- IR camera)

Fig. 3 Test sample

B. Results

The results of computer simulation showed that best result for the CFRP sample can detect a defect using the ultrasonic excitation frequencies between 15 kHz and 20 kHz. As a result of experimental tests, the highest increase of temperature signal above the defect was obtained at a frequency of 17 kHz. Figs. 4 and 5 show the change graph in temperature signal over defects (D1 - 1 and D - 2) for different ultrasonic excitation frequencies.

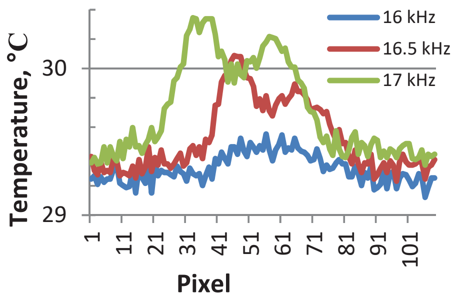

Fig. 4 Temperature signal over defect D1 for different ultrasonic frequencies

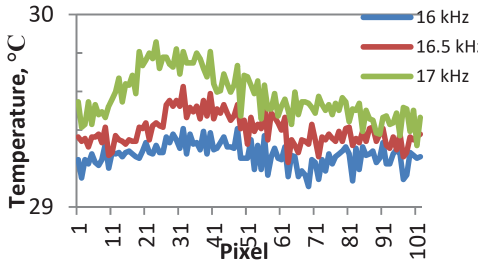

Fig. 5 Temperature signal over defect D2 for different ultrasonic frequencies

The selected thermograms from these tests are shown in Figs. 6-9. Fig. 6 shows the source thermogram made with thermal stimulation with 17 kHz ultrasound with well visible D1 and D2 defects. An improvement in defect visualization by phase analysis is also shown in Fig. 7.

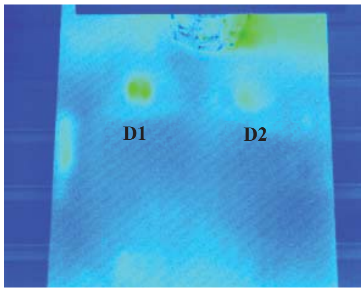

Fig. 6 Source thermogram – 17 kHz frequency

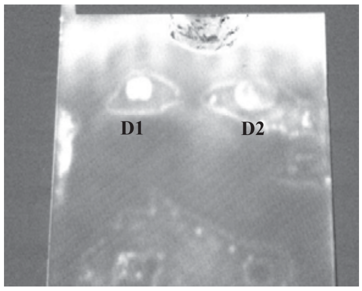

Fig. 7 Source thermogram (Fig. 6) by phase analysis

Fig. 8 shows a thermogram obtained at an ultrasound frequency of 18 kHz and an improvement in defect visibility by phase analysis of Fig. 9.

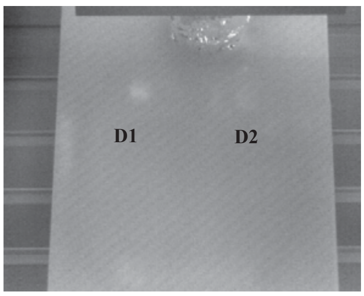

Fig. 8 Source thermogram – 18 kHz frequency

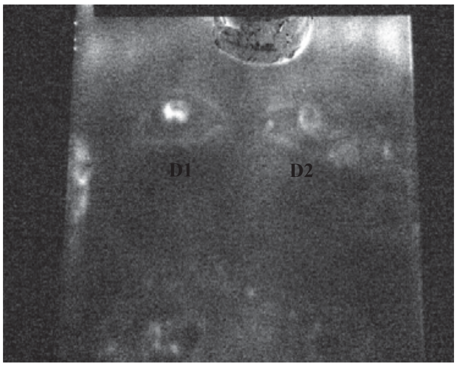

Fig. 9 Source thermogram (Fig. 8) by phase analysis

IV. Summary

The computer simulations and experimental testing have shown that ultrasonic thermography may be effective in detecting defects in multilayer structures of CFRP. Selection of suitable frequency of ultrasound for thermal excitation of the test material is an important success factor in this method. We have also demonstrated usefulness of computer simulations, which greatly facilitates the selection of suitable ultrasound wave frequency, which significantly shortens the time of experimental test.

The differences between the results of the computer simulation and the experimental results were as follows:

- thermophysical parameters of materials in computer simulations were accepted on the basis of literature data and may differ from real parameters;
- It assumes that the model of the sample is a single-layer composite due to the complexity of the propagation of ultrasonic waves in a multilayer structure in modelling.

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