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ACTIVE THERMOGRAFY AS A METHOD FOR NON-DESTRUCTIVE TESTING OF POLYMER COMPOSITE MATERIALS

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Abstract: Infrared (IR) thermography is a method for imaging thermal fields on the target surfaces in real time. It is a non-contact and non-destructive method of obtaining thermogram of tested material surface or inside of it. We can divide the IR thermographic testing methods into two basic groups – passive and active thermography. This article introduces a basic overview of IR active thermography.

Keywords: Thermography; Defectoscopy; Nondestructive testing (NDT); Discrete Fourier transform (DFT).

1 INTRODUCTION

Lock-in thermography (LiT) is a method of an active thermography [1][2][5], uses sinusoidal thermal excitation in order to obtain information from the observed phase and magnitude of reflected thermal wave. The phase angle has the advantage that it is independent of local variations of illumination or surface emissivity.

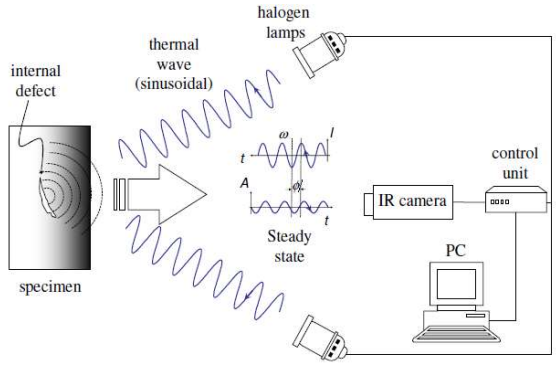

Fig. 1 Principle of Lock-in thermography
Source: [6].

2 THERMAL WAVE THEORY

Sinusoidal waves are typically used in LiT [2]. Using sinusoid input signal has the advantage that the frequency and shape of the response are preserved - change is only in the amplitude and phase delay. The periodic wave propagates by radiation through the air until it touches the sample‘s surface where heat is next propagates through the material. Defects inside, act as barrier for heat propagation and produces changes in amplitude and phase of the response signal at the specimen surface.

Heat diffusion through a solid material is a complex 3D problem that can be described by the Fourier’s law of heat diffusion

$$\nabla^2 - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0 \qquad (1)$$

where

$\alpha = \frac{k}{\rho c_p}\ [m^2.s^{-1}]$ is the thermal diffusivity of the tested material

$k\ [W.m^{-1}.K^{-1}]$is the thermal conductivity

$\rho\,[kg.m^{-3}]$ is the density

$c_p\ [J.kg^{-1}.K^{-1}]$ is the specific heat at constant pressure

The Fourier’s law 1D solution for a periodic thermal wave propagating through a semi-infinite homogeneous material may be expressed by equation

$$T(z,t) = T_0 e^{\left(-\frac{z}{\mu}\right)} cos\left(\frac{2\pi z}{\lambda} - \omega t\right) \qquad (2)$$

where

$T_0\ [°C]$ is the initial change in temperature produced by the heat source

$z\ [m]$ is the thermal wave penetration depth

$\omega = 2\pi f\ [rad.s^{-1}]$ is the modulation frequency

$\lambda \equiv 2\pi\mu\,[m]$ is the thermal wavelength

$\mu\,[m]$ is the thermal diffusion length

which determines the rate of decay of the thermal wave as it penetrates through the material and is defined by formula

$$\mu \equiv \sqrt{\frac{2\alpha}{\omega}} = \sqrt{\frac{\alpha}{\pi f}} \qquad (3)$$

For deeper penetration of thermal wave, the use of lower frequencies are needed.

Fig. 1 shows a lock-in thermography experiment. The lamps send periodic input thermal waves at a given modulation frequency ω, for at least one cycle. In practice however a few cycles are needed

to adequately retrieve phase and amplitude data of response thermal wave.

Fig. 2 Edevis-OTvis/Infratec thermography system
Source: authors.

The sinusoidal input signal I and the response signal S is depicted at Fig. 3. As mentioned before, input and output have the same shape when sinusoids are used.

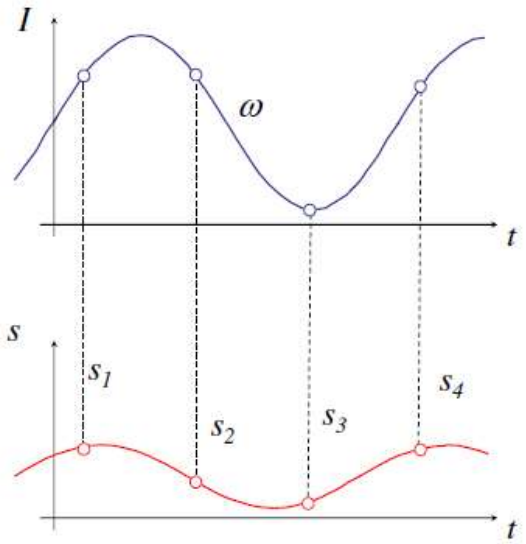

Fig. 3 Input and output thermal wave
Source: [2].

There is only a change in amplitude and phase that can be calculated as follows

$$A = \sqrt{(S_1 - S_3)^2 + (S_2 - S_4)^2} \quad (4)$$

$$\varphi = tan^{-1}\left(\frac{S_1 - S_3}{S_2 - S_4}\right) \quad (5)$$

This 4-point method can be used only for sinusoidal stimulation and is affected by noise. The signal can be denoised by averaging of several points instead of a single one and/or by increasing the number of cycles. Alternatively, the DFT can be used to extract amplitude and phase information from LiT data, according to the expression

$$F_n = \Delta t \sum_{k=0}^{N-1} T(k\Delta t)\, e^{(-i2\pi mk/N)} = Re_n + Im_n \quad (6)$$

where

k is the number of measuring cycles,

i is the imaginary number ($i^2 = -1$),

n is the frequency increment ($n = 0, 1, \ldots N$),

Δt is the sampling interval.

In this case, real and imaginary parts of the complex transform are used to estimate the amplitude and the phase

$$A_n = \sqrt{{Re_n}^2 + {Im_n}^2} \quad (7)$$

$$\varphi_n = tan^{-1}\left(\frac{Im_n}{Re_n}\right) \quad (8)$$

The DFT can be used with any waveform and has the advantage of denoising the signal. One of the most interesting characteristics of LiT testing is the possibility of performing quantitative operations in a straightforward manner. There is direct relationship between the depth of a defect and the thermal diffusion length μ. Empirical expressions have been proposed to extract the depth of a given defect from LiT data using a relationship of the form

$$z = C_1\mu = C_1\sqrt{\frac{\alpha}{\pi f_b}} \quad (9)$$

where

f_b is known as the blind frequency.

It is the frequency at which a given defect have enough (phase or amplitude) contrast to be detected (at frequencies higher than f_b is not possible to detect it), C_1 is an empirical constant. It has been observed that $C_1 = 1$ when using amplitude data. For working with the phase C_1 is in the range $1{,}5 < C_1 < 2$, with $C_1 = 1{,}82$ as the typical value. The phase is therefore more interesting in NDT than the amplitude, since it provides deeper probing capabilities.

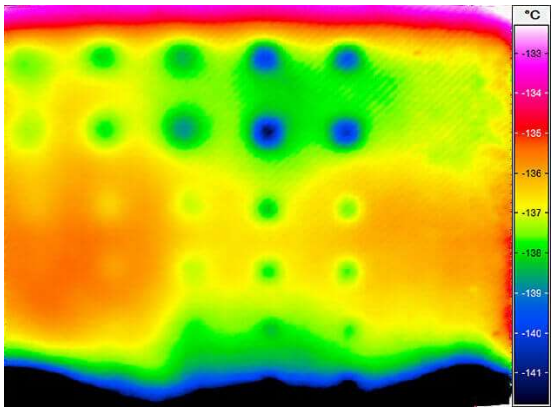

Fig. 4 Artificial defects (circle shapes) inside composite sample
Source: [7].

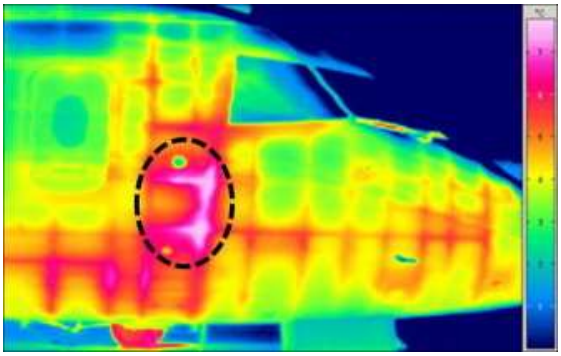

Fig. 5 Unspecified defect in aircraft's fuselage (violet colored shape)
Source: [8].

3 EXPERIMENTAL EXAMPLE OF LIT THERMOGRAPHY

Subject of interest (for LiT application) at Department of mechanical engineering of the Armed Forces Academy Liptovský Mikuláš is polymer composites material research [3][4]. These materials are widely used for example in advanced military technologies of ground and aerial vehicles.

A polymer composite is a multi-phase material in which reinforcing fillers are integrated with a polymer matrix, resulting in synergistic mechanical properties that cannot be achieved from either component alone.

Modern composites are usually made from two components – fiber and matrix. The fiber is most often glass, but sometimes Kevlar, carbon, or polyethylene. The matrix is usually a thermoset like an epoxy resin, polydicyclopentadiene, or a polyimide.

The performance of polymer composites is generally determined by

- the properties of the fiber,
- the properties of the polymer matrix,
- the ratio of the fiber to the polymer matrix in the composite (fiber volume fraction),
- the geometry and orientation of the fiber in the composite.

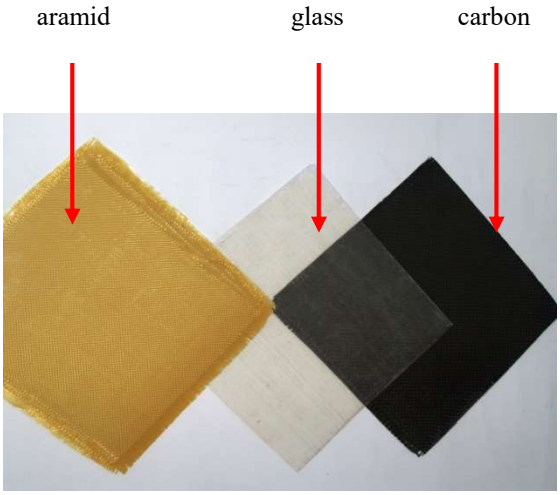

Fig. 6 Composite plates
Source: authors.

The performance is usually referred to as the mechanical properties of the polymer composites.

Hidden defects can occur in the production process of these materials, which have an impact on the mechanical properties. Therefore, it is important to detect these defects. One option is to use the active thermography.

Experimental sample (glass composite plate 300x300 mm) was created by four layers of glass fabric (with weight per unit area 390g/m^2). By inserting of impurity particles, between layers 2 and 3, was created three localities of artificial defects.

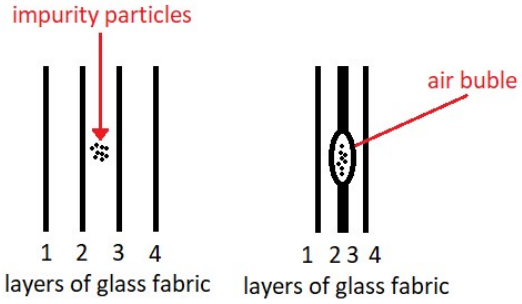

Fig. 7 Structural arrangement of the sample
Source: authors.

In these localities, inserted impurity particles prevented connection of layers 2 and 3 - in the same areas, air bubles were created.

Sequence of figures (Fig. 8 – Fig. 11) shows dependecy of depth thermal wave penetration on its frequency. For experiment was used Edevis-OTvis/Infratec thermography system.

Fig. 8 represents thermal wave penetration just below the surface - a faint hint of defective areas appears (circled areas).

Fig. 9 a Fig. 10 shows thermal wave penetration into depth of impurities.

Fig. 11 shows thermal wave penetration into depth beyond impurities.

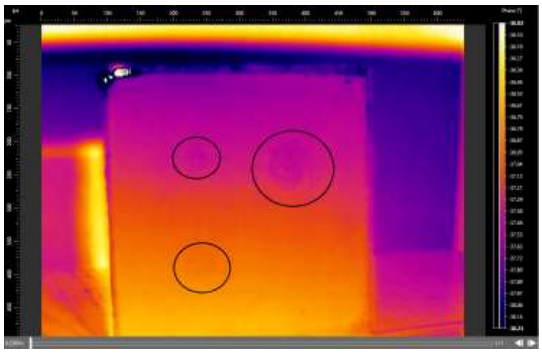

Fig. 8 Phase thermogram from LiT data (Thermal wave frequency 0,25 Hz)
Source: authors.

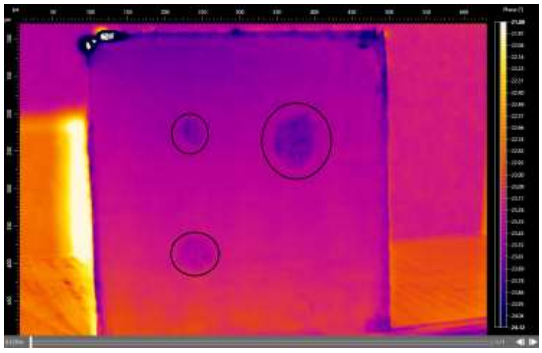

Fig. 9 Phase thermogram from LiT data (Thermal wave frequency 0,125 Hz)
Source: authors.

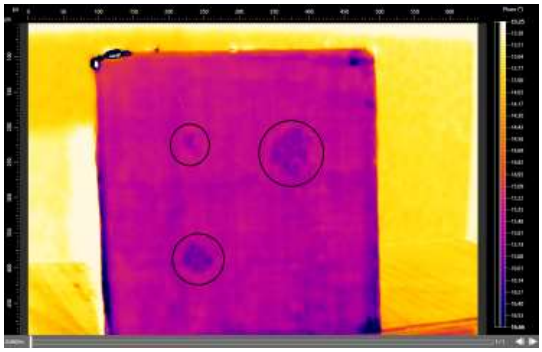

Fig. 10 Phase thermogram from LiT data (Thermal wave frequency 0,06 Hz)
Source: authors.

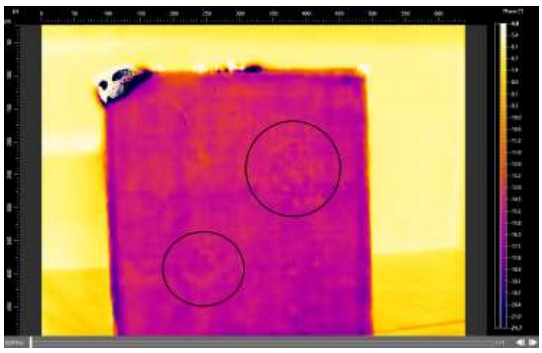

Fig. 11 Phase thermogram from LiT data (Thermal wave frequency 0,015 Hz – probably close to blind frequency)
Source: authors.

4 CONCLUSION

Active thermography is very useful method of structural investigation and detection of local invisible defects. The advantage of thermography method is fact, that it is a NDT method, without mechanical damage of the tested surface.

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