ESTIMATION OF DEFECT DEPTH IN STEEL PLATE USING LOCK-IN IR THERMOGRAPHY

Monika ZIMNOCH[*], Wiera OLIFERUK[*,], Michał MAJ[**]**

[*]Mechanical Engineering and Applied Computer Department, Bialystok Technical University,
45C Wiejska, 15-351 Bialystok, Poland
[**]Institute of Fundamental Technological Research, Polish Academy of Sciences, 5B Pawinskiego, 02-106 Warsaw, Poland

monaramona@wp.pl, wolif@ippt.gov.pl, mimaj@ippt.gov.pl

Abstract: The paper deals with the application of lock-in active infrared thermography as one of the non-contact and non-destructive techniques used for defect depth estimation. Preliminary research was done by testing a specimen made of austenitic steel plate with artificially created defects, i.e. flat-bottom holes. The obtained dependence between defect depth and phase shift was presented for different frequencies of "thermal waves" generated inside the sample. The experiment was carried out to determine the application of the lock-in thermography approach in testing materials with a high thermal diffusivity.

1. INTRODUCTION

Active infrared thermography is one of the most common methods used for nondestructive testing (NDT), and offers non-contact detection of defects occurring at a short distance below the surface. This method needs an external thermal stimulation of the tested material. The response of the material to the thermal stimulus is dependent on the existence of subsurface defects and their features. Thus, in order to obtain the information about defects, this response is studied. Depending on the external stimulus different approaches of active thermography have been developed. In recent years the most commonly used thermographic NDT technique is pulsed thermography. In this method the tested surface is flash-heated by one or more high energy flash lamps, and the temperature field on the surface during its self-cooling is recorded and analyzed. The duration of the pulse is usually very short (about a few ms). Defect presence is manifested by an increase in the surface temperature above the defective zone at the beginning of the self-cooling process after thermal stimulus (Maldague, 2001; Oliferuk, 2008).

Pulse thermography has some disadvantages, which may encourage advances in other approaches of active thermography. First of all, the tested surface should be uniform in terms of emissivity. Secondly, homogeneous heating up the surface is required. Therefore, only small parts can be inspected at the same time. Due to the above-mentioned problems the lock-in active thermography approach was taken into consideration.

The aim of this work is to find out the application of lock-in IR thermography in determining defect location under the tested surface for materials with a high thermal diffusivity.

2. LOCK-IN IR THERMOGRAPHY

The thermal stimulation in the case of lock-in thermography consists in heating the surface periodically by modulated high power lamps. A diagram of the IR thermographic system is presented in Fig. 1.

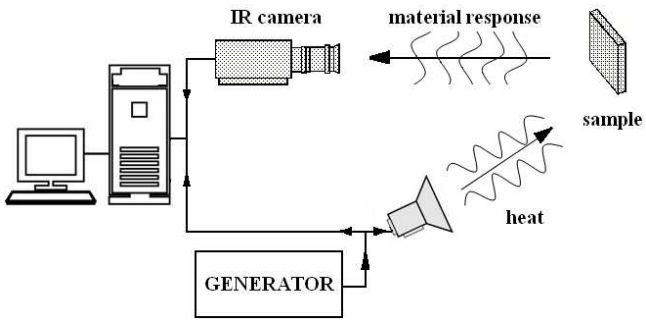

Fig. 1. Experimental setup for the lock-in IR thermography

Monitoring the exact time dependence between output and input signals, for instance thermal harmonic stimulation, it is possible to receive, on the basis of the obtained oscillating field of temperature, the amplitude and phase of the resulting "thermal wave" on the sample. Amplitude images are connected with tested material and the features of its surface, while phase images refer to wave propagation time. So lock-in thermography is based on "thermal waves" generated inside the sample. Quotation marks are used because wave equation should be the solution of the hyperbolic equation, and in this case it is the solution of the parabolic one (heat equation).

"Thermal waves" which were first studied, among other

things, by Fourier back in the XIX century, are highly attenuated (the amplitude becomes much smaller with increasing depth). Therefore, it is just possible to detect defects lying near to the tested surface. The "thermal wave" equation as a dependence of the temperature T on time t and depth z is formulated as follow (Maldague, 2001):

$$T(z,t) = T_0 e^{-\frac{z}{\mu}} \cos\left(\omega t - \frac{2\pi z}{\lambda}\right), \quad (1)$$

where: $\lambda = 2\pi\mu$ – wave length, $\mu = \sqrt{\frac{2\alpha}{\omega}}$ – thermal diffusion length ($\alpha = \frac{k}{\rho c_p}$ – thermal diffusivity, where: k – thermal conductivity, ρ – density, c_p – specific heat capacity). Propagation velocity of "thermal wave" equals:

$$v = \lambda f = \mu\omega = \sqrt{2\alpha\omega}, \quad (2)$$

where $f = \frac{\omega}{2\pi}$ – wave frequency. Presented formulas are true provided that a one-dimensional model for half space, heated up with sinusoidal changing intensity is assumed.

Thermal diffusion length means the distance after which wave amplitude becomes *e*-times smaller, and it is inversely proportional to $\sqrt{\omega}$, so waves with a higher frequency penetrate shallower in material than with lower frequency ones. Therefore, it is very important to employ a proper frequency, in case some of the defects are undetected. This is the main disadvantage of lock-in thermography. For each frequency it is necessary to do separate tests.

The most important advantage of lock-in thermography in many NDT applications is the fact that the φ phase is relatively independent of local optical and thermal surface features e.g. emissivity; whereas as it follows from the formula (1), directly depends on the defect depth z:

$$\varphi(z) = \frac{2\pi z}{\lambda} = \frac{z}{\mu}, \quad (3)$$

and it is the linear dependence. Therefore, in order to determine defect depth phase shifts are investigated.

3. EXPERIMENT

For the lock-in testing the FLIR IR Thermographic System with ThermaCam Phoenix camera was used. The camera, with electrically cooled InSb detector, has a maximum frame rate of 346 Hz and temperature resolution of 20 mK (at 30˚C). Other parameters are as follow: maximum frame size – 320 x 256 pixels (width x height), spectral range: 3-5 μm.

The camera was attached to halogen lamps (2,6 kW), which were used to generate harmonic heating of specimen surface with adequate heat intensity.

The specimen used in the tests (170 x 195 mm) was made of austenitic steel plate 316L, which is characterized by relatively high thermal conduction (about 15 J/kg·K). The simulated defects, i.e. flat-bottom holes were arranged as shown in Fig. 2. The distances between the defects' centers were equal to 25 mm and 35 mm from the boundary of the sample to the centre of the nearest hole. The thickness of the plate is 3 mm.

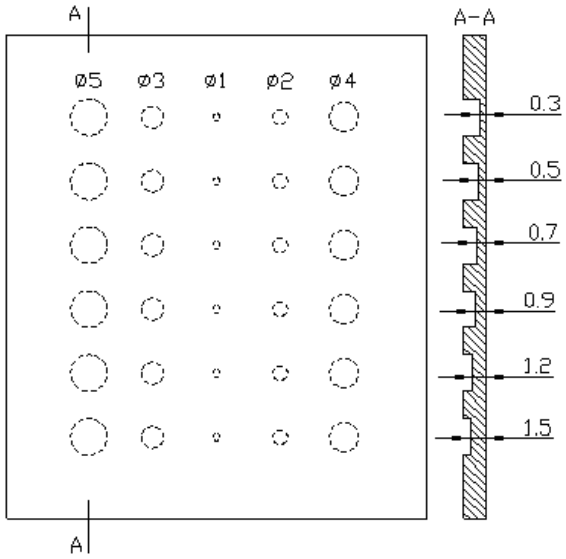

Fig. 2. Test sample

The tested surface was stimulated with halogen lamps, whose power was changed in a harmonic way. The specimen was heated up from the side where simulated defects are invisible. The following frequencies of the thermal stimulation were applied: 0.2 Hz, 0.4 Hz, 0.6 Hz; 0.8 Hz and 1 Hz. With the help of the lock-in IR thermographic system (Fig.1) the oscillating temperature field (on the tested surface) in the function of the time was measured and recorded. The response of the tested material on harmonic stimulation is not in fact a sinusoidal signal. Self-cooling of the tested specimen proceeded more slowly than the heating. Therefore the measured signal was approximated by analytic function. On the basis of this function, the "thermal waves" for each point of the surface were reconstructed. As a "thermal wave" of reference, the one on sound material surface was taken. Then the phase shift between "thermal wave" on surface above the defect and the reference "thermal wave", was determined as shown in Fig.3.

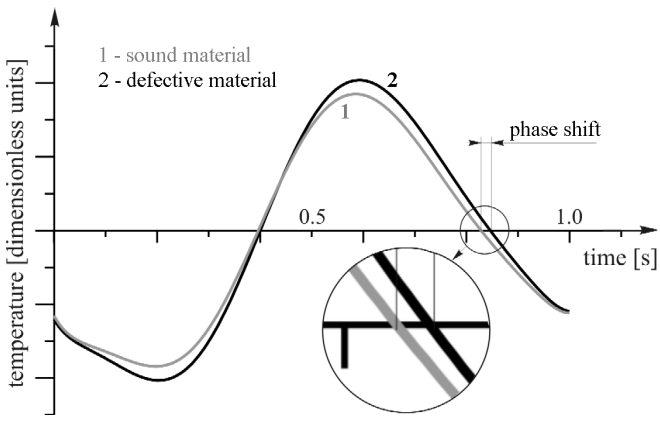

Fig. 3. Determination of phase shift

In order to identify the regions of the tested surface lying above sound material and defected one, the surface temperature distribution was used. As an example, the temperature distribution on the tested surface for thermal stimulation with frequency 0.6 Hz is shown in Fig. 4.

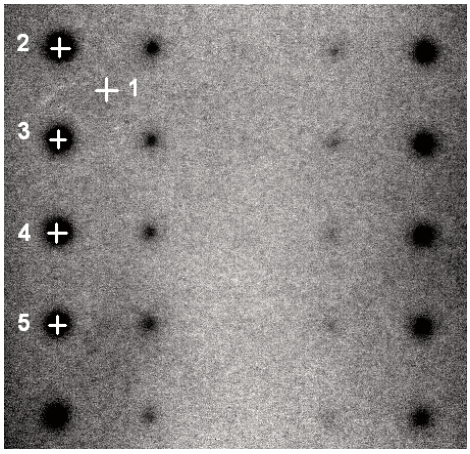

Fig. 4. Surface temperature distribution for 0.6 Hz stimulating signal

Analysis was made for the sixth period of the stimulation, for single pixels, corresponding to points on the tested surface, as shown in Fig. 4.

4. RESULTS

The analysis was made for the 5 mm diameter defects lying at different depth (0.3 mm, 0.5 mm, 0.7 mm and 0.9 mm) and for the stimulation frequencies 0.2 Hz and 1 Hz. The temperature of the tested surface was captured 346 times every second in the case of the 1 Hz frequency, whereas in the case of the 0.2 Hz – 172 times. The dependence between the phase shift (in relation to the sound material) and the defect depth was obtained as shown in Fig. 5.

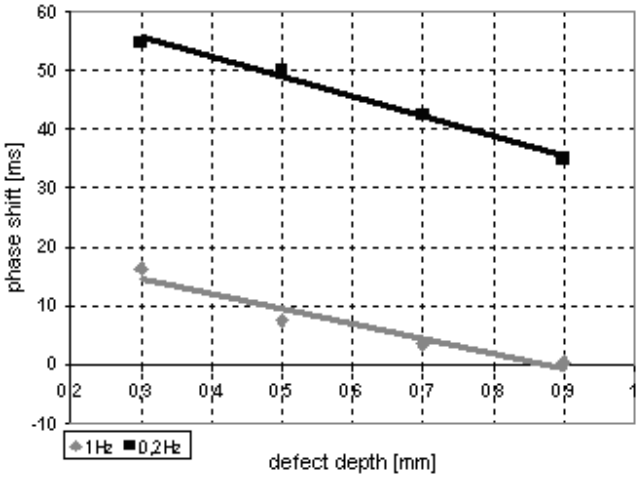

Fig. 5. Dependence of phase shift on defect depth for the defect diameter 5 mm and the frequencies of stimulation 1 Hz and 0.2 Hz

The obtained relation is linear and enables estimation of the depth of real defects. It is seen that for detecting 5 mm diameter of simulated defects (in the depth range shown in the diagram), it is better to use a lower frequency, like 0.2 Hz than a higher one, like 1 Hz. For instance, the phase shift for the 0.9 mm depth in the case of the 1 Hz stimulating signal is almost equal to zero. This means that the defect cannot be estimated using the above-mentioned frequency, which is called in this case the "blind frequency" (Manyong Ch. and others, 2008). The blind frequency exists for each specific defect lying at a certain depth.

It is seen in Fig. 5 that using lock-in IR thermography it is necessary to apply an appropriate frequency of stimulating signal in order to detect the defects lying at different depths. This is also seen in "phase diagram" (surface distribution of phase shift) available in the software operating the lock-in thermography system. Thus, there are phase shifts for each point of the tested surface (for each pixel) referring to the stimulating signal presented in that phase diagram (Fig. 6, 7).

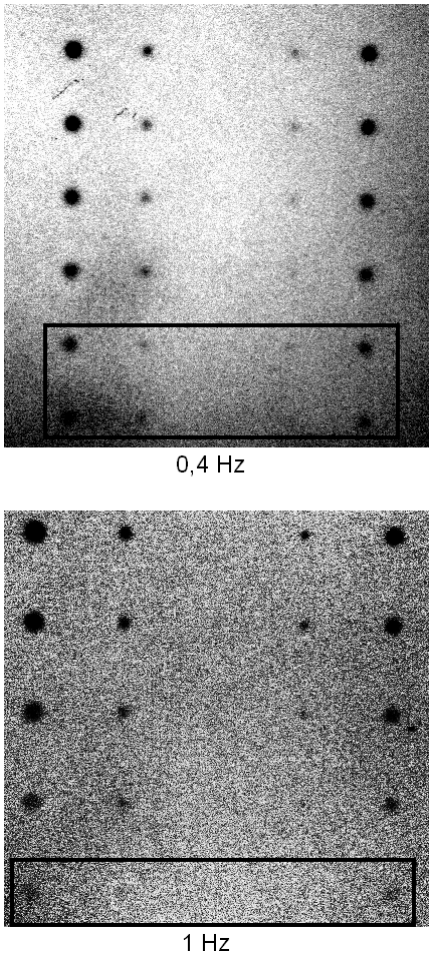

Fig. 6. Phase shift referring to stimulating signal for 0.4 and 1 Hz

In Fig. 6 it is seen that the deeper defects, such as 1.2 mm and 1.5 mm are better perceived for the lower stimulating frequencies like 0.4 or 0.2 Hz. Whereas, in the case of the higher frequencies, like 0.8 Hz or 1 Hz, even slightly shallower defects, like 0.9 mm are not seen clearly. This

is related to a general rule, namely that lower frequencies penetrate deeper in material than higher ones.

It was also noticed that in the event of higher frequencies, like 0.8 and 1 Hz, shallower defects (in depth range shown in the diagram) with a smaller diameter (2 mm) were seen more distinctly than in the case of lower frequencies (Fig. 7).

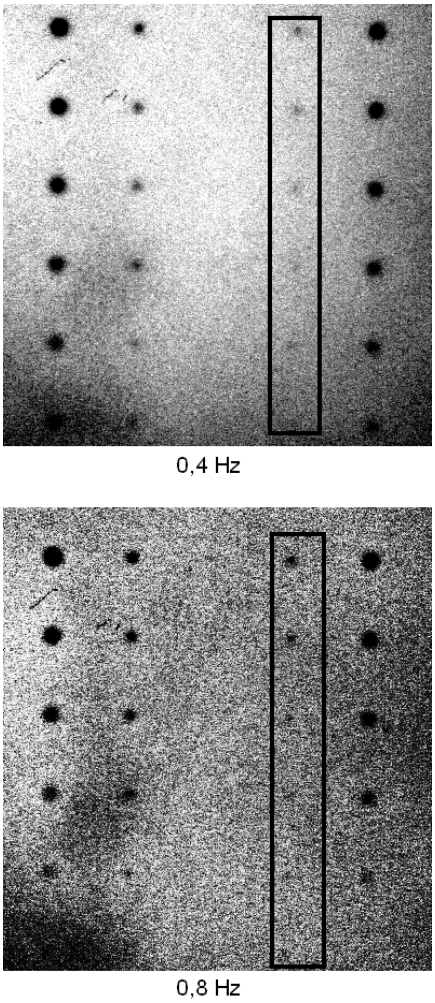

Fig. 7. Phase shift referring to stimulating signal for 0,4 and 0,8 Hz

5. CONCLUSIONS

In this paper use of lock-in IR thermography to detect subsurface defects (0.3-0.9 mm) for materials with a high thermal diffusivity was proposed. Several of the preliminary experimental results for the defect diameter 5 mm and the frequencies of the stimulating signal 1 Hz and 0.2 Hz were presented. On the basis of the obtained results it was found that the dependence between phase shift (in reference to sound material) and defect depth is linear.

Tests done for the defects with smaller diameters showed that for estimation of their depth it is necessary to use lamps with the power higher than 2,6 kW. Further tests for different frequencies, defect locations and sizes are necessary to estimate the depth of the real defects in material.

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