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Detection of Bonded Joint Defects by use of Lock-in Thermography

Abstract

Joining of two or more materials using adhesives is one of the most widely used way to connect and/or seal steel panels used in the automotive industry. Due to instabilities of the technological process a different kind of defects could appear in the adhesively bonded joints. There are many destructive and non-destructive methods allowing investigation of defects of bonded joints. In this article lock-in thermography (LT) technique was used to detect of discontinuities in sealing joints between two steel plates. Results of the research shown the defect of bonded joints could be recognised effectively however it is necessary to ensure proper test conditions.

Keywords: Lock-in thermography, NDT, bonded joints.

1. Introduction

Bonded joints are very popular methods of making connections between different parts at the automotive industry. The Adhesives perform many different functions in the vehicle construction creating stable and durable joint which also perfectly seals any gaps and dumps the vibrations.

Due to misleading procedures and instabilities of the technological process a different kind of defects like delamination, poor cure, cracks, porosity, voids, “kissing” bonds and discontinuities could appear in the adhesively bonded joint.

From the car manufacturers point of view it is necessary to provide effective detection of technological flaws of adhesive bonded joints. Currently, the Statistical Process Control (SPC) is one of the most famous tools used to achieve high quality of the products. SPC uses results of destructive (DT) and non-destructive (NDE) evaluation methods. The destructive methods are very common in assessment of bonded joint quality but are very costly due necessity of completely specimen destruction. For this reason, there are many various type of NDE methods in use to reduce applicability of destructive ones. To detect defects of bonded joints a vibroacoustic, radiographic, thermographic and ultrasound methods could be applied [2]. The ultrasound testing (UT) methods seems to be the most popular. However, the main nature of the UT techniques disallows them to be used to test large area parts in reasonable time. As an alternative, an active thermography methods [1,3] could be used.

Active thermography is a helpful tool for nondestructive evaluation of several kinds of materials [1–20]. Basically, two different approaches are possible: traditional pulse thermography (PT) and lock-in thermography (LT).

Application of the PT to detecting a bonded joint defects was investigated in previous authors research [29]. This paper presents an experimental investigation of lock-in thermography to detect of bonded joints defects.

2. Lock-in thermography – principles

Lock-in thermography (LT) also known as modulated thermography is an advanced non-destructive evaluation (NDE) technique applied for over a decade for the detection of defects and characterization a solid and composite structures used in aerospace, automotive, electronics and other industries [11, 21-23].

In LT, the investigated structure is thermally stimulated using heating lamps (halogens), which is called optical lock-in thermography (OLT) or elastic waves generators, called ultrasound lock-in thermography (ULT). As a stimulation source also eddy currents induced by electromagnetic induction could be used. In the article, only optical lock-in thermography is considered.

During optical thermal stimulation of the object (Fig. 1), periodic wave propagates by radiation through the air until it touches the investigated object surface where heat is produced and propagates through the structure. Periodic heating input leads to a similar transient variation of the surface temperature of the object. Sinusoidal waves are typically used in LT, although other periodic waveforms are possible. Using sinusoids as input has the advantage that the frequency and shape of the response are preserved and only the amplitude value and phase delay could change.

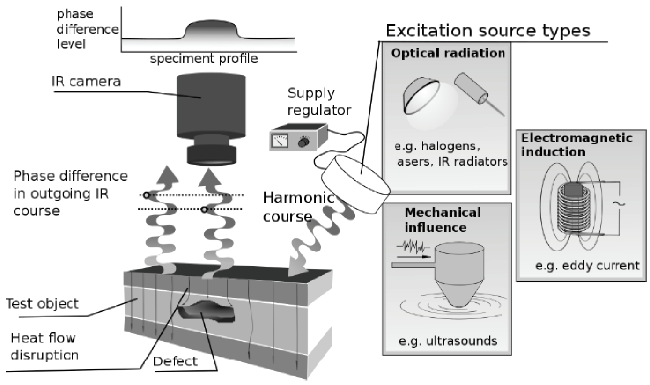

Fig. 1. Idea of Lock In thermography and different types of heat sources

In homogeneous material of the investigated object the harmonic heat transfer delivered at the surface (depth $x = 0$) results in a (time-dependent) thermal wave, which, follows from one dimension case of heat transfer equation and is given by [7]:

$$T(x=0,t) = T_0 \exp\left(-\frac{x}{L}\right)\exp\left(\omega t - \frac{x}{L}\right) = T(x)\exp j\left[\omega t - \phi(x)\right] , \quad (1)$$

where L is the thermal diffusion length:

$$L = \sqrt{\frac{2\alpha}{\omega}} = \sqrt{\frac{\alpha}{\pi f}} , \quad (2)$$

$\alpha = \frac{\lambda}{\rho c_p}$ – thermal diffusivity, m^2/s,
f – modulation frequency,
λ – thermal conductivity, W/m·K,
ρ – density, kg/m^3,
c_p – specific heat, J/kg·K.

The term $T(x)$ (in the third part of equation (1)) represents the decay of the thermal wave amplitude, while $\phi(z)$ is the phase shift with depth. Amplitude and phase of the thermal wave could be evaluated on the basis of a thermal mapping of the object surface using infrared camera and image processing methods like Fast Fourier transform.

The depth range for the amplitude is given by L, while the maximum depth which can be inspected by the phase image corresponds to $1.8L – 2L$ [24-26].

During heat transportation, some kind of inhomogeneities, like defect, flaws etc. could appear in the structure. In such case the

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heat propagation parameters locally change causing reflections and interferences of thermal wave which results in change of amplitude and phase of temperature signal measured by infrared camera on object surface.

In case of multilayer bonded joint, propagating heat meat interface between first and second layer of a joint (e.g. steel and adhesive). The interface between layers affects heat propagation process and reflects some portion of the transferred heat. Thermal behaviour at the interface between two materials depends on their effusivities, and is characterised by thermal reflection coefficient R:

$$R = \frac{e_1 - e_2}{e_1 + e_2}, \quad (3)$$

where: $e = \sqrt{\lambda \rho c_p}$ – thermal effusivity.

In case of properly manufactured adhesive bonded joint interface between layers should be uniform. However, if adhesive discontinuity occurs the thermal coefficient will locally change causing also a phase angle change. If the phase differences $\Delta\phi = \phi_s - \phi_d$ by the phase angle in the sound region of joint ϕ_s and the phase angle in the defected region ϕ_d is large enough, the defect can be detected in contrast phase images.

To obtain the best inspection result, the optimum modulation frequency and heat source power, which can lead to the maximum difference between the defective and non-defective area, should be used. Modulation frequency could be calculated based on analogy to theoretical analysis proposed by Bennett and Patty (BP) [27, 28]. The BP model allows calculation of the phase angle for two layer sample in the following way:

$$\phi = \frac{R_b(1+R_g)\exp(-2a_s d)\sin(2a_s d)}{1 - R_g\left[R_b \exp(-2a_s d)\right]^2 + R_b(1-R_g)\cos 2a_s d}, \quad (4)$$

where: R_b and R_g are the reflection coefficients of sample-backing material interface and sample-gas interface respectively. The term $a_s d$ is the thermal thickness of the material where ($a_s = 1/L$).

The equation (4) was used to calculate phase angles as a function of modulation frequency for two cases: steel – adhesive and steel – air. Assumed material properties are shown in Table 1.

Tab. 1. Physical parameters of layers considered bond structure

	steel	air	adhesive
λ, W/m·K	43.00	0.02	0.20
ρ, kg/m^3	7800.00	1.20	1300.00
c_p, J/kg·K	473.00	700.00	1700.00
φ	12595.40	4.10	664.83

The calculation result is shown in Fig. 2.

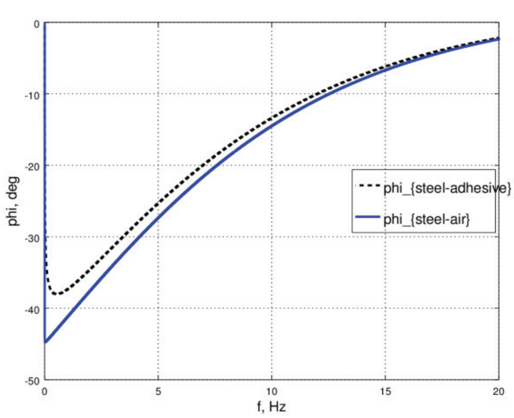

Fig. 2. Plot of phase angle variation as a function of frequency obtained from Benett Patty model for steel-adhesive and steel-air samples

The characteristics allowed estimating modulation frequency corresponding to maximum phase difference what is shown in Fig. 3.

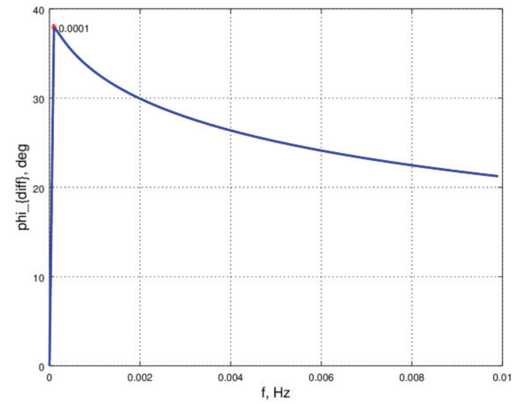

Fig. 3. Plot of phase angle difference between steel-adhesive and steel-air interfaces

Due to high thermal conductivity of steel estimated frequency is very low. Estimation of the modulation frequency allowed us to prepare and conduct experiments on real samples.

3. Experimental research

The experimental research was performed in Laboratory of Technical Diagnostics of Institute of Fundamentals of Machinery Design at Silesian University of Technology. The aim of the research was determination of optimal modulation frequency and heating source power in order to obtain phase images with optimal contrast between bonded and none bonded regions. For research purposes two samples which simulated adhesively bonded structures were prepared. The samples consisted of two steel plates between which was the path of the adhesive. In one of the samples simulated a break in the adhesive path (Fig. 4).

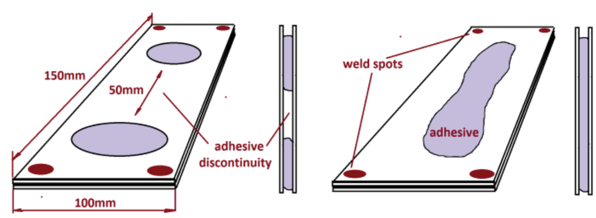

Fig. 4. Samples investigated during the research

Experiments were performed using laboratory stand (Fig 5) dedicated to application of active thermography methods. The IR camera was positioned 0.5 m from the tested sample and perpendicular to its surface. Tested sample was mounted in wooden holder. The heat source was integrated with testing cabinet as shown in Figure 5. Proposed localization of heating sources (halogen lamps) allowed reduction of reflections of IR radiation from the surface of investigated object. The lens of the camera was then focused on the specimen. The specimen was heated periodically at different modulation frequencies ranging from 0.1 to 0.008 Hz. During the experiments the infrared images of a sample surface under thermal stimulation were acquired with frequency 5 Hz synchronically to heat source period. Overall lamps power during excitation were oscillating between 0 and 680W (34% power of two 1kW halogens). The room temperature was about 23°C.

Sequences of recorded infrared images were tranformed to phase images using FFT technique which allows us to find the best image for each test. In Figures 6 and 7 exampary phase images obtainded for tested samples were presented

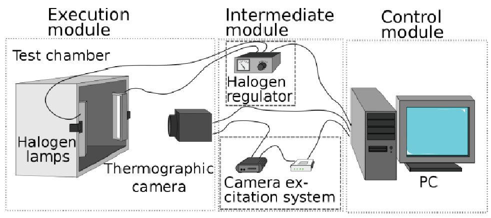

Fig. 5. The Laboratory stand used during the research

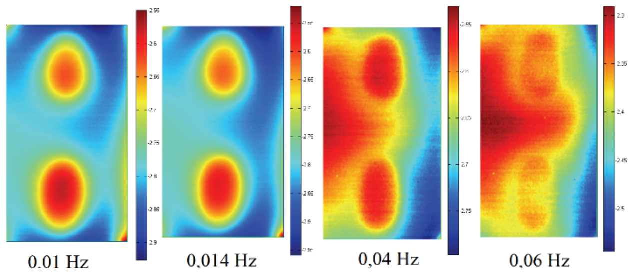

Fig. 6. Phase images of sample with adhesive discontinuities obtained for different modulation frequencies

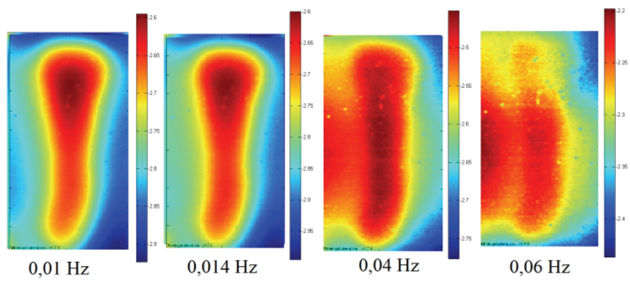

Fig. 7. Phase images of sample with continuous adhesive path obtained for different modulation frequencies

For each phase image a line profile along image and investigated bonded joint was defined (Fig. 8). It allows to obtain series of profiles which ordered acording to modulation frequency shows which frequency gives the best thermal contrast between bonded and no bonded region (Fig. 9). As an optimal harmonic excitatin frequency selected 0.014 Hz. The frequency is very low and it is close to frequency calculated analyticaly using the BP model.

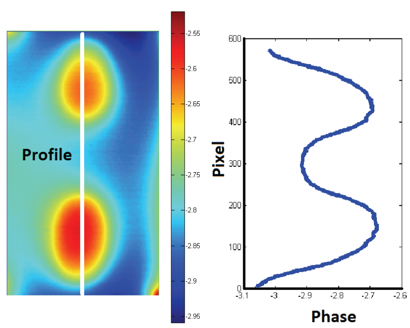

Fig. 8. Phase images profile for further estimations set on specimen with adhesive discontinuity

Having found optimal excitation frequency investigated also how excitation power affects on defects visibility. In Figure 10 profiles of infrared images recorded at excitation frequency 0.014 Hz at different source excitation power were presented. One can see that power above 30% gives the best contrast of defect visibility.

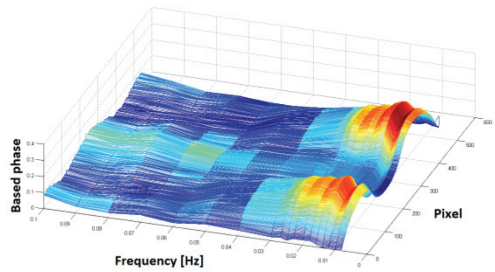

Fig. 9. Series of phase image profiles ordered by excitation frequencies

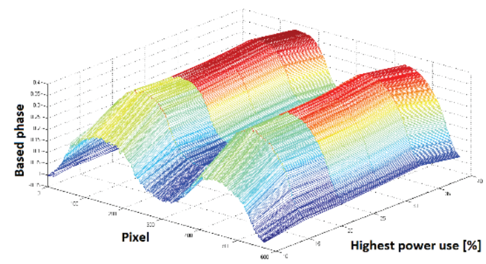

Fig. 10. Series of phase image profiles acquired at excitation frequency 0.014 Hz ordered by excitation power

Phase images obtained for optimal excitation frequency and power were processed in order to improve visibility of bonded and unbonded regions. Firstly, for each image pixel a phase difference $\Delta\Phi$ between sound and defect area was calculated. A differential images were presented in Fig.11a. Next operation was filtering by Gaussian low-pass filter and median filter with 3×3 mask and then binarization performed using Bernsen, Otsu and global methods. Binarization allowed us to separate regions with and without adhesive. Results of image processing operation were presented in Fig. 11.

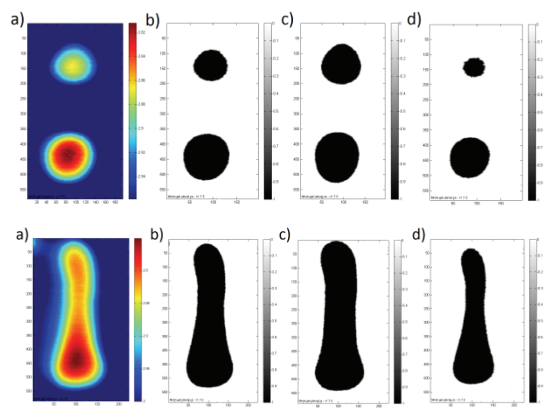

Fig. 11 Phase differential images of investigated specimens (a) and results of their thresholding using Bernsen (b), Global (c) and Otsu (d) methods

4. Conclusions

The presented research shows that application of lock-in thermography allows us to precisely detect discontinuities and irregularities in the adhesive path what confirms possibility of this NDE method to detection of bonded joints defects in industrial condition. Effective defect detection requires selection of optimal excitation parameters where the most important is modulation frequency. The frequency value could be preliminary estimated analytically. However, accuracy of the estimation depends on good knowledge of the material adhesive and bonded elements parameters. In case of steel plates bonded by elastic adhesive an excitation frequency is very low which follows from high conductivity of steel. Such low frequency makes each test very time consuming. In presented research each experiment takes about 190 seconds.

5. References

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