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Development of Reference Specimen in Thermography for NDT

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Abstract

This paper proposes the reference specimen for lock-in photo-infrared thermography. Basically, thermography depends on environmental disturbances, which is related to the defect detection ability of thermography system in non-destructive testing. Reference specimen can be useful in evaluating the detection capacity and the detection range of a defect under a given environmental condition. The proposed reference specimen can be supply the defect size, location and depth by the shearing phase technique and the depth inversion technique. The defect information can be effectively acquired with the well-designed reference specimen. We hope that a reference specimen will improve the reliability of thermography in nondestructive testing.

1. Introduction

Infrared thermography has been used for the evaluation of thermal characteristics of structure by providing the surface temperature distribution. This technology in nondestructive testing is well known as the technique used for detecting the abnormal heating of component, resulted from the deterioration of electronic power system or from the increased friction of mechanical part. Recently, a modulated external heat source, induced to the object, is used to improve the defect detecting capacity of infrared thermography and this technology is focused on the development of the signal processing technologies such as lock-in and pulse. In addition, the improved technology is widely applied to various areas such as metal material corrosion testing, fine surface crack test, composite delamination test and so on[(1-3)]. Since infrared thermography is used for detecting the infrared energy emitted from the object and converting the detected infrared energy into the temperature, the environmental variables existing between object and detection device such as humidity, surrounding temperature, wind and so on may influence on the inspection results[(4)]. Most of nondestructive test

technologies are exposed to these problems and the reference specimen in each method has been used for the evaluation or calibration of detecting capacity depending on the surrounding environments or material properties of object. We may not disregard the effect of surrounding environments in the nondestructive test using the infrared thermography. The development of reference specimen required for evaluating the detecting capacity of inspection system helps improving the reliability of thermography. This paper proposes reference specimen of lock-in photo-infrared thermography, which can supply defect size, location and depth by conventional inversion technique. As testing technique, lock-in photo-infrared thermography is used and it makes fully non-contact possible by using high power lamps as external source and also enables its user to recognize the defective part of object by measuring the temperature distribution of object surface occurred when heating the modulated heat source. In addition, thermal phase from this technique is insensitive to non-uniform surface emissivity.

2. Lock-in Infrared Thermography

The lock-in infrared thermography technique is the method used for acquiring the change of phase and amplitude by processing the response signal detected when inducing the infrared heat source to the object modulated as the periodic function. The photo, ultrasound, vibration and eddy current, controlled by the periodic function according to type of detect, are commonly used as the stimulus source. In this paper, lock-in photo-infrared thermography uses the light sources such as halogen lamp as a stimulus source. This technique is used for detecting the defect by observing the change of heat source, penetrated with periodic function into the object. Lock-in technique is explained from heat conduction equation and the one-dimensional heat conduction equation of a solid is known with equation (1)

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial x^2} \quad \text{.....(1)}$$

Here, T indicates the temperature, t indicates the time, k indicates thermal conductivity, ρ indicates the density and c_p indicates the specific heat capacity respectively. For a periodic function, we have $T = T_0\, e^{i\omega t}$ and obtain from equation (1):

$$\begin{aligned} T(x,t) &= T_0\, e^{-x/\mu}\, e^{i(\omega t - x/\mu)} \\ &= T_0\, e^{-x/\mu}\cos(\omega t - x/\mu) + i\sin(\omega t - x/\mu) \end{aligned} \quad \text{……(2)}$$

Here, thermal diffusion length, μ and thermal diffusivity, α are expressed as $\mu = \sqrt{\frac{\alpha}{\pi f}}$ and $\alpha = \frac{k}{\rho c_p}$ respectively. We may express the correlation like the equation (3) in consideration of only the real part of equation (2).

$$T(x,t) = T_0\, e^{-x/\mu}\cos(\omega t - x/\mu) \quad \text{……...(3)}$$

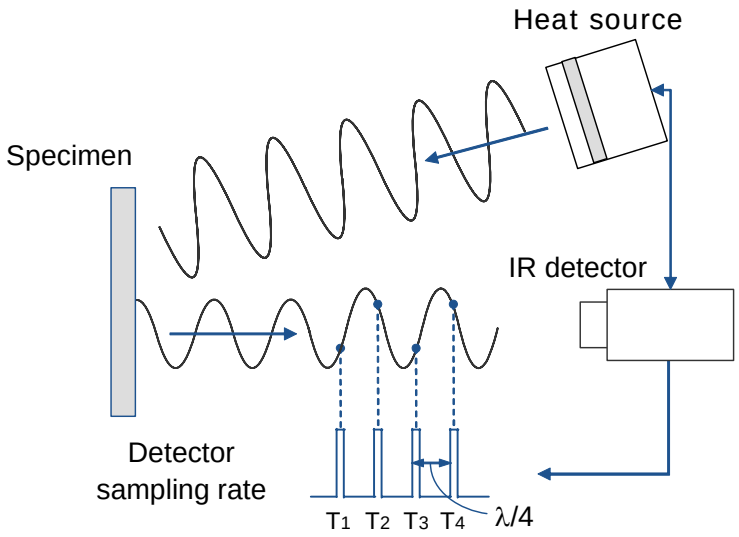


Figure 1. System configuration and signal processing of lock-in thermography

The equation (3) shows that the phase is delayed as much as x/μ according to object's depth, x, when heating the solid using the $T = T_0\, e^{i\omega t}$. If the modulation frequency of stimulus source is increased, penetration depth is decreased and only the information of being adjacent to the surface may be acquired. Also, the penetration depth is increased at low frequency, so the information of deep area may be detected. The defect detecting capacity of lock-in technique can be improved by extracting the phase using the test results acquired in the equation (3), and also, this technique is insensitive to the non-uniformity surface emissivity. If the system is configured as shown in Figure 1, periodic function is induced from the heat source to the object and surface thermal response of object are expressed as the equation (3). We can measure the infrared detection signals, S_1, S_2, S_3 and S_4 in the interval of stimulus source, $\lambda/4$ by synchronizing and controlling the stimulus source and infrared detection device. The successive signals are expressed like the equation (4). We can acquire the phase and amplitude of equation (3) using the equation (5) and equation (6) [5].

$$\begin{aligned} S_1(x,y) &= T_0\, e^{-x/\mu}\cos(\omega t - x/\mu) \\ S_2(x,y) &= T_0\, e^{-x/\mu}\cos(\omega t - x/\mu - \pi/2) \\ S_3(x,y) &= T_0\, e^{-x/\mu}\cos(\omega t - x/\mu - \pi) \\ S_4(x,y) &= T_0\, e^{-x/\mu}\cos(\omega t - x/\mu - 3\pi/2) \end{aligned} \quad \text{.....(4)}$$

$$\phi(x,y) = x/\mu = \tan^{-1}\left(\frac{S_4(x,y) - S_2(x,y)}{S_1(x,y) - S_3(x,y)}\right) \text{.....(5)}$$

$$A(x,y) = T_0 e^{-x/\mu} = \sqrt{(S_4(x,y) - S_2(x,y))^2 + (S_1(x,y) - S_3(x,y))^2} \text{ .....(6)}$$

3. Design of Reference Specimen and Test Results

3.1 Design of Reference Specimen

Reference specimen for the lock-in photo-infrared thermography can be used in the test site for forecasting the size, location and depth of detectable defect. Therefore, the reproducibility of detecting the same size and depth of defect must be guaranteed under the same test conditions. We manufacture the specimen as shown in Figure 2 in consideration of influence factors when deciding the size and depth of defect. Firstly, the maximum size of specimen is decided in consideration that the whole surface of specimen has to be uniformly heated by the lamp. In order to eliminate the interference between defects in evaluating the defect size, the distance between defects is experimentally designed as 40 mm. The minimum size of detectable defect is determined with ϕ 4 mm in consideration of the spatial resolution (±0.7 mm) of infrared detection device and quantitative evaluation of defect size in experiment. The bottom-plate-back-drilled defects are manufactured from the minimum size up to ϕ 16 mm with 4 mm increase. The depth of detectable defect depends on heat capacity of material. Experiment uses the stainless steel 304 (STS304, AISI304, SUS304) for the reference specimen in consideration of workability and storage property. However, we need to consider the use of other materials according to purpose and object to be inspected. Machining error of specimen has to keep ±0.05 mm in size and ±0.1 mm in depth, independent on total uncertainty. The thermal properties of STS304 test piece used as the material of test piece are as Table 1.

Table 1. Thermal properties of reference specimen

Thermal conductivity (k)	Density (ρ)	specific heat capacity (c_p)	thermal diffusivity (α)
16.2 W/m-K	7900 kg/m^3	500 J/kg-K	4.05 x 10^{-6} m^2/s

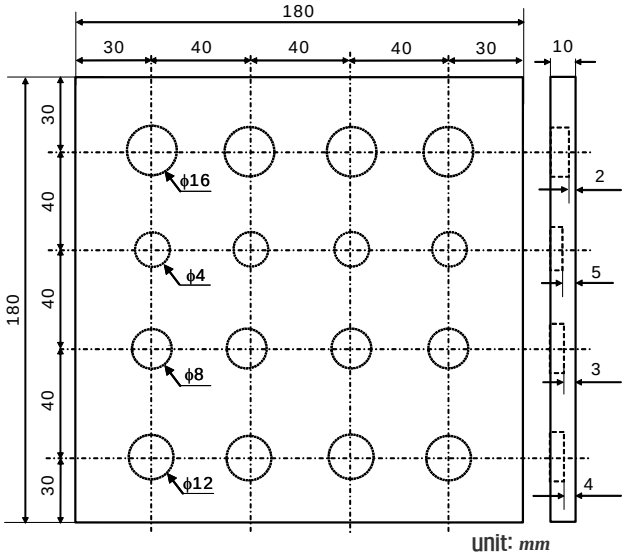


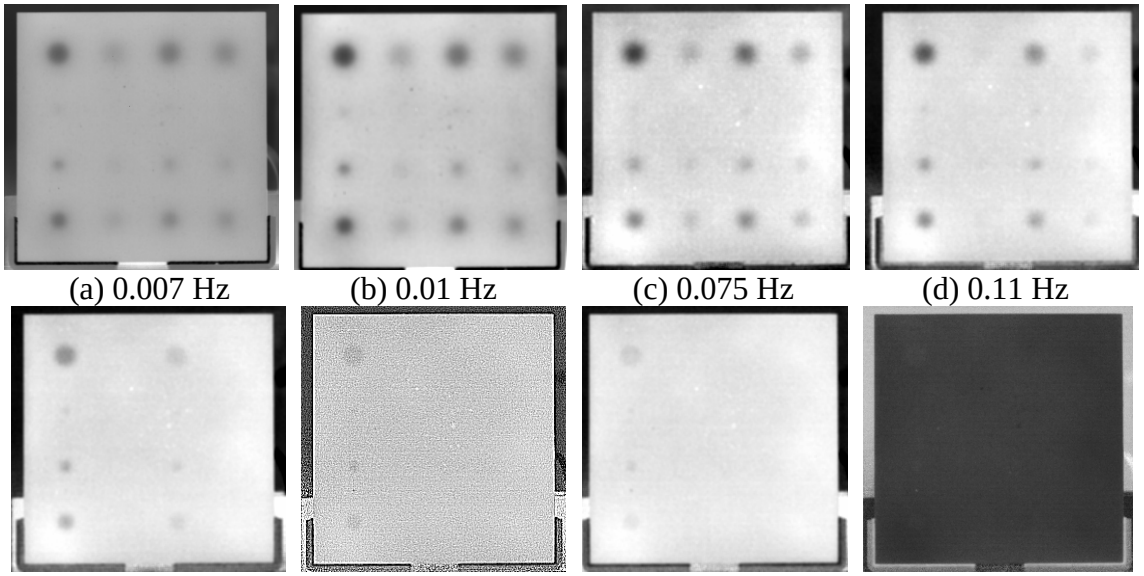
Figure 2. Reference specimen for lock-in photo-infrared thermography

3.2 Evaluation of Defect Depth

The defect depth is estimated by using the thermal diffusion depth[6], μ of equation (3). The maximum thermal diffusion length is a key to determine the defect depth, where the induced light source penetrates into the object and is closely related to the frequency of induced heat source. The higher the induced frequency is, the shorter the diffusion length is. Therefore, the detectable depth is limited according to frequency of induced heat source. The limiting frequency is known as blind frequency, where the defect of specific depth is not detected[7]. In experiment, the blind frequency, acquired by decreasing the frequency, is the frequency at which a certain deep defect is started to appear. The defect depth, d is evaluated by using the acquired blind frequency, f_b and equation (8).

$$d = C \cdot \mu = C \cdot \sqrt{\frac{\alpha}{\pi \cdot f_b}} \quad \text{.....(8)}$$

In this paper, the correlation coefficient, C of reference block is investigated by diffusion length from the blind frequency and the known defect depth. The frequency-detectable defect depth diagram is plotted, which will be available to forecast the defect depth in field test. Figure 3 shows the thermal phase image measured according to frequency change of induced heat source. In figure 3, all defects is not detected at frequency of 0.46 Hz but according to decreasing frequency, 2 mm deep defects except ϕ 4 mm are stared to appear at 0.41 Hz, 3 mm deep defects are also stared to appear at the frequency of 0.19 Hz, 4 mm deep defects is at 0.11 Hz, and 5 mm deep defects is at 0.075 Hz.



(a) 0.007 Hz (b) 0.01 Hz (c) 0.075 Hz (d) 0.11 Hz

(e) 0.19 Hz (f) 0.31 Hz (g) 0.41 Hz (h) 0.46 Hz

Figure 3. Thermal phase images of reference specimen at each induced heat source

Table 2 shows the blind frequency at each defect depth, diffusion length, and the estimated correlation coefficient is estimated by dividing actual defect depth by diffusion length. From these values, the correlation coefficient of reference specimen is as decided as 1.15. The detectable defect depth on each induced frequency is plotted as shown in the Fig. 4.

Table 2. Correlation coefficient of reference specimen

Actual defect depth (mm)	2	3	4	5
Blind frequency (Hz)	0.41	0.19	0.11	0.075
Diffusion Length (mm)	1.8	2.6	3.4	4.1
Correlation coefficient	1.13	1.15	1.17	1.21

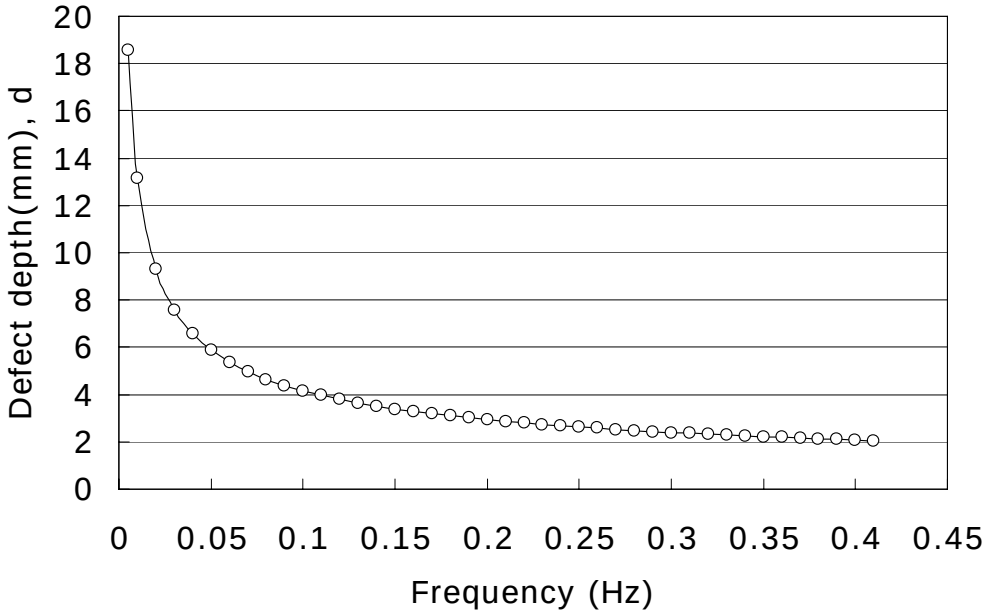


Figure 4. Detectable defect depth diagram according to induced frequency

3.3 Evaluation of Defect Size

The size of defect is evaluated by applying the shearing phase technique[8] to the thermal phase image at the optimum frequency, at which a defect produces a maximum phase difference between the healthy part and the defective part, and this frequency was selected for use in the shearing phase technique. Figure 5 shows the thermal phase distribution and the shearing phase distribution on ϕ 12 mm defects at the frequency of 0.01 Hz. Four defects is easily recognized from the phase distribution of figure 5 and the shearing phase distribution gives the maximum, minimum and zero points for each defect. The defect size is decided between maximum and minimum points and the location can be determined as the zero point. The results acquired by measuring three defects of 8, 12 and 16 mm are shown in the Table 3. Although the defects with 5 mm-

deep ϕ 8 mm have large error, the other test results show the high accuracy within the range of 10%.

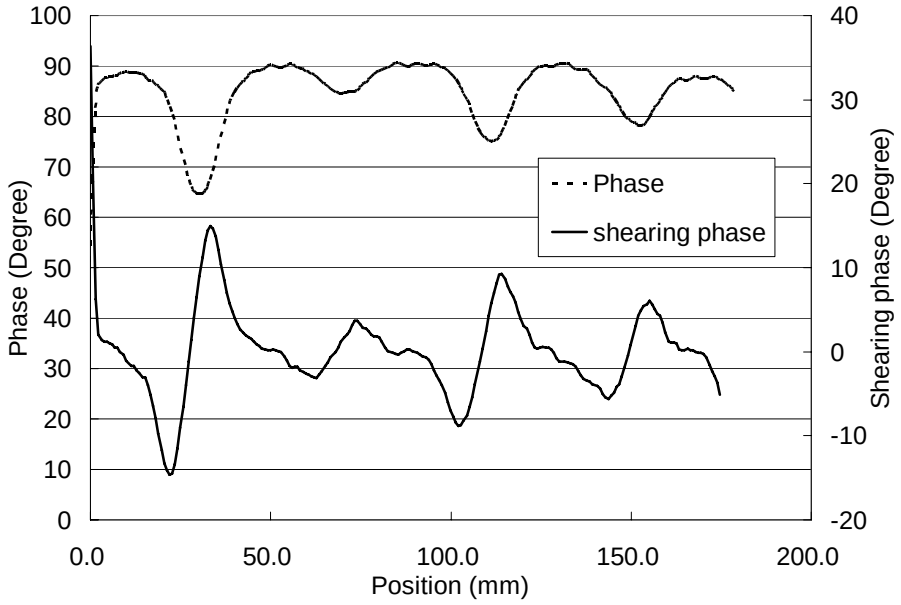


Figure 5. Thermal Phase and shearing phase distribution at 0.01 Hz of ϕ 12 mm

Table 2. Inspected defect size (mm) of reference specimen

Size / Depth	ϕ 8 mm	ϕ 12 mm	ϕ 16 mm
2 mm	8.32	11.34	15.13
3 mm	9.08	12.10	15.88
4 mm	9.08	11.34	15.13
5 mm	11.34	10.59	17.39

4. Conclusions

In this paper, we propose the reference specimen which is used for the evaluation of detecting capacity of the lock-in photo-infrared thermography. The proposed specimen can be supply the defect size, location and depth with the shearing phase technique and thermal diffusion length of blind frequency. The defect information can be effectively acquired with the well-designed reference specimen. Currently, study on reference specimen of thermography, evaluated as the beginning stage, are to be used for the standardization through the discussion with relevant researchers.

Acknowledgements

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References and footnotes

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