Development of a New Crack Identification Technique Based on Near-Tip Singular Electrothermal Field Measured by Lock-in Infrared Thermography*

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A new thermographic NDT technique was proposed, in which singular electrothermal field near crack tips under the application of periodically modulated electric current was measured using an infrared thermography combined with lock-in data processing technique. Experimental investigations were made on the resolution and the applicability in the identification of through-thickness artificial cracks and fatigue cracks embedded in steel and aluminum alloy plate samples. Modulated electric current was applied to the cracked sample by an induction coil. Lock-in thermal images synchronized to the reference current modulation signal were taken by the lock-in thermography. Significant singular electrothermal field was observed at the crack tip in the lock-in thermal image. The fatigue cracks as well as artificial cracks were found to be sensitively identified by the proposed technique in good resolution compared with the singular method using a conventional thermographic temperature measurement.

Key Words: Nondestructive Inspection, Infrared Thermography, Lock-in Thermography, Crack Identification, Singular Electric Current Field, Induction Heating, Joule Effect

1. Introduction

The recent improvement of the infrared thermography with high precision infrared detectors has brought about remarkable progresses into the thermographic NDT techniques. Thermographic NDT has been developed as one of the powerful non-contact NDT techniques by many researchers⁽¹⁾⁻⁽³⁾, and it made us possible to detect flaws and defects with good resolution. Recently a new approach using lock-in thermography has been examined for the thermographic NDT by several researchers⁽⁴⁾⁻⁽⁸⁾. In this approach, periodical thermal oscillations were applied to the objective body, and thermal images synchronized to the reference oscillation signal were taken by the lock-in thermography. This technique contributed for the improvement of resolution and accuracy of the temperature measurement. Further, it also contribut-

ed for the utilization of the phase delay data and frequency dependent data, which is effective for accurate and quantitative identification of flaws and defects.

Lesniak et al.⁽⁴⁾ developed the forced diffusion thermography, in which a continually repeated full field thermal oscillations on the sample were generated by a projection of multiple parallel moving line heat sources, and were measured very accurately by the lock-in thermography. Wu et al.^{(5),(6)} developed the phase sensitive modulation thermography, in which advantages of using the phase delay distributions of the lock-in thermal images were shown in the application of defect measurement of advanced composite materials. Favro et al.⁽⁷⁾ examined the applicability of the lock-in thermography technique at high frequency oscillation under the AC current application combined with snapshot mode high speed infrared camera. The present authors⁽⁸⁾ proposed a new hybrid NDT technique called as thermal wave CT method, in which temperature distribution data taken under periodical heating were numerically processed to identify crack location and size by using the inverse method

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based on the boundary element method.

In previous papers, one of the present authors^{(9),(10)} proposed a new thermographic NDT technique termed “singular method” for crack identification. In this technique, significant heat concentrations around crack tips due to the singularity of the electric current field at crack tips were detected. The feasibility of the proposed technique was numerically and experimentally demonstrated, and it has been applied to the detection of cracks in electric-conductive materials. In this paper, a new thermographic NDT technique based on the singular method combined with the lock-in thermography technique is proposed. The proposed technique is experimentally tested for the detection of the through thickness artificial cracks and fatigue cracks introduced in steel and aluminum alloy plates under an induced current application.

2. Singular Method

Basic principles of the singular method are explained for two-dimensional crack identification problem under DC current application. In the singular method, cracks are identified from the singular electrothermal field generated around the crack tips. When a crack crosses the streamline of the applied electric current, as illustrated in Fig. 1, a singular electric current field is generated in the vicinity of the crack tip^{(11),(12)}. The current density increases near the crack tip and theoretically goes to infinity at the crack tip in the singular electric current field. For a two-dimensional homogeneous body, a heat generation rate Q , defined as the heat generation during unit time in unit volume by Joule effect heating, is given as follows, using the Cartesian coordinates (x, y) since two components of the electric current are expressed in terms of the derivatives of electric potential, ϕ , and specific resistance ρ_e :

$$Q = \frac{1}{\rho_e} \left\{ \left(\frac{\partial \phi}{\partial x} \right)^2 + \left(\frac{\partial \phi}{\partial y} \right)^2 \right\} \quad (1)$$

Consequently, the heat generation rate theoretically goes to infinity at the crack tip. This results in a singular electrothermal field of concentrate tempera-

ture rise at crack tips, as shown in Fig. 1.

When cracks of limited length open on a sample surface and are inspected from the surface, the location of the crack tips can be easily identified from the singular electrothermal field appearing on the surface for both through-thickness cracks and surface cracks. The depth of the semi-elliptical surface cracks may also be estimated by analyzing the intensity of the singular electrothermal field⁽¹³⁾.

Under the application of AC current, electric current stream is concentrated beneath surface due to the skin effect. The singular electrothermal field appears around through-thickness cracks in the AC current field even though it has a skin effect. Thus through-thickness cracks can be identified from the singular electrothermal field under AC current application as well as under DC current application. In the case of surface cracks, however, no singular electrothermal field can be observed if the skin depth is extremely smaller than crack depth. When a skin depth is adjusted to the similar order of the depth of the surface crack by selecting suitable frequency of the AC current according to the material's electromagnetic properties, the singular electrothermal field again appears around the tips of surface cracks and surface cracks can be identified from the singular electrothermal field. An experimental confirmation was made for identification of surface cracks in the stainless steel plate under AC current application of 60 Hz⁽¹³⁾.

The resolution of crack detection by the singular method was influenced by several factors, such as the dimensions of the crack, the intensity of applied current and the thermal conductivity of samples. The present authors discussed the resolution in the singular method by considering both the intensity of the singular current field and the thermal diffusion from the crack tip to the surrounding area⁽¹⁰⁾. The intensity of the singular current field at the crack tip was characterized by introducing the current intensity factor $K^{(11)}$, given by the following equation for two-dimensional problem using the polar coordinates r and θ with the origin at the crack tip.

$$i_r = \frac{K}{\sqrt{2\pi r}} \sin \frac{\theta}{2}, \quad i_\theta = \frac{K}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \quad (2)$$

Since a heat generation rate Q is in proportion to the square of the current, the electrothermal field near the crack tip is expected to be quantified by the current intensity factor K in the early stage of heat conduction process. In the case of smaller crack lengths, the near tip singular current field becomes less predominant and the concentrated temperature rise at crack tips are degraded. The higher current density is required to secure the enough current inten-

Fig. 1 Illustration of singular method thermographic NDT technique

sity factor for the smaller cracks. In the actual applications, however, it is sometimes difficult to apply a high power current to the objective body. Therefore the temperature measurement in high resolution is required for the detection of small cracks. This is one of the problems of the conventional singular method.

The resolution of the crack detection by the singular method was also influenced by the thermal diffusion, which reduces the significant temperature rise at the crack tip. The heat concentration is poorly detected in the samples with high thermal conductivity, even if the intensity of the singular current field is the same. This can be discussed in terms of the thermal diffusion length d and the crack length a . The thermal diffusion length d , which characterizes the thermal diffusion of materials, is given as follows.

$$d = \sqrt{\frac{\lambda t}{\rho c}}, \quad (3)$$

where t is a elapsed time, λ is a thermal conductivity, ρ is a density and c is a specific heat. In order to detect cracks accurately, d must be much smaller than a . It is required for the detection of small cracks that the temperature measurement is completed during a very short elapsed time after current application when the influence of the thermal diffusion is less dominant. This is another problem of the conventional singular method.

A new approach for the singular method, in which fluctuations of the singular electrothermal field under the periodically modulated current application are precisely measured by the lock-in infrared thermography, is proposed to solve these problems in the conventional singular method in the following paragraphs.

3. Singular Method by Lock-in Infrared Thermography

3.1 Basic principles

When a periodically modulated electric current is applied to the cracked sample, the intensity of the singular current field expressed in terms of the current intensity factor K oscillates in the same frequency. The singular electrothermal field near the crack tip also shows a cyclic change, since the heat generation rate Q at the crack tip is dominated by the current intensity factor. Therefore, the lock-in measurement using the reference signal of the modulated electric current can be made for the cyclically changing temperature distribution near cracks to be detected. The lock-in data processing technique enables us to measure the amplitude of the oscillating temperature with the resolution of 1 mK. Thus the singular electrothermal field near the crack tip can be precisely measured

even for low current intensity factors in the case of small cracks or low nominal current density.

The lock-in technique also has the following advantages in avoiding the degradation of crack identification due to the thermal diffusion. First, in the lock-in technique, the temperature difference during each cycle of the current modulation is measured, and the effect of the thermal diffusion is significantly reduced when an optimal modulation frequency is chosen according to the thermal conductivity of the objective body. Secondly, the lock-in technique provides us the data of phase-delay distribution against the reference signal. The location of the crack tip can be also identified from the phase-delay distribution data. The highest heat generation rate is found at the crack tip and heat diffuses from the crack tip to the surrounding area. Then the phase of the thermal oscillation in the surrounding area is delayed from the phase at the crack tip due to the thermal conduction. The phase-delay distribution can be successfully employed for the crack detection in the materials with high thermal conductivity, when the effect of rapid thermal diffusion during each modulation cycle can not be disregarded.

3.2 Experimental systems

A schematic illustration of the proposed lock-in thermographic NDT system is shown in Fig. 2. A DC or AC direct current application method and an induction method can be used to generate periodically modulated electric current. Induction method was examined in this experiment, because of the advantage of the non-contact current application method considering the practical use of the proposed method for actual structural members. A high frequency AC signal in 250 kHz was generated by the two-channel signal generator. The amplitude of the output signal was periodically modulated according to the low frequency modulation signal generated by the same sig-

Fig. 2 Illustration of the proposed singular method thermographic NDT system combined with lock-in infrared thermography

nal generator. Sinusoidal waveform was used as the modulation signal, and its frequency was adjusted from 0.5 Hz to 15 Hz according to the thermal conductivity and the thickness of the employed specimen. The modulated high frequency AC signal was amplified by the high frequency amplifier and applied to a plane spiral induction coil, which was located under the specimen. A doughnut-like circumferential induced current field was generated above the plane spiral coil. In this experiment cracks to be detected were located in the region near the outer rim of the doughnut where the density of induced current was expected to be nearly homogeneous.

The lock-in infrared thermography system (Stress Photonics, DeltaTherm 1200), designed for the stress measurement based on thermoelasticity, was employed in this experiment. Continuous data on infrared radiation from the surface of the specimen were measured by the infrared camera (Raytheon Radiance HS), and transferred to the control box of the DeltaTherm system. The digital lock-in processing of the infrared signal was carried out in the control box by using the frequency modulation signal from the signal generator as the reference signal. This enabled us to take high-resolution lock-in thermal images of the singular electrothermal field around cracks generated by the modulated electric current.

4. Experimental Results for Artificial Cracks

Rectangular shaped stainless steel plates and aluminum alloy plates (110 mm in width and 140 mm in length) were used as the artificial cracked specimens. The combinations of the material and thickness of the plate, and the size of cracks are shown in Table 1. Values of the maximum amplitude of the applied voltage shown in Table 1 were read from voltage meter installed in the high-speed power amplifier. The cracks were introduced to the specimens by the electric discharge machining. The surface of the plate was coated with flat black paint to keep high emissivity.

Figures 3, 4, 5 and 6 show the lock-in thermal

images taken for stainless steel plates under the condition of the experiment number SS-01a, SS-04a, SS-03a and SS-03b respectively in Table 1. The distribution of amplitude R of the oscillated infrared emission

(a) Amplitude (R -image) (b) Phase delay (θ -image)

Fig. 3 Lock-in thermal images taken for stainless steel plate under condition of SS-01a

(a) Amplitude (R -image) (b) Phase delay (θ -image)

Fig. 4 Lock-in thermal images taken for stainless steel plate under condition of SS-04a

(a) Amplitude (R -image) (b) Phase delay (θ -image)

Fig. 5 Lock-in thermal images taken for stainless steel plate under condition of SS-03a

(a) Amplitude (R -image) (b) Phase delay (θ -image)

Fig. 6 Lock-in thermal images taken for stainless steel plate under condition of SS-03b

Table 1 Employed specimens and experimental conditions

Exp. No.	Material	Thermal diffusion length	Specimen thickness	Crack length	Current modulation frequency	Max. amplitude of applied voltage to induction coil
SS-01a	SUS304 Stainless steel	$d = 2.0\text{mm}$ ($t = 1\text{s}$)	0.5mm	10mm	1Hz	92V
SS-01b			0.5mm	10mm	3Hz	92V
SS-02a			0.5mm	5mm	1Hz	92V
SS-02b			0.5mm	5mm	3Hz	92V
SS-03a			0.5mm	3mm	1Hz	92V
SS-03b			0.5mm	3mm	3Hz	92V
SS-04a	A2024 Aluminum alloy	$d = 7.0\text{mm}$ ($t = 1\text{s}$)	1mm	10mm	1Hz	92V
SS-04b			1mm	10mm	3Hz	92V
AL-01a			0.5mm	10mm	1Hz	92V
AL-01b			0.5mm	10mm	3Hz	92V
AL-04a			1mm	10mm	1Hz	92V
AL-04b			1mm	10mm	3Hz	92V

(a) R -value (b) Θ -valueFig. 7 Line profiles of value R and Θ obtained along line A-A in Fig. 4 (a) Amplitude (R -image) (b) Phase delay (Θ -image)

Fig. 8 Lock-in thermal images taken for aluminum alloy plate under condition of AL-01a

(a) Amplitude (R -image) (b) Phase delay (Θ -image)

Fig. 9 Lock-in thermal images taken for aluminum alloy plate under condition of AL-01b

(a) Amplitude (R -image) (b) Phase delay (Θ -image)

Fig. 10 Lock-in thermal images taken for aluminum alloy plate under condition of AL-04b

Fig. 11 Configuration of specimen employed for fatigue crack measurement and process of fatigue crack introduction in specimen

(a) Amplitude (R -image) (b) Phase delay (Θ -image)

Fig. 12 Lock-in thermal images taken for aluminum alloy plate specimen with fatigue cracks, Crack length: 4 mm (top crack), 5 mm (bottom crack), Specimen thickness: 2 mm, Current modulation frequency: 12 Hz

(R -image) is shown on the left hand side, and the distribution of phase delay (Θ -image) is shown on the right hand side. The line profiles of the R -values and Θ -values obtained for the experiment number SS-04a are shown in Fig. 7. R -values are expressed by 16-bit output values from the lock-in infrared thermography, which shows the amplitude of the intensity of the infrared radiation energy. Positive values in Θ -values mean the phase delay from the reference signal. It can be seen in all R -images that significant high

values due to the singular electrothermal field are found at crack tips. The location and size of the cracks are easily identified from the concentrated high R -values at the crack tips. It is also found in all Θ -images that the location of the crack tips can be identified from the phase delay distribution. The concentrations in R -value at crack tips are degraded in the images taken under the condition of low current intensity factors for smaller cracks. It is noteworthy, however, that the use of the Θ -image can improve the resolution of crack identification in these cases. It is also found in Figs. 5 and 6 that the use of the higher current modulation frequency can also improve the resolution of crack identification for small cracks, in which the current intensity factor is low and the thermal diffusion from the crack tip to the surrounding area becomes dominant.

Figures 8, 9 and 10 show the lock-in thermal images taken for aluminum alloy plates under the condition of the experiment number AL-01a, AL-01b, and AL-04b respectively in Table 1. It can be seen in all of these figures that the location and size of the cracks are identified from both R -images and Θ -images. Because of the high thermal conductivity of the aluminum alloys, the concentrations in R -value at crack tips in Fig. 8 are degraded compared with those for stainless steel plates shown in Fig. 3. On the other hand, significant changes in the phase delay values are still observed at crack tips in Θ -images in Fig. 8. It can be concluded that the use of the phase delay distributions can effectively improve the resolution of crack identification for materials with high thermal conductivity. It is also found from figures that the use of the high current modulation frequency is again effective for materials with high thermal conductivity. The thermal images were taken by the conventional thermography technique in the same conditions in Table 1. It was found that any visible singular electrothermal field could not be detected under those conditions, and the outstanding performance of the singular method by the lock-in thermography was demonstrated.

5. Experimental Results for Fatigue Cracks

An aluminum alloy (A2024) specimen with fatigue cracks propagated from a circular hole, which was modeled on an aircraft structure with multiple-site cracks propagating from rivet holes, was employed for the experiment. Configuration of the specimen is shown in Fig. 11. The thickness of the specimen was 2 mm. The process of introducing fatigue cracks was also shown in Fig. 11. A crack starter slit 5 mm in length was introduced to the central part of the specimen by the electric discharge

machining. (See Step 1 in Fig. 11.) Cyclic tensile load was applied to the specimen in order to propagate fatigue cracks from the slit. The cyclic nominal stress with the amplitude of 170 MPa was applied to the specimen for 2×10^4 times at 5 Hz. Fatigue cracks propagated from the both tips of the slit, and at the end of loadings the fatigue cracks were 4 mm and 5 mm in lengths. (See Step 2 in Fig. 11.) A circular hole of 5 mm in diameter was machined in order to remove the slit. (See Step 3 in Fig. 11.) As the result, the aluminum alloy plate specimen, in which fatigue cracks propagated from a circular rivet hole, was prepared for the crack measurement.

The amplitude-modulated high frequency AC current at 250 kHz was applied to a plane spiral coil (30 turns, 50 mm in diameter), which was located under the specimen. The value of nominal current density became lower than those in the experiments for artificial crack measurements, since a thicker aluminum alloy plate was used for the specimen. The use of the higher current modulation frequency improves the contrast of the near-tip thermal concentration in the R -image as described in the foregoing chapter. Therefore the amplitude-modulation frequency was selected to be 12 Hz.

Lock-in thermal images taken for the aluminum alloy specimen with a through-thickness fatigue cracks are shown in Fig. 12. The circular regions, which appear in the center of R -image and Θ -image, indicate the localized R and Θ values on the induction coil observed through the hole. It is found in the R -image that significant high values due to the singular temperature field are found at the tips of the fatigue cracks propagated from the hole. The location and size of the cracks are easily identified from the concentrated high R -values at the crack tips. It is also found in the Θ -image that the location of the crack tips can be identified from the phase shift distribution. It can be concluded that fatigue cracks, which were hardly identified by the human eyes, can be easily detected by the use of the proposed lock-in thermography technique.

6. Conclusions

A new thermographic NDT technique based on the singular method combined with the lock-in thermography technique was proposed. The proposed technique was experimentally examined for the detection of the through-thickness cracks in steel plates and aluminum alloy plates under the induced current application. The results showed that singularities were found at crack tips both in the amplitude images and in the phase delay images, and cracks were found to be sensitively identified by the proposed technique

in good resolution compared with the singular method using conventional thermographic temperature measurement. Experimental studies were made on the applicability in the detection of through-thickness fatigue cracks embedded in the aluminum alloy plate sample. It was found that the fatigue cracks were sensitively detected both in the temperature amplitude and phase-delay thermal images taken by the lock-in thermography.

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References

- (1) Maldague, X.P.V., *Nondestructive Evaluation of Materials by Infrared Thermography*, (1993), Springer-Verlag.
- (2) Snell, Jr., J.R. and Wurzbach, R.N.(ed.), *Thermosense XX*, Proceedings of SPIE, Vol. 3361 (1998).
- (3) Sakagami, T.(ed.), *Proceedings of the 2nd Symposium on Thermographic NDT & E Techniques*, The Japanese Society for Non-Destructive Inspection, (in Japanese), (1998).
- (4) Lesniak, J.R. and Bazile, D.J., *Forced-Diffusion Thermography Technique and Projector Design*, Proceedings of SPIE, Vol. 2766 (1996), pp. 210-217.
- (5) Wu, D., Salerno, A., Schonbach, B., Hallin, H. and Busse, C., *Phase-Sensitive Modulation Thermography and Its Applications for NDE*, Proceedings of SPIE, Vol. 3056 (1997), pp. 176-183.
- (6) Wu, D., Salerno, A., Sembach, J., Maldague, X., Rantala, J. and Busse, C., *Lock-in Thermographic Inspection of Wood Particle Boards*, Proceedings of SPIE, Vol. 3056 (1997), pp. 230-234.
- (7) Favro, L.D., Ouyang, Z., Wang, L., Wang, X., Zhang, F. and Thomas, R.L., *Infrared Video Lock-In Imaging at High Frequencies*, Proceedings of SPIE, Vol. 3056 (1997), pp. 184-188.
- (8) Sakagami, T., Kubo, S. and Miki, Y., *Numerical Investigation on Quantitative Crack Measurement Using Thermal Wave CT Method*, Journal of the Japanese Society for Non-Destructive Inspection, (in Japanese), Vol. 48, No. 10 (1999) pp. 688-696.
- (9) Sakagami, T. and Ogura, K., *New Flaw Inspection Technique Based on Infrared Thermal Images under Joule Effect Heating*, JSME Int. J. Ser. A, Vol. 37, No. 4 (1994), pp. 380-388.
- (10) Sakagami, T. and Ogura, K., *Thermographic NDT Based on Transient Temperature Field under Joule Effect Heating*, Proceedings of SPIE, Vol. 2245 (1994), pp. 120-130.
- (11) Hoenig, A., *Some Implications of an Elastic-Electrostatic Analogy on Certain Path-Independent Integrals*, Int. J. of Engineering Science, Vol. 22, No. 1 (1984), pp. 87-95.
- (12) Saka, M. and Abe, H., *A Path Independent Integral for 2-Dimensional Cracks in Homogeneous Isotropic Conductive Plate*, Int. J. Engng. Sci., Vol. 21, No. 12 (1983), pp. 1451-1457.
- (13) Sakagami, T., Ogura, K. and Taga, Y., *3-D Crack Identification Using Singular Transient Temperature Distribution under Current Application*, Proceedings of JSME, No. 914-3 (1991), pp. 13-15.