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NDE for Metals, Composites and Semiconductors by Frequency Modulated Thermography

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Abstract

Active thermography is a relatively new NDE technique, in which either a pulse or sinusoidal thermal stimulus forms the basis for conventional Pulsed (PT) and Pulsed Phase (PPT), and Lock-in (LT) Thermography respectively. Recently a new approach to active thermography was proposed in which the thermal stimulus is frequency modulated. In Frequency Modulated Thermal Wave Imaging (FMTWI), a specimen is heated for launching thermal waves into the sample, not at a single frequency (lock-in) or at all frequencies (pulsed), but in a desired range of frequencies in a decided time span. While peak power requirement is reduced, phase images obtained retain known advantages of reduced sensitivity to surface conditions, variations in emissivity and non-uniform heating. The techniques applicability to a variety of materials is highlighted by providing experimental results for metal, semiconductor and composite samples.

Keywords: *Thermal NDE, Thermal wave, Frequency modulation, FMTWI*

1. Introduction

Significant work has been done and understanding achieved in the propagation of thermal waves in solids, in recent years [1-6]. It forms the basis for Thermal Non-Destructive Evaluation (TNDE) of materials for subsurface defects, and is achieved by observing, recording and analyzing the thermal response at the material surface to a heat stimulus (broadly known as active thermography), in contrast to passive thermography where no heat stimulus is applied.

Pulsed thermography (PT) [2] and modulated lock-in thermography (LT) [1,3,5], are two major approaches to active thermography. In pulsed thermography, the tested material is warmed or cooled with a short duration energy pulse (example optical, induction heating and ultra sonic heating etc.) and a measurement of the temporal evolution of the surface temperature is performed with an infrared (IR) camera. The surface temperature gradients on the sample help to localize the defects inside the material. However the surface temperature gradients are caused not only because of hidden defects but also affected by local variations of emissivity on the material surface as well as due to non-uniform heating.

Lock-in thermography uses periodic sinusoidal thermal excitation in order to derive information of reflected thermal wave phase and magnitude [3,5] even at considerably low peak powers. The phase angle has the advantage of being less sensitive to local variations of illumination and/or of surface emissivity. Because of its mono-frequency excitation, the depth resolution of a test is fixed (i.e. fixed 'thermal wavelength'). To detect defects located at various depths in the test sample, repetition of the test at various frequencies becomes a time consuming process. Experimental arrangement for another technique, pulsed phase thermography (PPT) [1,4] is similar to that of PT, but the image sequence captured during the experiment, is processed differently. In PPT, the extraction of various frequency components present is performed by Fourier transform on each pixel of the thermal image sequence [1,3]. The phase images thus obtained show the merits of these obtained with LT [3]. To overcome some of the traditional limitations of conventional thermal wave imaging techniques (resolution, peak power, depth of penetration), the present work focuses on non-stationary forms of thermal excitation technique: frequency modulated thermal wave imaging [7-14].

2. Thermal Waves: Sinusoidal and Frequency Modulated

The model for studying thermal waves is based on the equation of heat flow due to conduction, which in a one-dimensional case (in the absence of heat sources and sinks) is given as follows [6],

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} \qquad (1)$$

where *T(x,t)* is the temperature, $\alpha = k/\rho c$ is the thermal diffusivity, k is the thermal conductivity, ρ is the density and c is the specific heat. The space coordinate is x, and t is time.

The solution for the *T(x,t)* is obtained after taking into account the boundary conditions at the irradiated sample surface (x=0) and the opposite face (x=d), with $d \to \infty$ in case of semi-infinite solid. The expression for *T(x,t)* can be written in terms of real and imaginary parts,

$$T(x,t) = T_0 e^{-x\sqrt{\frac{\pi f}{\alpha}}}[\cos(\kappa) + j\sin(\kappa)] \qquad (2)$$

where $$\kappa = 2\pi ft - x\sqrt{\frac{\pi f}{\alpha}} \qquad (3)$$

Eq. (2) shows the resultant temperature distribution caused by the wave-like propagation of the heat flow into the bulk of the sample. Damping of the thermal waves as they propagate into the sample depends not only on the thermal properties of the sample but also on the frequency of incident heating. From Eq.(3), a thermal diffusion length μ, which is a measure of the depth probed by the thermal waves within the sample, can be written as follows [1-6]

$$\mu = \sqrt{\frac{\alpha}{\pi f}} \qquad (4)$$

Unlike the case of sinusoidal intensity modulated surface heating of the sample, the proposed technique utilizes frequency modulated waves instead. Frequency modulated surface heat cycle of duration τ with a bandwidth *B* is obtained by means of linear frequency modulated heat flux (Figure 1(a)) incident on the sample surface [14],

$$Q(x=0,t) = Q_0 e^{j2\pi(ft + \frac{Bt^2}{2\tau})} \qquad (5)$$

The wavelength in FMTWI is not fixed but varies as a function of frequency during the experiment, leading to variation in the depth resolution for detection of defects at different depths.

In Digitised Frequency Modulated Thermal Wave Imaging (DFMTWI) (Figure 1(b)), the input analog frequency modulated signal (Figure 1(a)) is clipped and converted into a binary (digital) form [12]. More energy is injected comparably at the fundamental frequency in the digitized version leading to increased amplitude of reflected signal.

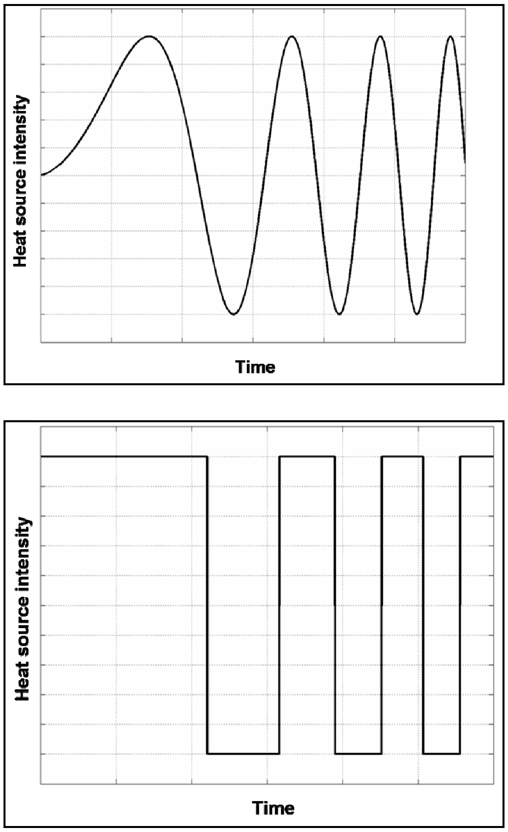

Fig. 1: **(a)** and **(b)** shows a linear frequency modulated signal (chirp) and it's digitized form, respectively [10]

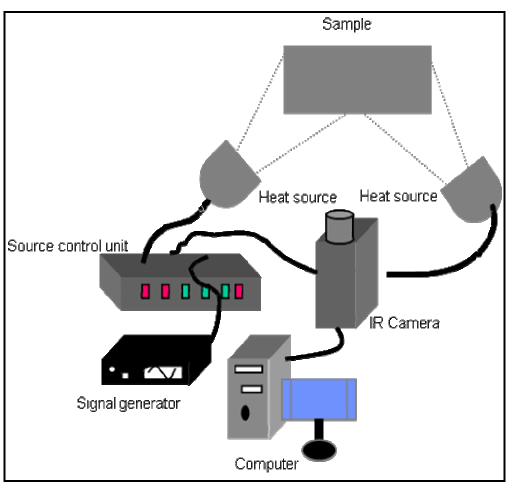

Fig. 2: Experimental arrangement for Digitized Frequency Modulated Thermal Wave Imaging (DFMTWI) [12]

3. Results and Discussion

To validate the proposed frequency modulated thermography techniques, experiments were carried out using a CEDIP IR (Jade MWIR, 3-5μm) system as shown in Fig. 2.

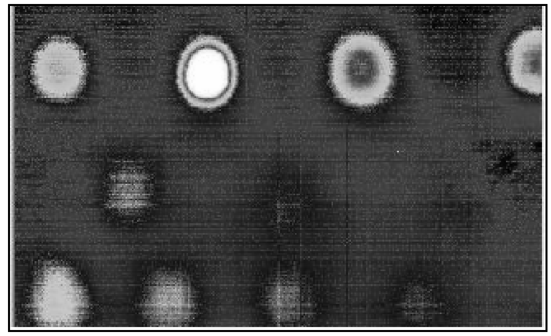

Fig. 3: Phase image at 0.05 Hz, of the 11 mm thick mild steel sample with blind holes at various depths, experimentally obtained using DFMTWI. Measurements are made over only one frequency-modulated cycle [12]

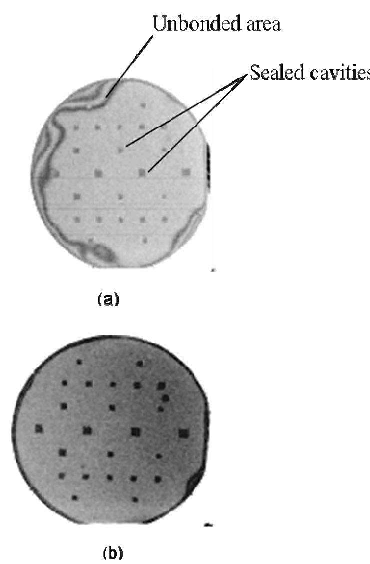

Fig. 4: **(a)** Thermal images of the bonded wafer after annealing for two hours at **(a)** 400 ºC, **(b)** after annealing at 1100 ºC for ten hours [9]

Experiments have been conducted on metal (Fig. 3), semiconductor (Fig. 4) and composite specimens (Fig. 5). Phase images obtained have all the advantages as obtained from LT and PPT, i.e. insensitivity to non-uniform heating and non-uniform surface emissivity variations on the sample surface.

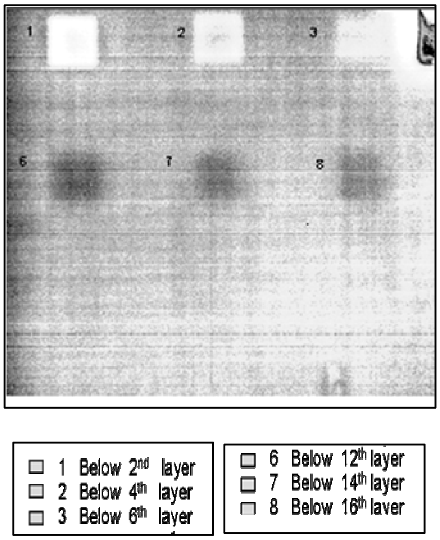

Fig. 5: Phase images of the CFRP sample with Teflon inserts, experimentally obtained using 0.08 Hz. Measurements are made over only one frequency-modulated cycle [10]

5. Conclusions

A novel frequency modulated thermography approach has been described which circumvents some of the limitations of the conventional infrared thermographic techniques. High peak power heat source requirement in pulsed thermography, and limited depth resolution of lock-in thermography due to fixed modulating frequency of sources, are over come by the proposed new technique by use of appropriately modulated excitation signal limited both in time (duration) and frequency (bandwidth). Further compared with PPT, the proposed method controls the band-width of the thermal waves being launched into the sample thickness of interest leading to higher sensitivity. By extracting the phase information from the observed thermal response, all advantages of a phase based approach are retained. Experimental results demonstrate the defect detection capability of D/FMTWI on metal, semiconductor and composite specimens.

7. References

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