Remote nondestructive material analysis by photothermal interferometry

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Abstract

Interferometry is used for the detection of thermal waves to study material properties. A symmetrical interferometer as thermal expansion detector was developed for photothermal nondestructive material analysis. After mixing a phase shifted reference signal electrically to the interferometer signal, phase and amplitude exchange phenomena have been observed.

Introduction

In a photothermal process the absorption of modulated light modifies the surface temperature of a specimen and causes a heat diffusion, called thermal wave, to propagate through the material. Any inhomogenities in the material modify the heat flow, which is directly or indirectly monitored, and can be detected. In our indirect measurements it is assumed, that the thermal waves are reflected at subsurface defects and lead to thermal expansions to be detected interferometrically. Measuring the amplitude and phase of the interferometer signal with a lock-in-amplifier leads to interesting results, when a fraction of the reference (modulation) signal is mixed (or as we call it: injected) to the interferometer signal. In contrary to other publications we found our system to be equal sensitive if measuring phase response or amplitude.[1]

Experimental arrangement

Interferometer

To minimize the influence of vibrations a symmetrical interferometer is used (See Fig. 1).[1,2,3] Because of it's symmetry only asymmetrical thermal expansions with respect to the position of the reflected interferometer beams lead to an interferometer signal. A piezo element is used for computer controlled adjustment of the interferometer.

The thermal wave is generated by periodical heating of the specimen's surface. In our expeririments we frequently used a 500 mW Argon-laser at a wavelength of $\lambda = 488$ nm. The laserbeam is chopped at frequencies between 10 and 250 Hz and focussed, after passing through a dichroic colour filter, onto the surface in between the two interferometer beams.

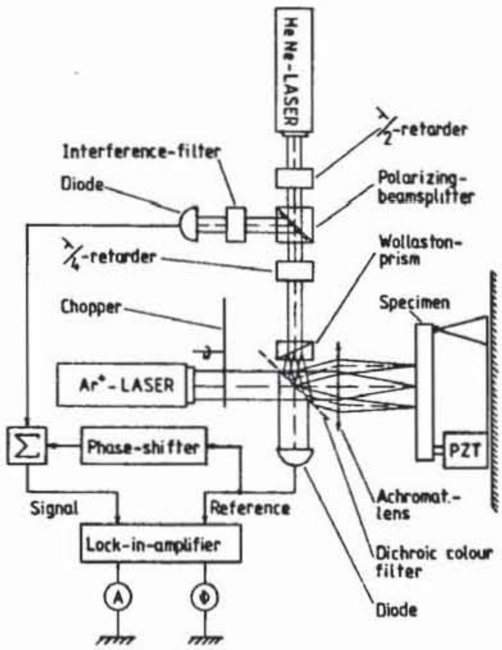

Figure 1. Experimental arrangement

Phase shifter. Measuring the phase shift between the modulation beam and the interferometer signal with a lock-in-amplifier leads to some problems, when perfect symmetry of the specimen within the detection radius, with respect to the HeNe-laser spots, occures. In that case the amplitude of the detected signal is zero, leading to stochastic phase measurements.

An injection signal (taken from the modulation) is electrically mixed to the interferometer signal, to stabilize the lock-in-amplifier. Due to the chopperwheel modulation, the injection signal is binary, it can therefore easily be phase shifted.

Theory

Thermal wave propagation

Heat conduction in solids is a three dimensional diffusion phenomenon, which can only be solved numericaly.

An one-dimensional approach was found to be adequate

$$\frac{\partial^2 T(x,t)}{\partial x^2} - \frac{1}{D}\frac{\partial T(x,t)}{\partial t} = 0 \qquad (1)$$

with the temperature T(x,t) and the thermal diffusivity

$$D = \frac{\varkappa}{\rho\, c} \qquad (2)$$

which depends on the thermal conductivity $\varkappa$, the density ρ and the heat capacity c.

The solution for sinusodial modulation at a frequency ν with $\omega = 2\pi\nu$ is given by

$$T(x,t) = T_o\, EXP(-\frac{x}{\mu})\; EXP(\, i(\omega t - \frac{x}{\mu})) \qquad (3)$$

with T_o as the amplitude of the temperature modulation of the incident Argon-laser and the thermal diffusion length

$$\mu = \sqrt{\frac{2\,D}{\omega}} \qquad (4)$$

which depends on the thermal diffusivity D and ω.

<u>Transition from temperature to thermal expansion</u>. Equation (3) describes the time dependant temperature variation at a certain position x and does not describe the thermal expansion.

The resulting thermal expansion is obtained from an integration of local expansions, obtained along the thermal propagation length from generation to detection and multiplied by the appropriate thermal expansion coefficient. If the specimen is small in comparison to the thermal diffusion length, one must take reflections of the thermal wave at the specimen's surfaces into account.

Although a one-dimensional model is used, the volume of the specimen expands in all directions. The contribution of a particular thermal expansion to the detectable expansion depends on it's distance to the place of detection.

We found a one-dimensional description in agreement with the results of the expansion, which works in transmission as well as in reflection, by multiplying equation (3) with a quadratical detection distance weighting factor and by integration from heat generation to expansion detection.

The resulting thermal expansion A(l,t) at a distance l from the heat source is

$$A(l,t) = \frac{C}{l^2}\int_0^l x^2\; T(x,t)\; dx \qquad (5)$$

with the thermal expansion coefficient C.

Figure 2 shows the principle for the detection of a subsurface hole using a symmetric differential expansion detector with the two HeNe-laser beams of the interference arrangement.

The centered Argon-laser beam serves for heat generation and two reflected thermal waves of interest are shown. The absorption of a focussed Argon-laser heats the surface and causes a spherical temperature distribution to propagate through the material, undetectable for the symmetrical interferometer. As soon as a reflection occures and the point of reflection is not symmetrical to the two HeNe-laser beams, the expansions A_1 and A_2 will be different, leading to an optical path difference δ in the interferometer.

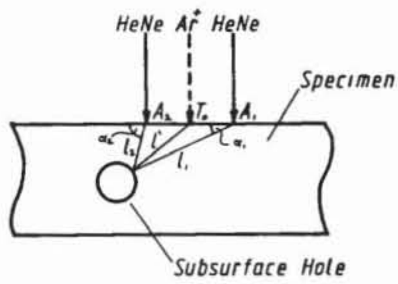

Figure 2. Thermal wave detection

The expansions A_n can be written as

$$A_n = \frac{C\ T(l',t)}{l_n^2} \int_0^{l_n} x^2\ \mathrm{EXP}(-\frac{x}{\mu}(1+i))\ dx \qquad n = 1,2 \tag{6}$$

The optical path difference due to asymmetrical thermal expansion is given by

$$\delta_t = A_1 \sin \alpha_1 - A_2 \sin \alpha_2 \tag{7}$$

with the angles of incidence α of the expansion vectors.

The linearized intensity I_s at the photodiode of the interferometer is[1]

$$I_s = \frac{I_{max} + I_{min}}{2} + (I_{max} - I_{min}) \frac{2\pi}{\lambda_s} \delta_t \tag{8}$$

with the HeNe wavelength λ_s.

The lock-in-amplifier ignores the DC part of the interferometer intensity. Added to this interferometer signal is a phase shifted injection signal coming from the modulation, which can be written as

$$I_r = I_o\ \mathrm{EXP}(\ i(\omega t + \phi_o)) \tag{9}$$

with the reference amplitude I_o and the reference phase shift ϕ_o.

Finaly the signal under investigation is

$$I = I_o\ \mathrm{EXP}(\ i(\omega t - \phi_o)) + (I_{max} - I_{min}) \frac{2\pi}{\lambda_s} \delta_t \tag{10}$$

which is fed to the lock-in-amplifier.

Noise reduction

The interferometer signal is strongly dependant on two opposite parameters. The first one is the absorption of the Argon-laser, which defines the amount of heat generated in the specimen or the temperature at Argon-laser incidence. The second is the optical surface quality of the specimen, that affects the interferometer performance. Equation (8) shows, that $(I_{max} - I_{min})$ determines the signal amplification of the interferometer. This factor is measured when scanning the specimen and serves for compensation, while the absorption of the Argon-laser can not easily be measured.

Results

A prefabricated aluminium test sample (See Figure 3e) with a subsurface hole of 0.8 mm diameter located 0.8 mm below the surface was examined at a modulation frequency of 140 Hz and 12 mV injection voltage phase shifted in four steps between 0 and -135 degrees.

Both phase and amplitude can have the same information about the subsurface structure, as shown by comparing the 0 and the -90 degree phase shift measurements (See Figure 3a, 3c) respectively. The measurement at a phase injection of -90 degrees compares well with the amplitude measurement at 0 degrees.

Furthermore, the amplitude at -90 degrees corresponds to the inverse phase measurement at 0 degrees. Fig. 3b and 3d show the result when a fraction of the reference signal, phase shifted by -90 degrees, is mixed (injected) to the interferometer signal. The theoretical results are overlayed as dashed lines in the diagrams (See Figure 3a...d).

It should be noted, that a phase shift of 180 degrees was added by the apparatus in Figure 3c and in Fig. 3d and that the mean values of all plots correspond to the injection phase (with an offset) and the injection voltage respectively.

These four measurements were obtained one after the other scanning the same line on the specimen. They show very low noise, due to the interferometer gain compensation. The remaining peaks are caused by changeing Argon-laser absorptions at different scanning positions.

In some publications[4] it is pointed out, that the phase information is twice as sensitive as the amplitude information, results obtained with the described technique found both to be equal.

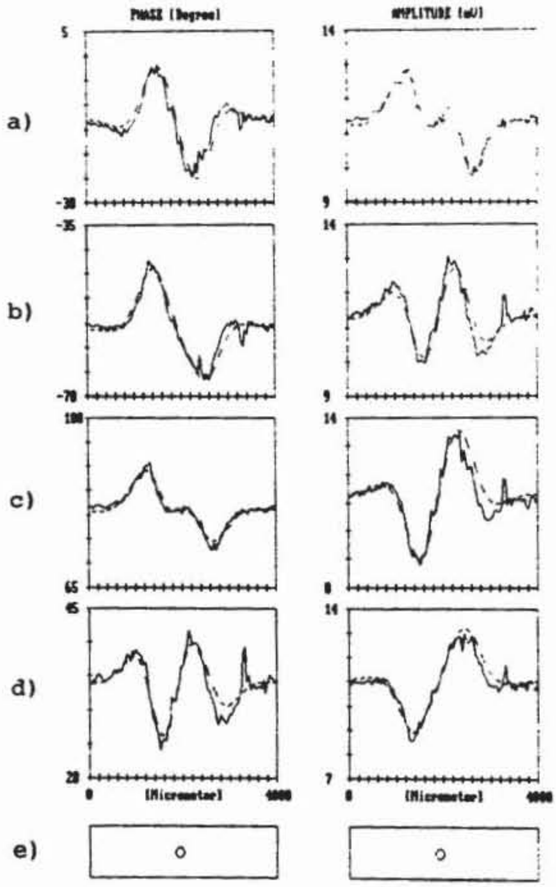

Figure 3. Experimental and theoretical results, obtained at 140 Hz modulation frequency and with an injection voltage of 12 mV, phase shifted by a) 0, b) -45, c) -90 and d) -135 degrees. e) the specimen

Conclusions

Subsurface defects as small as 0.1 mm diameter and as deep as 1 mm below the surface can be detected with this technique. For higher resolution the modulation frequency must be increased, leading to a reduced thermal penetration depth and detection radius. With frequencies of several thousend Hz resolutions in the order of micrometers can be achieved.

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