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THERMAL WAVE NONDESTRUCTIVE DEPTH PROFILING WITH STEREOSCOPIC PHOTOTHERMAL DETECTION

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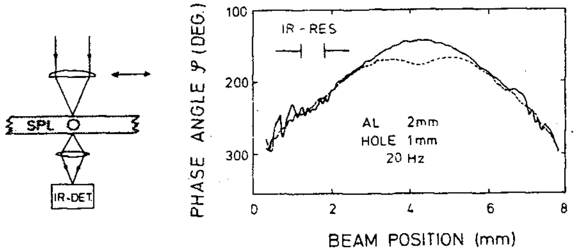
Résumé - Un montage stéréoscopique pour l'analyse en profondeur par onde thermique est présenté. Pour de l'aluminium la précision est de 0,1 mm pour des trous de 0,4 mm de diamètre à des profondeurs comprises entre 0,4 et 1,5 mm.

Abstract - Experimental results are shown for depth resolved thermal wave analysis in a stereoscopic arrangement. On an aluminum sample it is found that depth accuracy is about 0.1 mm for 0.4 mm diameter holes in depths between 0.4 mm and 1.5 mm.

When intensity modulated radiation is absorbed in a solid a temperature modulation is produced that propagates as a heavily damped wave ("thermal wave") into the solid (1,2).
With a focused optical beam and opaque material (e.g. metal) one obtains in a good approximation a point source for thermal waves which is of interest with respect to scanned thermal wave material probing where one uses optoacoustic or photothermal detection methods /3/. While with optoacoustic methods one finds only the integrated thermal wave, photothermal detection /4/ with focusing infrared optics in front of the detector allows for a true spatially resolved mapping of temperature modulation. This way both phase lag and magnitude can be scanned across a transmitted thermal wave /5/. As an example, the solid line in Fig. 1 is the phase lag φ observed in a diametral scan across the thermal wave at the rear surface of a 2 mm thickness aluminum plate at 20 Hz modulation frequency and about 0.6 mm infrared resolution. In fact the point source is moved with respect to the stationary detector. However, only the relative shift is of interest.

Fig.1

Phase angle φ in a diametral scan across a thermal wave at the rear surface of a 2 mm aluminum plate. Solid curve obtained with no hole, dashed curve with hole in front of detector.



Subsurface structure affects thermal wave propagation as can be seen from the observed distortion: With a 1 mm subsurface hole (circle in Fig. 1) just in front of the detector spot the phase curve is changed (dashed line), the maximum difference of about 30 degrees is found when the hole is just between source and detector. If source and detector are kept opposite to each other while the sample is scanned one consequently finds a phase change by about 30 degrees as the hole passes by (curve for D/2 = 0 in Fig. 2). When the detector is shifted by D/2 with respect to the source and perpendicular to the hole axis

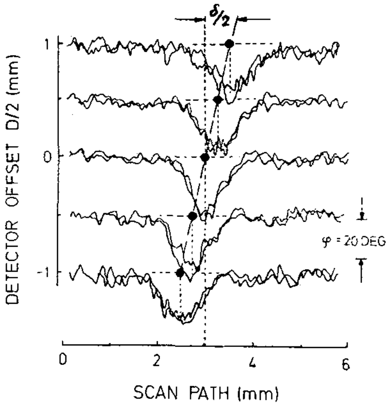


Fig.2

Effect of detector off-center position D/2 on signal structure shift δ/2. Same sample as in Fig.1

the sample position where this maximum phase angle change occurs is shifted by δ/2. Signal shift as a function of detector off-center position is shown in Fig. 2 for the 1 mm hole drilled in the middle of the d = 2 mm thickness aluminum plate. One finds that δ = D/2. This result confirms that signal change is strongest when the subsurface hole is just between the source and the shifted detector. Therefore one can use a stereoscopic arrangement for depth location as shown in Fig. 3 where with symmetrical detector positions P_1 and P_2 (distance D in between) one can observe two signal changes as the sample is scanned. From the distance δ between these changes that are obtained when the hole passes through the "thermal wave rays" SP_1 and SP_2 one can calculate the subsurface depth x with a simple formula resulting from the geometry of the arrangement:

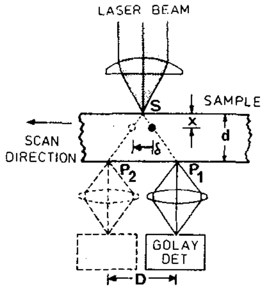


Fig.3

Stereoscopic arrangement with two detector positions P_1 and P_2 for thermal wave depth analysis.

$$x = d \cdot \delta / D \qquad (1)$$

This formula is equivalent to applying geometrical optics laws to thermal wave propagation. The result of Fig. 2 is consistent with this crude assumption. But one has to establish additionally that from an observed split δ one can calculate a realistic depth x of the subsurface hole.

Experiments were performed at a modulation frequency of 20 Hz using the same detector (Golay cell) first at P_1 and then at P_2 on a sample that was described previously /6,7/: an aluminum plate with 2.2 mm thickness is provided with a 0.4 mm diameter subsurface hole drilled at an angle so that its distance x to the illuminated front surface increases gradually between 6 successive sample scans (see dots in Fig. 4a) with a distance of 1 mm in between. First and last scan are

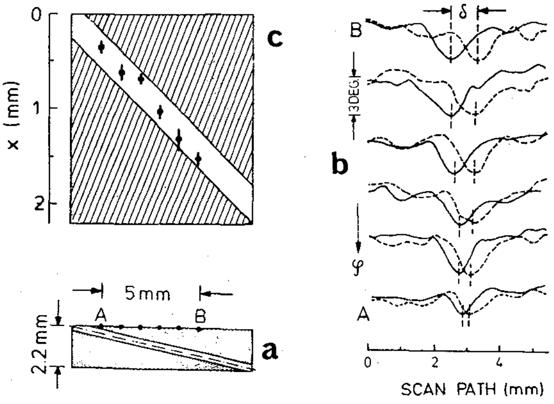


Fig.4

a) Sample geometry. Dots indicate beam positions for 6 sample scans .

b) Stereoscopic scans with D=1.2mm detector shift from P_1 to P_2 .

c) Depth data points from stereoscopic splitting compared to known subsurface structure.

indicated by A and B, respectively. As a result Fig. 4b shows the phase angle φ of the temperature modulation as observed during the scans across the subsurface hole. The dashed curves were obtained for the dashed detector position in Fig. 3. The shift δ between the minima increases from A to B as is expected from equ. 1 for an increasing distance x between the hole and the front surface. With more scans instead of only six and with halftone representation instead of the curves one would obtain an image of the subsurface hole (as in /6/) for each detector position. Due to the distance D in between, this is a pair of stereoscopic pictures that gives a three dimensional effect when viewed with a stereoscope or special spectacles. Thus it is possible to see subsurface thermal structures in opaque solids as if they were optical structures in transparent material. Instead of visualising how the distance between the 0.4 mm hole and the front surface increases, the depth x was calculated from equ. 1 for each of the six scans. The obtained data are shown in Fig. 4c together with the known geometry. The data points are well within the hole region, so the stereoscopic thermal wave method gives the correct depth of the subsurface hole. The accuracy is about 0.1 mm for hole center depths ranging from 0.4 mm to 1.5 mm, while thermal diffusion length is 1.2 mm in this example.

In optics one is used to invert beam directions. From there it is obvious that the stereoscopic method works as well with two source positions and one detector. The results have been published recently together with the suggestion for the present work /7/. With two sources operated simultaneously one obtains only one curve (instead of two) which results from the superposition of two coherent thermal waves. Consequently at small distances x one finds only a broad curve as is shown in Fig. 5 /7/ obtained at the same modulation frequency (20 Hz) and D = 1.2 mm on the same sample (thickness was 2.3 mm at

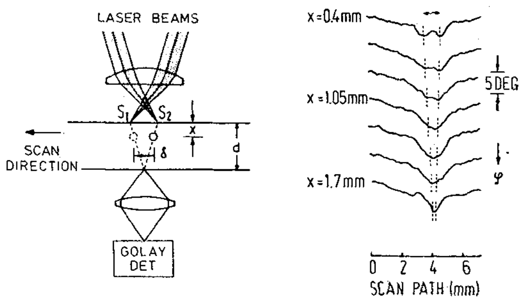


Fig.5

Stereoscopic arrangement with two thermal wave sources (left) and results for simultaneous operation (right). Sample as in Fig.4.

that time). Infrared resolution was better in this earlier experiment where one had to be careful to see any splitting at all, while in Fig. 4b detector spot size is not much smaller than the observed halfwidth. It should be pointed out, however, that resolution is not so important when one compares only the shift between two curves. With the two source arrangement one can measure small distances x only when numerical deconvolution is performed on the observed curves in Fig. 5, or one can measure the shift between the two curves that are obtained separately when the two sources are not operated in parallel but one after the other. Though for stereoscopic applications the arrangement with two sources is equivalent to the one with two detectors, the second arrangement might be of general interest for correlation experiments on thermal waves.
To summarize, the results have shown that the depth profiling capability of optoacoustic detection can also be achieved in a remote way by photothermal analysis of thermal waves in a stereoscopic arrangement either for the source or the detector.

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