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Measurement of the Thermal Diffusivity of Materials by Diverging Thermal Wave Technique

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ABSTRAK

Kami melapurkan penggunaan teknik gelombang terma mencapah untuk mengukur kebauran terma bahan. Inti teknik ini adalah menggunakan maklumat yang terkandung dalam gelombang terma yang dicerap oleh pengesan infra-merah jalur lebar, apabila pengesan ini tersesar daripada punca haba, selepas sahaja pengujaan bahan dengan laser denyut. Kami paparkan beberapa cerapan yang diperolehi dari sampel aluminium, plumbum, kerajang grafit dan grafit zirkonium.

ABSTRACT

The applications of diverging thermal wave technique to measure thermal diffusivities of materials are reported. In essence, the technique makes use of the information content of the thermal waves observed by means of a wide band infrared detector, that laterally displaced from the heat source, following pulsed laser excitation of the materials. Some observations obtained from aluminium, lead, graphite foil, and zirconium graphite samples are presented.

Keywords: thermal wave, thermal diffusivity, diverging, excitation

INTRODUCTION

Thermal wave techniques are increasingly being used to study thermo-physical properties of materials (e.g. Enguehard *et al.* 1990; Imhof *et al.* 1991; Moksin 1993). In this technique, the heat deposited by the laser pulse diffuses to cooler regions of the sample, at rates determined by its thermal diffusivity. Optical properties also play a part in determining the initial temperature gradient within the sample and the way the heated spots emit thermal infrared radiation. Therefore, the thermal waves as detected by the change in the emitted grey body radiation subsequent to pulse laser illumination can be analysed to study the surface and subsurface properties of the materials.

In this paper, the discussion is restricted to thermal waves in which the source of heat and the point of detection are spatially separated, i.e. the thermal waves diverge radially from their source before they can be detected, in contrast to the converging technique described by Enguehard *et al.* (1990).

The former can be used to characterize materials for their radial anisotropies, while the latter has the advantage for detecting weak signals.

EXPERIMENTAL TECHNIQUE

Previous work on diverging thermal wave technique was reported by Luukkala *et al.* (1982). They used a line-focused cw-modulated laser for excitation. The phase of the thermal waves was then detected by an infrared detector with horn attached to limit its angle of view. In the present work, thermal waves were generated by using a tightly focused pulsed laser. They were detected at several distances from the laser spot by using a focused wideband infrared detector.

Fig. 1 shows a schematic diagram of the apparatus. A 266 nm pulsed laser was used for excitation to illuminate an area of diameter ~ 20μm. The CdHgTe infrared detector and the sample remain fixed, while the laser spot was line-scanned at regular steps away from detection point. A distance of typically ~ 100 - 150μm was required before the thermal waves were clearly resolved from the direct opto-thermal decay signal. The strong attenuation makes it increasingly difficult to detect the thermal waves as the displacement is increased. Measurements were taken from homogeneous samples (aluminium and lead) and refractory materials (zirconium graphite and graphite foil).

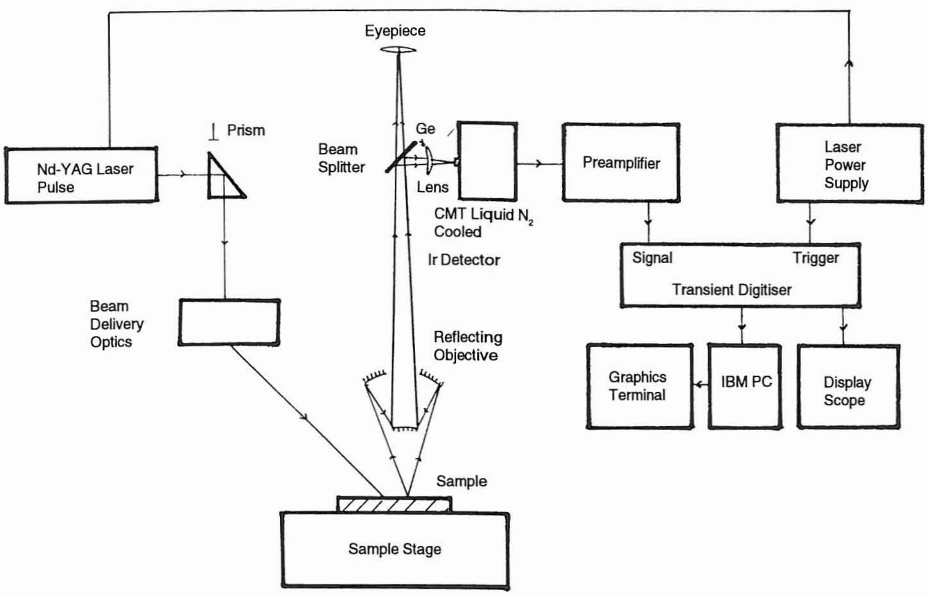

Fig. 1. Schematic diagram of the apparatus

A simple model for such thermal waves can be constructed by considering a thermal wave, generated at a point within an infinite isotropic medium, whose subsequent spread is described by radial diffusion equation, for which an approximate solution is given by Carslaw and Jaeger (1959) and Imhof *et al.* (1991) as

$$\theta(r,t) = [\theta_o \exp(-r^2/4Dt)]/(4\pi Dt)^{3/2}$$

where r is the radius, θ_o is the initial temperature jump at r = 0, and D is the thermal diffusivity. This point source can be replaced at the surface of a semi-infinite isotropic medium without changing the form of the solution by invoking a mirror symmetry argument and noting that there are no thermal gradients and therefore no heat flow across this surface. An expression for the thermal diffusivity can then be obtained by setting the derivative $\partial\theta/\partial t$ to zero, i.e. $D = r^2/(6t_o)$ where, t_o is rise-time.

RESULTS AND DISCUSSION

Typical results of series of measurements consistently take the form of curves, as shown in *Fig. 2.* At small displacements, a normal opto-thermal decay is observed, since the signal is dominated by the contribution from the area of overlap between the excitation and detection areas. When displacement is further increased, a thermal wave becomes apparent with curves displaying a rise in intensity to peak value at time, t_o, before a lingering decay.

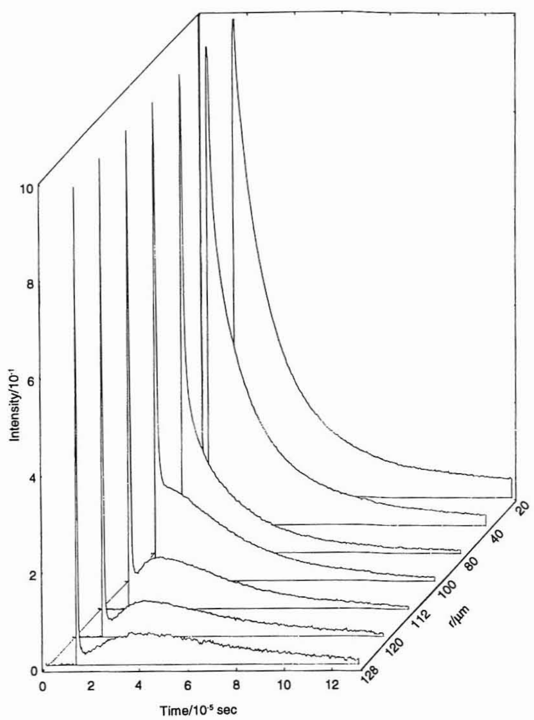

Fig. 2. Thermal waves in lead, from back to front, the lateral displacements between heating and detection points are 20, 40, 80, 100, 112, 120, and 128 μm

Fig. 3 and 4 show direct proportionality between r^2 and t_o, as required in theory, except for deviation at short rise-times. The deviations are much more obvious in *Fig. 4*, where slopes of the lines are the least. The superposition of opto-thermal decay and thermal wave signals at short rise-times may be responsible for this. Data for short rise-times in *Fig. 4* were excluded from the least-squares fit calculation.

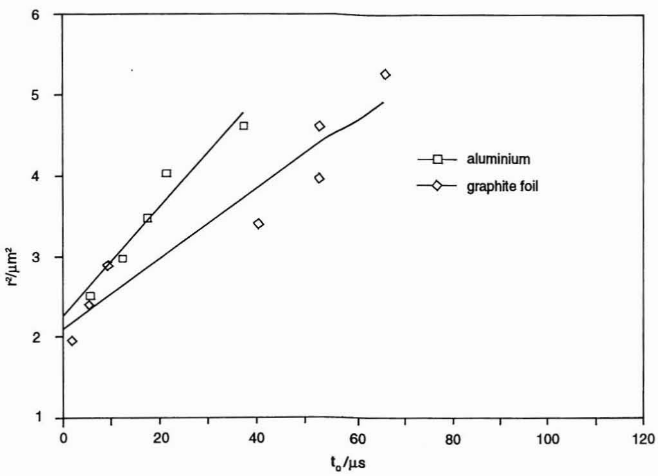

Fig. 3. Square of displacement (r) versus rise-time to for high thermal diffusivity

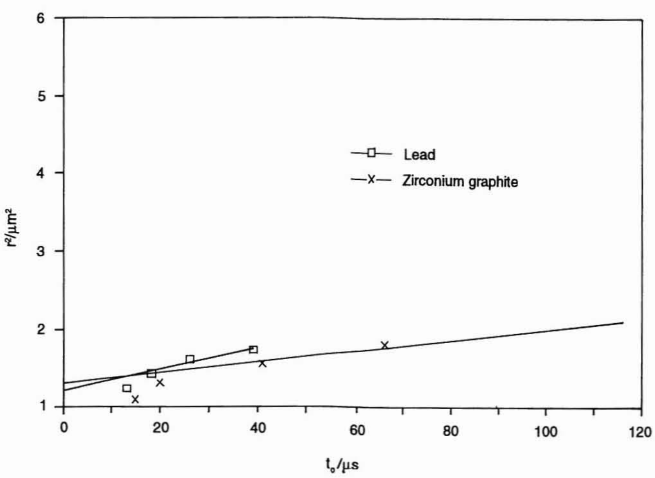

Fig. 4. Square of displacement (r) versus rise-time to for low thermal diffusivity

Table 1 shows that the measured thermal diffusivities are within 16% of the available accepted values. As comparison, the thermal diffusivity measured by Luukkala *et al.* (1982) was found to be 36% lower than the accepted value. The deviation of the measured values are wider as the thermal diffusivities get smaller. Low thermal diffusivities make measurement difficult because insufficient separation between opto-thermal decay and thermal wave can be obtained.

TABLE 1
Measured and accepted values of thermal diffusivities/(10^{-5} m^2/s)

Sample	Measured	Accepted (from Touloukian *et al.* 1973)
Aluminium	11.21 ± 1.5	9.68
Graphite foil	7.3 ± 0.8	7.89
Lead	2.3 ± 0.6	2.43
Zirconium graphite	1.2 ± 0.2	not available

CONCLUSION

Diverging thermal wave technique was found best for samples of high thermal diffusivities where thermal waves can be observed at appreciable distances from the heating spots. Further work on theoretical description of the thermal waves to account for optical absorption by the samples and reflections at the interface is in progress. However, with the present theoretical and data analysis, thermal diffusivities measured agree reasonably well with the accepted values. With further developments in experiment and theoretical analysis, this could become an important alternative for measuring absolute thermal diffusivities of condensed media.

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