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Evaluation of Finite Pulse Time Effects using Azumi Method

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1. Introduction

In the flash diffusivity technique a pulse of energy is incident on one of two parallel faces of a sample. The subsequent temperature history of the opposite face is then related to the thermal diffusivity. When the heat pulse is of infinitesimal duration, the diffusivity is obtained from the transient response of the rear face temperature proposed by Parker *et al*[1]. The diffusivity α is computed from relation

$$\alpha \equiv \frac{a^2}{\pi^2 t_c} = 1.37 \frac{a^2}{\pi^2 t_{1/2}} \quad (1)$$

Where a is the sample thickness and $t_{1/2}$ is the time required for the rear face temperature to reach half-maximum, and $t_c \equiv a^2 / \pi^2 t_{1/2}$ is the characteristic rise time of the rear face temperature. When the pulse-time τ is not infinitesimal, but becomes comparable to t_c, it is apparent that the rise in temperature of the rear face will be retarded, and $t_{1/2}$ will be greater than 1.37 t_c. This retardation has been called the " finite pulse-time effect." Cape and Lehman [2] derived a general expression which included the finite pulse time effects. Some others papers deal with a finite pulse time function as a square-wave, exponential wave and triangle-wave form[3-5]. Equation (1) is accurate to 1% for $t_c > \sim 50\tau$. For many substances this inequality cannot be achieved with conventional optical sources (e.g. $\tau \approx 10^{-3}$ sec for a solid state laser) unless the sample thickness is so large that its rise in temperature is too small for accurate measurement. One must therefore make an appropriate correction for the retardation of the temperature wave. The best method for correction of finite pulse-time effect is Azumi [6] time delay method, because of several merits. The merits are : (1) Irrespective of the pulse shape, the major part of the pulse-duration effect can be accounted for by finding the gravity of pulse shape alone; (2) Practically no correction is needed in K_g value and we can always use an ideal value, K_g = 0.1388; and (3) The thinner sample than before can be used, because the restriction caused by the pulse-width effect is now appreciably weakened, and thus the heat-loss effect can be diminished.

2. Azuimi correction method of finite pulse-duration

Equation (1) is valid only when the pulse-duration time τ is sufficiently short as compared with $t_{1/2}$. If it is not the case, the following equation (2) should be used instead of (1):

$$\alpha = K_0 \, a^2 / t \quad (2)$$

where K_0, defined as $K_0 = t_{1/2}/t_0$, is a parameter which now depends on the values of τ and t_c. In the case of no heat leak from the sample, the values of K_0 can be evaluated as a function of τ/t_c by resolving analytically the thermal diffusion equation. The temperature rise of the rear surface of the sample T(t) is given convolution of the laser pulse function and the temperature rise function as follows:

$$T(t) = \int_0^t f(t') T_{\#}(t - t') \quad (3)$$

$$T_{\#} = 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp\left[-n^2 \pi^2 (t - t')/t_c\right] \quad (4)$$

Where f is the pulse function, and $T_{\#}$ is the temperature rise with infinite pulse duration. By specifying the shape of pulses, all of these calculated results can be represented as $K_0 \approx 0.1388 + b\tau/t_c$. The dependence of K_0 on τ/t_c , which is denoted as b, can be changed by introducing a new time axis having the same scale but the different origin. After shifting the time axis, a new parameter K_g can be given as

$$K_g = \left(t_{\frac{1}{2}} - t_g\right) t_c = K_0 - t_g \quad (5)$$

Where t_g is the value of shift. Major concern should be to find a suitable value of the shift that can make K_g nearly independent of τ/t_c . Equation (5) gives some idea about the appropriate magnitude of t_g. When we can choose the value of $t_g \approx b\tau$, K_g would be nearly constant. t_g can be obtained analytically as follows : when we replace t in Eq.(4) by $(t + t_g)$ and develop it in Taylor series on $(t' - t_g)/t_c$, it turn out that the linear term in this series vanishes when the following relation:

$$t_g = \frac{\int_0^t t' f(t')}{\int_0^t f(t')} \quad (6)$$

is satisfied. The derivation indicates that t_g should be regarded as a adjustment for the infinite pulse width with respect to the "effective" irradiation time. Taking adjustment, the thermal diffusivity can be expressed by following equation:

$$\alpha = K_g a^2 / (t_{\frac{1}{2}} - t \quad (7)$$

3. Experimental

The thermal diffusivity analysis equipment in experiment is LFA-427 Laser Flash supplied by NETZSCH. The laser pulse generator of equipment can make heat pulse duration from 0.3 ms to 1.2 ms. To maximize finite pulse time effect, we have to select high thermal diffusivity materials and very thin specimens. The available material is industrial pure copper because of easy handling in experiment and machining in precise dimension. Six test specimens are machined to get disk type form with diameter 12.5 mm and thickness 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 mm respectively. Because generally for most pure metal thermal diffusivity decrease with temperature, it is needed to test in low temperature, for example room temperature. The experiments have performed under test conditions with varying laser pulse durations, 0.3 ms, 0.6 ms and 0.9 ms respectively for each specimen. And the test temperatures are 24℃. Finally, to determine the real thermal diffusivity of a specimen, test was performed for a 3mm thick specimen by being expected to neglect the finite pulse time effect.

4. Results

4.1 Real thermal diffusivity of specimen

In order to verify the precision of testing equipment and ascertain a repeatability, the real thermal diffusivity of a specimen for a 3 mm thickness was measured by a 0.6 ms laser pulse duration and this was repeated nine times. Measured average thermal diffusivity value and uncertainty is 121.98 ± 1.42 mm^2/sec in a 95% confidence interval. The standard deviation of the measured thermal diffusivity is 0.71 mm^2/sec. Due to such high a thermal diffusivity property, finite pulse time effects are easily investigated even though the generating laser pulse duration is limited.

4.2 Typical laser pulse shape and rear face thermo-gram(detector signal)

Laser pulse shape in an experiment is almost a square-wave for 0.9 ms and approximately a triangle for 0.3ms as shown in Fig 1.

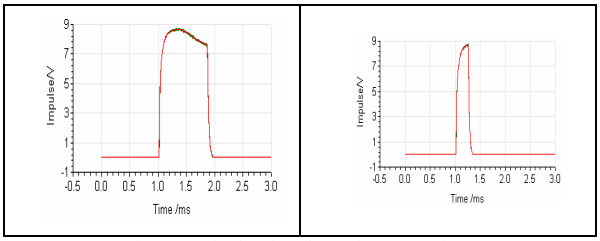

Fig 1. Typical pulse shape for 0.9 and 0.3 ms

Detector signal on a rear face and a shooting pulse shape are revealed as typical thermo-gram related to a finite pulse time effect as shown in Fig 2. In this figure, pulse duration time is 0.9 ms and the half rise time($t_{1/2}$) is 2.044 ms. If the duration of the energy pulse is not short compared to $t_{1/2}$ then the energy pulse affects the thermo-gram on a rear face and it increases the half rise time. As a result of increasing the half rise time, the measured thermal diffusivity of a sample is underestimated owing to the finite pulse time effect.

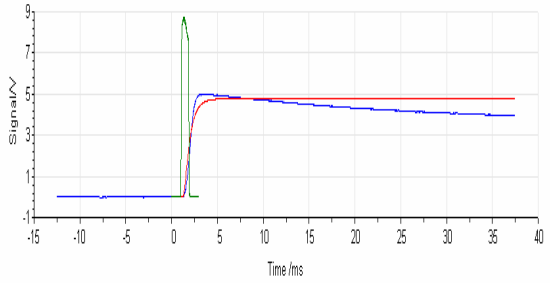

Fig 2. Typical thermo-gram on rear surface for 0.5 mm thickness Cupper with pulse duration 0.9 ms

4.3 Finite pulse time effects

All the test runs are repeated three times for each test condition. Results measured three times are averaged and adopt a representative value for each test condition. Adiabatic-no pulse correction model is assumed for thermal diffusivity due to the purpose to investigate finite pulse time effect. Azumi correction of finite pulse time effects are recalculated by adiabatic with pulse correction model using Azumi time delay method. The measured results with adiabatic no pulse correction model are plotted from the view for a pulse duration and thickness of a specimen. Fig 3. are plots of the diffusivity change for a pulse propagated time(specimen thickness change) and pulse duration time at room

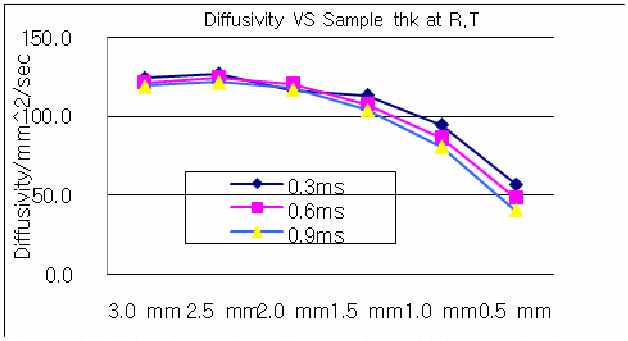

Fig 3. Diffusivity change for various specimen thickness and pulse duration on room temperature

Fig 4. are plots of the corrected diffusivity change for a pulse propagated time(specimen thickness change) and pulse duration time at room. Fig 5. are plots of the associated diffusivity plots with corrected and non-corrected results. Fig 3. and Fig 4. reveal that a sufficient specimen thickness is needed in order not to be affected by a pulse duration time. Below of 2.0 mm of a specimen thickness, there is always finite pulse time effect even if finite pulse time effects are corrected. But in the case above 2.0 mm thick, measured diffusivity values are not affected by finite pulse time. Obviously there is appropriate ratio value ($\tau / t_{1/2}$) for neglecting a finite pulse time effect, e.g. $\tau / t_{1/2} \leq 0.04$.

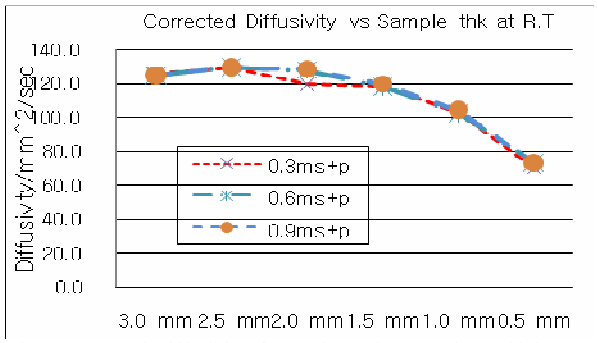

Fig 4. Corrected Diffusivity change for various specimen thickness and pulse duration on room temperature

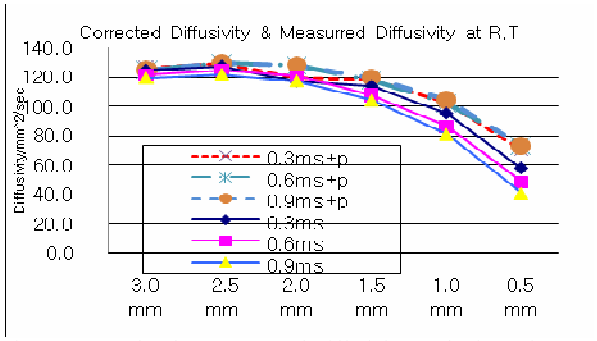

Fig 5. Corrected and Non-corrected Diffusivity results for various specimen thickness and pulse duration

5. Conclusion

First above all, sufficient specimen thickness is needed in order not to be affected by a pulse duration time. Even though correction of finite pulse time effects are performed for a high diffusivity thin material, we can not achieve accurate results without selection of a appropriate sample thickness. Experimenters have to take account into a appropriate sample thickness and pulse time duration for reducing a measurement error. In the case of industrial copper, above a 2 mm thick sample, the finite pulse time effect can be neglected. There is an appropriate ratio value ($\tau / t_{1/2}$) for neglecting finite pulse time effect.

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