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A New Pulse Hot Strip Sensor for Measuring Thermal Conductivity and Thermal Diffusivity of Solids[1]

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The pulse hot strip method is a newly developed dynamic method to measure the thermal conductivity and thermal diffusivity of solids. It is based on monitoring the temperature response of a sample to a very short heat pulse liberated by a strip heat source. The instrument's uncertainty is estimated to be less than 3% for both quantities.

KEY WORDS: pulse hot strip; thermal conductivity; transient hot strip, transient technique.

1. INTRODUCTION

The transient hot strip technique (THS) can be used for simultaneous measurements of the thermal conductivity, λ, and thermal diffusivity, a, of solids and liquids. The setup used so far is relatively simple and fast acting (e.g., Refs. 1–7). However, the results for thermal diffusivity are considered to be of a high uncertainty [6]. This is mainly due to the following fact: the sensitivity of the THS technique for determining the thermal diffusivity has its maximum at very low non-dimensional times, $\tau < 1$. The quasi-linear evaluation procedure of a THS signal, however, does not work below $\tau \approx 2$ [3]. Other evaluation procedures [2, 8] cover both small and long times but furnish results that have to be interpreted as averages over the whole length of the experiment. In Ref. 7, Gustafsson et al. published the so-called short time approximation to the complex THS working equation. This quasi-linear approximation for the temperature excursion of the strip,

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$\Delta T \propto \sqrt{t}$, is valid for transient times $\tau \leqslant 0.7$ and, thus, can yield reliable thermal diffusivity results. The authors claim an uncertainty of 3 to 4%.

However, at small transient times, the signal-to-noise ratio is usually very poor and, additionally, the signal may be disturbed by the inner boundary effect, the so-called heat source effect (e.g., Refs. 6–9).

The objective of this paper is to present a new approach for the measurement of the thermal diffusivity by means of the THS or the closely related transient hot wire [9] techniques. The newly developed pulse hot strip (PHS) sensor combines the advantages of a strip heat source with the accurate temperature measurement capability of a thin platinum wire.

It will be demonstrated that, with a further knowledge of the enthalpy of the measurement process, the thermal conductivity can be determined from the signal of the pulse sensor as well.

2. THEORY

The thermal diffusivity a (units of $m^2 \cdot s^{-1}$) is defined as

$$a = \frac{\lambda}{\rho c_p} \tag{1}$$

Here, ρ denotes the density of the material under test and c_p is the heat capacity. Physically, the thermal diffusivity can be considered as a ratio of the rate of heat conducted to the amount of heat stored per unit area, ρc_p. Nevertheless, this unit can still be interpreted as an areal velocity as well. Therefore, independent of the measurement technique, a characteristic length is needed as well as two related characteristic signal levels to be used as time marks to start and end the process. From this point of view, a transit-time measurement of a suggests itself because the units of length and time can be measured very precisely. This is the basic idea of most of the heat pulse methods like, e.g., the laser flash method [9] or the pulse transient method [10].

During a regular THS run, the metal strip is activated by a *step-wise* electrical pulse to emit continuously a constant rate of heat flow. The heat is absorbed by the surrounding specimen depending on the material's thermal transport properties a and λ. From the slope and intercept of the resulting quasi-linear temperature excursion, $\Delta T \propto (1/\lambda) \ln(at)$, of the strip, the thermal diffusivity is calculated. Here, the width, D, of the strip is the characteristic length and the slope implicitly determines the required period. However, for reasons discussed elsewhere [6], the uncertainty in the thermal diffusivity is very large.

For a transit time measurement of a, a short electrical pulse of sufficient height (strength) is fed to the strip of length L. Here, the electrical input power, $P = UI$, is converted to a rate of heat flow of Gaussian pulse shape whose maximum can be taken as the starting signal. The heat pulse travels through the specimen and, at time t, reaches the temperature station, T1, that is located at a precisely known distance r_1 from the strip. Provided that $r_1 \geqslant D$ [3], the signal at T1 is closely approximated by

$$T(r = r_1, t = t_1) = T_0 + \frac{H_0}{4\pi L \lambda t_1} \exp\left(-\frac{r_1^2}{4at_1}\right). \tag{2}$$

Here, $H_0 = \int UI \, \mathrm{d}t$ is the enthalpy from the input power and T_0 is the homogeneous temperature at time zero. The term $\exp(-r^2/(4at))$ governs the loss of heat depending on the position, r, and time of transit, t.

To find the same pattern (maximum) in the temperature signal of T1 as used to start the process, Eq. (2) has to be differentiated with respect to t and the result set to zero. The temperature maximum, $T_{\max}(r_1, t_{\max})$, occurs at

$$t_{\max} = \frac{r_1^2}{4a} \tag{3}$$

Recalculation of Eq. (3) furnishes the measurand,

$$a = \frac{r_1^2}{4t_{\max}} \tag{4}$$

Equation (2), however, does not take into account the nonvanishing heat capacities of the strip and the thermometer T1. In practice, the strip first has to heat itself so that its enthalpy output to the specimen is delayed (inner boundary effect). For the same reason, the temperature excursion at T1 is also delayed. Since both thermal elements generally are of different heat capacity and thermal resistance to their surroundings, their individual time lags are not equal. Therefore, the period $t_{\max}$ is not a proper measure for the quantity considered.

Instead, to numerically correct for the perturbing time delays, it is more precise to compensate for this source of error. Therefore, a second thermometer, T2, of the same kind is added to the setup by locating it at a distance $r_2 > r_1$ from the center axis. Then, the difference in time between the maxima of T1 and T2, $\Delta t = t_{2\max} - t_{1\max}$, is the measure for a:

$$a = \frac{r_2^2 - r_1^2}{4\,\Delta t} \tag{5}$$

Obviously, a drawback of this two-thermometer arrangement arises from the fact that the signal of station T2 is even smaller and more spread out than that of T1 but its maximum has to be detected at an adequate resolution (cf. Fig. 2).

To overcome this problem, both temperature signals are pairwise analyzed as a whole. The ratio of both temperature excursions, $T(r_1, t)/T(r_2, t)$, where

$$T(r_1, t) = T_1 = T_0 + \frac{H_0}{4\pi L\lambda t} \exp\left(-\frac{r_1^2}{4at}\right) \tag{6}$$

and

$$T(r_2, t) = T_2 = T_0 + \frac{H_0}{4\pi L\lambda t} \exp\left(-\frac{r_2^2}{4at}\right) \tag{7}$$

yields the thermal diffusivity,

$$a = \frac{r_2^2 - r_1^2}{4t \ln(T_1/T_2)} \tag{8}$$

as a pseudo-function of time. This procedure results in a time plot of the measurand (cf. Fig. 3).

With a further knowledge of the enthalpy H_0 and the thermal diffusivity a, the thermal conductivity λ can simultaneously be determined from the same run (cf. Fig. 4).

3. EXPERIMENTS

The results of the mathematical model formulated above can easily be transformed into a physical model of the setup. Although the working equations of the pulse hot strip technique can be applied likewise to a line heat source ("pulse hot wire"), it is more advantageous to use a strip source: since the active part of a strip's surface is larger than that of a wire, the density of heat flow is smaller, i.e., the self-heating of the strip is considerably smaller. Even when the wire is entirely embedded inside the specimen, the part of the surface, A_S, of a strip of thickness $v = r_0 \ll D$ that is in close thermal contact with the specimen is larger than that (A_W) of a wire of radius r_0:

$$\frac{A_S}{A_W} \approx \frac{D}{\pi r} \tag{9}$$

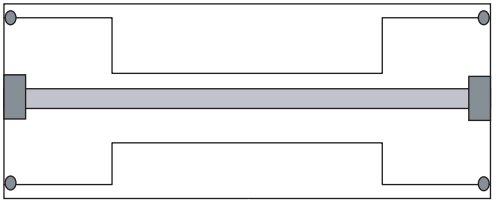

Fig. 1. Heater/Sensor foil for the pulse hot strip mode of operation. The strip (center) is made from manganine; both temperature sensors (cold wires) are made from platinum.

For a strip of $D = 3$ mm and a wire of radius $r = 0.0875$ mm [13], the ratio of active surfaces is equal to eleven. Thus, for a given temperature maximum, the strip is able to emit a larger amount of heat per unit time than the wire. This results in a better signal-to-noise ratio of the temperature measurement at T1 and T2.

For their pulse transient method, Kubiçar et al. (e.g., Refs. 10 and 11) use a plane source in conjunction with a thermometer that is separated from the source by the center part of the three part specimen. For the PHS technique, a specially designed heater foil (Fig. 1) is clamped between the two sample halves. The latter arrangement has advantages concerning sample preparation and assembly of the setup, the first one is a benefit when materials of very poor thermal conductivity are to be measured because there is no stray heat flow along a foil to the thermometer.

As schematically shown in Fig. 1, laminated between thin sheets of polyimide (Kapton), there is a strip made of manganine and two cold wires made of platinum. The materials of strip and wires are chosen with respect to their function as heat source and temperature sensor. Manganine has a very low temperature coefficient of resistance (TCR), which helps to emit a constant rate of heat flow at constant current input to the strip. The TCR of platinum is relatively high to furnish a large change in electrical resistance with temperature. Both cold wires have their active zones along the center of the strip to avoid the so-called end effect, the decrease in temperature at both ends of the strip due to heavy electrical leads. The distances of the wires from the long axis of the strip are 3.5 and 4.5 mm.

The pulse experiments were performed on an epoxy resin, manufactured by DLR (Deutsches Zentrum für Luft- und Raumfahrt). This resin is the raw material of carbon fiber reinforced plastics for aerospace applications. From guarded hot plate and laser flash[3] measurements, the

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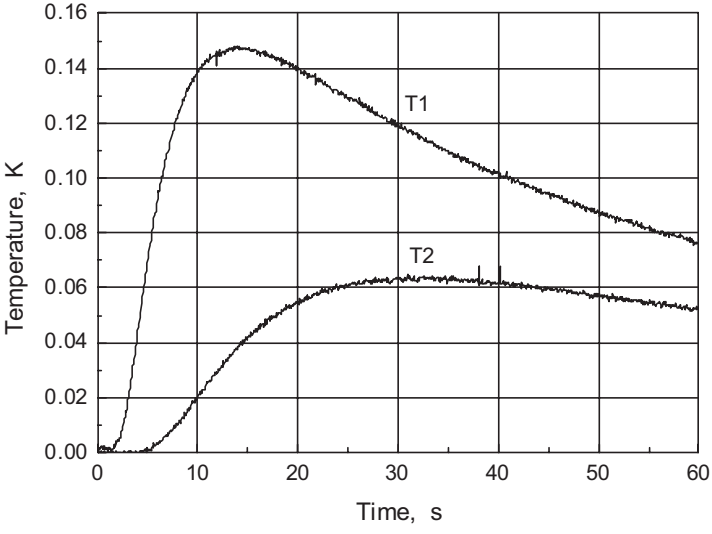

Fig. 2. Temperature excursions of the two cold wires, T1 and T2, during a PHS run on epoxy resin at room temperature.

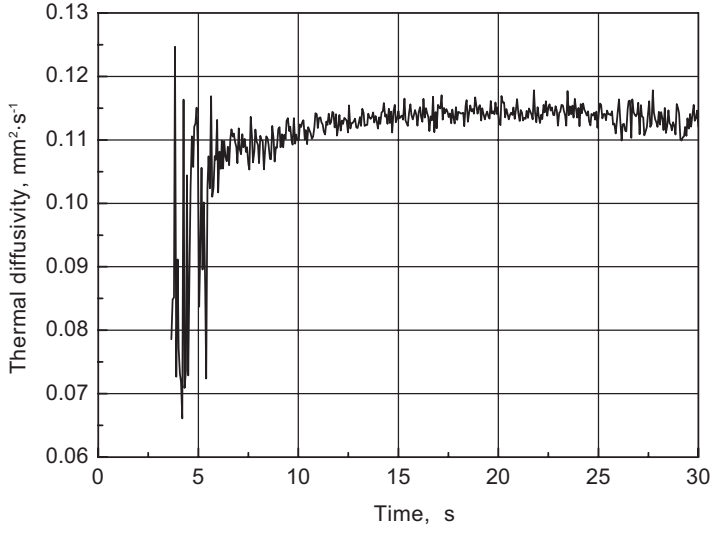

Fig. 3. Thermal diffusivity of epoxy resin at room temperature as pseudo-function of time.

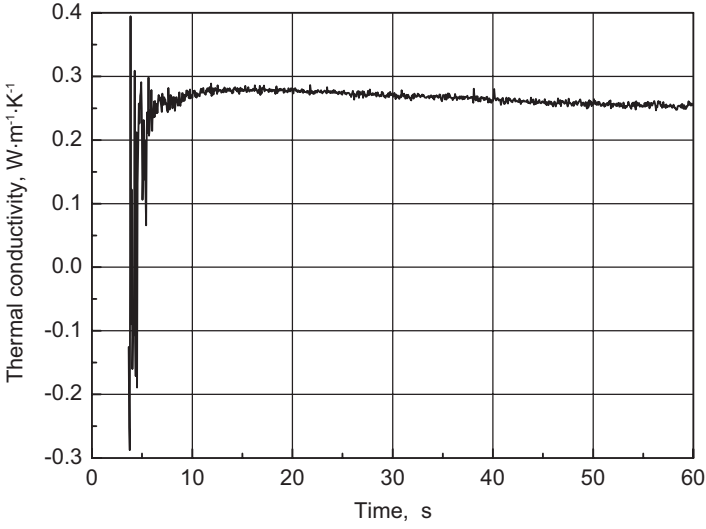

Fig. 4. Thermal conductivity of epoxy resin at room temperature as pseudo-function of time.

thermal transport properties of this material are precisely known ($\lambda = 0.28\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$, $a = 0.12\ \mathrm{mm^2 \cdot s^{-1}}$). As can be seen from Fig. 2, after firing the heat pulse at time zero, it takes about 30 s to complete a PHS measurement on this material. The temperature excursions, $T_1(t)$ and $T_2(t)$, were analyzed twice, first by using Eq. (5) and then according to Eq. (8). The latter method yields the thermal conductivity (Fig. 3) and the thermal diffusivity (Fig. 4) versus time. The results are in good agreement with each other and with those from the reference measurements mentioned above.

A preliminary assessment of the uncertainty of the method results in an estimate of 3% for λ and 6% for a.

4. SUMMARY

The pulse hot strip method has now been developed based on the transient hot strip technique. The technique makes use of a new sensor that integrates the heat source and two thermometers at different mutual distances to the foil. In contrast to the THS technique with its step-wise heating, a PHS run is initiated by a short pulse. Even after some seconds, both thermal transport properties are determined with remarkably low uncertainties.

Compared with a laser flash apparatus to measure the thermal diffusivity, the new sensor is much cheaper and more versatile.

REFERENCES

1. S. E. Gustafsson, *Z. Naturforschg.* **22**:1005 (1967).
2. S. E. Gustafsson, E. Karawacki, and M. N. Khan, *J. Phys. D* **12**:1411 (1979).
3. U. Hammerschmidt, in *Proc. 24th Int. Thermal Cond. Conf.*, Pittsburgh, Pennsylvania, P. S. Gaal, ed. (Technomic, Lancaster, Pennsylvania, 1997).
4. M. A. Chohan, Thesis (Chalmets University of Technology, Göteborg, 1987).
5. U. Hammerschmidt, *Int. J. Thermophys.* **23**:975 (2002).
6. U. Hammerschmidt and W. Sabuga, *Int. J. Thermophys.* **21**:217 (2000).
7. S. E. Gustafsson, K. Ahmed, A. J. Hamdani, and A. Maqsood, *J. Appl. Phys.* **53**:6064 (1982).
8. W. Sabuga and U. Hammerschmidt, *Int. J. Thermophys.* **16**:557 (1995).
9. K. D. Maglic, A. Cezairlyan, and V. E. Peletsky, eds., in *Compendium of Thermophysical Property Measurement Methods, Vol. 1: Survey of Measurement Techniques* (Plenum, New York/London, 1984).
10. L. Kubicar and V. Bohac, *High Temp.–High Press.* **33**:1 (2001).
11. L. Kubicar, in *Pulse Method of Measuring Basic Thermophysical Parameters* (Elsevier, Amsterdam, 1990).
12. J. V. Beck and K. J. Arnold, in *Parameter Estimation* (Wiley, New York, 1977).
13. Methods of test for dense shaped refractory products—Determination of thermal conductivity by the hot-wire (parallel) method, in *EN 993-15* (Beuth Verlag, Berlin, 1998).