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Contact measurement of thermal conductivity and thermal diffusivity of solid materials: Experimental validation of feasibility with a prototype sensor

Syamsul Hadi [a], Mamoru Nishitani [a], Agung Tri Wijayanta [b], Takanobu Fukunaga [a], Kosaku Kurata [a], Hiroshi Takamatsu [a,*]

[a] *Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan*
[b] *Department of Mechanical Engineering, Sebelas Maret University, Jl. Ir. Sutami 36 A, Surakarta 57126, Indonesia*

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ABSTRACT

A contact method has been proposed for measuring thermal transport properties of solids including soft materials. The method has an advantage of potential utilization for in-situ measurement without preparing a sample specimen. A unique feature of the method is to prepare a shallow cavity around a film sensor for a layer of a gel that is used to eliminate the thermal contact resistance between the sensor and the sample. A prototype sensor, 3 mm in diameter, was fabricated on the surface of 0.16-mm thick glass substrate, and used with a 50-μm thick silicon rubber sheet as a spacer for the gel. The transient temperature rise of the sensor was determined from the electrical resistance after heating the sensor at a constant current. The thermal conductivity and the thermal diffusivity of a sample as well as the thickness of the gel layer were then determined from an iteratively obtained theoretical temperature rise that agreed with the measured temperature rise. The results obtained by the experiments with four different materials indicated that the thermal conductivity could be determined within 10% errors. The present study therefore demonstrated feasibility of the method, while improvement is still needed to reduce the error particularly in the thermal diffusivity.

1. Introduction

Thermal transport properties of solid materials are measured with some commercially available devices with different principles and methods. Application of these methods depends on the sample material and conditions. When we measure the thermal diffusivity as standard reference data particularly at extreme conditions, we presumably use the laser flash method. In this method, the temperature change at a surface of a specimen is measured after pulse-heating at its back side by laser irradiation [1–4]. It has an advantage in terms of the accuracy, but it requires preparation of a specimen with precise thickness. It also requires coating of the specimen to absorb the laser power at the surface when the sample is transparent or semi-transparent to the laser light. When we need the data for a poorly conducting material, we may use the transient plane source method, which measures the temperature of the heater, a hot-disk or a hot-strip, that are sandwiched between two pieces of samples [5–12]. It has been used for a variety of materials [13–19], but clamping the sensor strongly with the samples after polishing surfaces [13,14], sometime with a small amount of liquid in between [6], is crucial for reducing the thermal contact resistance between the sample and the sensor. It also requires two identical specimens. For non-invasive, in-situ measurement of solid materials, we can apply the point contact-probe method. The thermal transport properties are obtained with only pressing a small spherical heated probe onto the surface of a sample material [20–22]. However, the effect of thermal contact resistance between the material and the probe on the measurement is also inevitable in this case as well. To reduce its effect, the probe is pressed at a constant pressure.

Although these methods, which have advantages and limitations, are to be used for a variety of materials, none of these is appropriate for soft materials including biological materials. Preparing a specimen of soft material with precise dimension is difficult in the laser flash method. Clamping soft specimens hard without deformation is difficult in the transient plane method. Pressing a bead probe on a soft sample would alter the contact area in the point contact-probe method, although the method assumes point contact between the sensor and the sample.

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[*] Corresponding author. Tel./fax: +81 92 802 3123.
E-mail address: takamatsu@mech.kyushu-u.ac.jp (H. Takamatsu).

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Nomenclature

i	number of iteration
Q	heating power (W)
$SD_{\Delta T}$	standard deviation of difference between the calculated and measured temperatures (K)
T	temperature (K)
t	time (s)
t_0	time at the start of heating (s)
α	thermal diffusivity (m^2/s)
Δt	difference in time (s)
δ	thickness of gel layer (m)
λ	thermal conductivity (W/m K)

Subscripts

cal	calculated or theoretically obtained value
exp	experiment
ref	reference

Hence to develop a convenient method for measuring solids including soft materials, we have proposed a new contact method using a 'stamp-type sensor' [23]. The thermal transport properties are measured by pressing a small thin film sensor that was fabricated on a surface of a thin plate. It could therefore be used for non-destructive, in-situ measurement. The uniqueness of this method is to put a gel between the sensor and a sample to eliminate the thermal contact resistance. In addition, a shallow cavity with given dimensions has been prepared around the sensor for the gel. The feasibility of the method to determine the thermal conductivity and the thermal diffusivity has been checked using virtual experimental data that have been generated by adding an artificial scattering to a theoretical temperature change of the sensor [23]. The results indicated that the thermal conductivity was determined within the error less than ~2% and the thermal diffusivity within ~5% error. Since the theoretical examination showed that the method did work, the next step is to demonstrate the measurement by experiments. In this paper, we present preliminary results obtained by using a prototype sensor with several samples, i.e. acrylic resin, agar gel, machinable ceramic, and stainless steel.

2. Sensor and methods

2.1. Sensor

A conceptual design of the prototype stamp sensor is shown in Fig. 1. A thin metallic film heater that works as a resistance thermometer as well is deposited on the top of a glass substrate. A circular sensor is used so that the system could be described by an axisymmetric 2-D model. The sensor is pressed against the surface of a sample with a gel spread on the sensor to eliminate the contact thermal resistance between the sensor and the sample. The important feature of the sensor is that the sensor is placed at the bottom of a shallow cavity made by a spacer between the substrate and the sample, which roughly determines the thickness of the gel layer irrespective of the contact pressure.

The final design of the sensor would be a stamp-type device where a sensor is fabricated on the bottom of a cylindrical holder (Fig. 1). However, as a preliminary study, a platinum film of a pattern of the sensor and electrodes, 53 nm in thickness, was fabricated on a 0.16-mm thick 22 × 40 mm^2 glass substrate by physical vapor deposition (PVD) (Fig. 2). A circular pattern of 3 mm in diameter was drawn with a single stroke of a 125 μm wide line. A 50-μm thick annular silicone rubber sheet with a 15-mm diameter hole was attached on the opposite side of the glass substrate as a spacer to provide a shallow cavity for the gel. The glass substrate was held with a hollow cylinder (Fig. 3). A sample was heated through the substrate, not directly by the sensor, to protect the sensor during cleaning up of the gel after experiments, even though the sensor was coated by a glass layer.

2.2. Measurement

Four different samples were prepared for measurement: an acrylic resin block of 40 × 30 × 15 mm^3, a stainless steel SUS304 block of 40 × 40 × 30 mm^3, and a machinable ceramic cylinder of ø 30 × 20 mm^3, and 1% agar gelated in a 20 mm deep plastic dish 100 mm in diameter. In the present experiment, the measuring

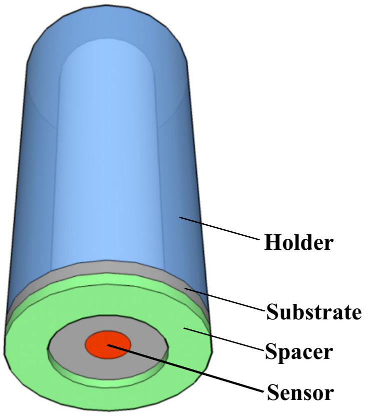

Fig. 1. Schematic of stamp sensor.

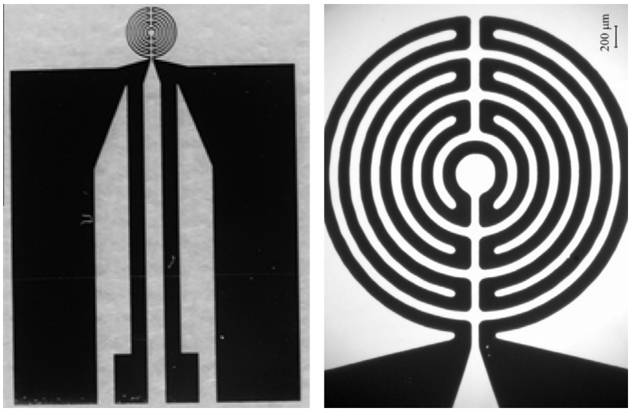

Fig. 2. Pattern of the sensor deposited on the glass substrate.