Polymer Testing 40 (2014) 187–195

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Test method

Inkjet printing technology for polymer thermal conductivity measurement by the three omega method

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ARTICLE INFO

Article history:
Received 31 July 2014
Accepted 6 September 2014
Available online 21 September 2014

Keywords:
Thermal conductivity
Inkjet printing
Polyimide
Three omega method

ABSTRACT

The three omega method has proven ability to accurately measure the thermal conductivity of solid and soft materials. Nevertheless, in the case of soft materials, the application of the three omega method is still challenging because up to now it generally requires techniques that are time consuming and costly, such as lithography. In this paper, we present an alternative for this kind of material based on inkjet printing technology. To evaluate the performance of this technique, polyimide samples have been prepared by photolithography and inkjet printing. We show that the thermal conductivities measured in both cases by means of the 3ω method are very close; demonstrating that inkjet printing technology is a good candidate for characterization of flexible materials in terms of thermal conductivity. Besides the experimental study, a theoretical investigation based on an analytical approach, namely Cahill's method, and a numerical method based on a FEM tool is proposed.

1. Introduction

Flexible electronic technology is rapidly growing and finds applications in different fields such as lightning, radio frequency identification circuitry, displays and photovoltaics [1,2]. Polymers exhibit different mechanical, optical and chemical properties which render them competitors in such flexible electronic applications. Among these properties are optical clarity, high exploitation temperatures possibility, high flexibility and robustness that are essential features when fabricating flexible electronic devices. Some of the polymers which have mostly emerged in the field of flexible electronics are polycarbonate (PC), polyethylene terephthalate (PET) [1,3], polyethylene naphthalate (PEN) [1,3], polyetheretherketone (PEEK) [4] and polyimide (PI) [5]. In different applications, alternative thermal management is necessary. The material used must either prevent heat transfer or be a good thermal conductor. For example, low thermal conductivity materials are required in thermoelectric fields [6]. However, materials of high thermal conductivity are desired to achieve heat dissipation in different electronic applications [7].

Therefore, there is a need to know the material thermal conductivity. There are many methods available to measure the thermal conductivity both steady state and transient. The most popular methods are probably the guarded hot plate method [8], the hot wire method [9], the time domain thermo-reflectance [10] and the three omega method [11]. However, due to its simplicity and accuracy, the three omega method is the method of our choice. It requires heating a metallic line conductor just in contact with the surface of the material under test by an alternating current source [11,12]. Thermal conductivity of different polymers such as polyimide [13], polyaniline [14], and polymethyl methacrylate [15] has been successfully measured by the three omega method. Nevertheless, the application of the

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http://dx.doi.org/10.1016/j.polymertesting.2014.09.008
0142-9418/

method on several types of polymer is difficult due to the inability to deposit metallic line conductors on polymers surface by lithography [16], which entails a basic procedure of multiple and expensive steps. Moreover, it includes the use of different chemical products that might be harsh on some polymers such as polycarbonate (PC) and polyether sulfone (PES).

In this work, we demonstrate the possibility of using the three omega method when metallic line conductors are prepared by means of inkjet printing technology. This technology is widely used these days, especially in plastic electronic applications. When applying such technology, the metal-based ink is directly printed onto the substrate where no chemical and solvent application is required and no mask patterning is needed. In this way, the number of processing steps and the amount of material used is reduced, which implies reduction of time, cost and waste [17]. It is the first time, to the best of our knowledge, that the three omega method has been associated with inkjet printing technology for the measurement of thermal conductivity of polymers. After a brief description of the three omega method, we depict the sample preparation when using a photolithography process and a technique based on inkjet printing technology. Then, the measurement results obtained by these two methods are presented in section IV. Finally, a numerical approach based on FEM is proposed for the implementation of the 3ω method to determine the thermal conductivity of polymers.

2. The three omega method

2.1. Theory

The three omega method requires a metallic line, deposited on the surface of the sample to be tested, which serves as a heater and a temperature sensor. The metallic line has two contact pads, as shown in Fig. 1. Passing an alternating current at frequency ω through the metallic line heats it up, producing temperature oscillations at frequency 2ω. Consequently, metallic line resistance fluctuations will be generated at frequency 2ω. The resistance of the metallic line at temperature $T_0+\Delta T$ is given by the following equation [18]:

$$R = R_0(1+\beta_h(\Delta T)) \tag{1}$$

where β_h is the temperature coefficient of resistance in $^{\circ}C^{-1}$, R_0 is the resistance of the metallic line at room temperature T_0. Multiplying these resistance fluctuations by the alternating current at frequency ω yields a third harmonic voltage $V_{3\omega}$ through the metallic line.

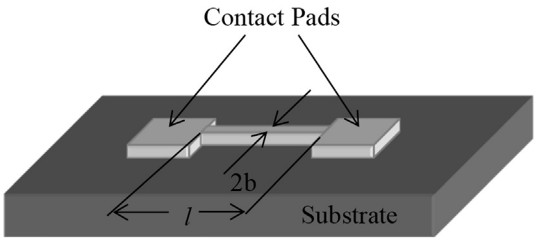

Fig. 1. A two contact pads metallic line of width 2b and length l.

In 1990, Cahill found an equation (2) through which we can determine the temperature oscillations at frequency 2ω at the level of the metallic line [11].

$$\Delta T_{AC}(2\omega) = \frac{p_{rms}}{\pi k}\int_0^\infty \frac{\sin^2(\eta b)}{(\eta b)^2\sqrt{\eta^2+q^2}}d\eta \tag{2}$$

where p_{rms} is the input power per metre of length in W/m, k is the thermal conductivity of the sample under study in W/m.K, and b is the half width of the metallic line in metres. q represents the complex wavenumber of the thermal wave in radians per metre and is given by [19]:

$$q = \sqrt{\frac{i2\omega}{\alpha}} \tag{3}$$

where i is the complex number ($i^2 = -1$) and α is the thermal diffusivity in m^2/s of the material under test.

Cahill was able to examine the solution of equation (2) where the thermal penetration depth is far larger than the half width of the metallic line b. He found an approximate solution for a semi-infinite substrate through which we can determine the real and imaginary parts of the temperature oscillations. This solution was based on an assumption of a semi-infinite substrate and a thermal penetration depth far smaller than the thickness of the substrate to guarantee no back surface reflection. According to the aforementioned assumptions, the frequency zone, where the real part of the temperature oscillations is linear, can be determined as presented in equation (4) and, consequently, the thermal conductivity can be calculated as will be explained in the next section.

$$\frac{25\alpha}{4\pi t_s^2} \le f \le \frac{\alpha}{100\pi b^2} \tag{4}$$

Here, t_s is the thickness of the sample in metres.

2.2. Thermal conductivity measurement

Fig. 2 shows the experimental setup of the three omega method. It makes use of two AD624C (Analog Devices) differential amplifiers (DA1, DA2) to isolate the voltages across the metallic line resistance and the potentiometer, respectively. The potentiometer has a maximum resistance of around 60 Ω. It is varied until reading a minimum fundamental voltage at frequency ω at the output of the lock-in amplifier (Standford Research SR830). Accordingly, the third harmonic voltage $V_{3\omega}$ across the metallic line resistance can be measured. It has to be noted that all the components of the experimental setup have very small temperature coefficients of resistance compared to that of the metallic line in order not to add any undesirable third harmonic voltages to the measurements. The knowledge of the in-phase $V_{3\omega}$ in the linear frequency zone allows determination of the thermal conductivity of the sample by using equation (5) [20]: