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Thermal characterization of some dental resins using the photoacoustic phase lag discontinuities

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Abstract

In this paper we describe a new photoacoustic methodology to measure thermal properties of materials. This methodology is based on the identification of the first discontinuity in the photoacoustic phase lag predicted by using the Roscencwaig model. The thermal characterization is done for a variety of dental material resins by measuring their thermal diffusivity. We compare our results with those obtained by using other photoacoustic method and we obtain, essentially, the same results. Finally, it is found a very good agreement with reported values for similar materials.

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I. Introduction.

Since the discovery of the photoacoustic effect, by A. G. Bell in 1880, the related experimental techniques, called photoacoustic techniques, have been applied to a large range of problems [1]. One of the main applications of these techniques is in the thermal characterization of materials. This characterization measures the thermal diffusion coefficient, the thermal effusivity and the thermal linear expansion coefficient. Related with measurements of the thermal diffusion coefficient, there is a variety of photoacoustic methodologies to carry out this thermal characterization [1]-[3]. One of these techniques involves the fitting of the photoacoustic signal as a function of the chopper frequency [3,4]. The method consists in finding one parameter which involves the thermal property of interest. In other methods the experimental photoacoustic phase lag is used to solve a transcendental equation which involves this thermal property [5,6].

In this article we present a new methodology based on the photoacoustic phase lag discontinuity. Using this method we do not need to fit a set of experimental data, it only requires to identify the discontinuities in the photoacoustic phase lag predicted by the Roscencwaig model [7].

The new method presented here is tested by measuring the thermal diffusion coefficient of a variety of dental resins commonly used in the dental practice. As a comparison, we used the alternative measurements on the same materials by the direct fitting of the photoacoustic signal following the model mentioned previously. In both cases we obtain, essentially, the same results. In all cases, we found a very close agreement between the properties measured in this work and the reported ones. To carry out the measurements described in this article we made use of the open photoacoustic cell (OPC) experimental array [8].

II. Theory.

By considering the surface absorption regime, in the OPC configuration, provided the predomination of the diffusion mechanism, it is

shown that the complete photoacoustic signal for optically opaque samples is given by the expression [7,8]

$$S_D = \frac{Y}{s_g s_s}\frac{1}{\sinh(l_s s_s)} \qquad (1)$$

In this equation Y is a coefficient involving optical, thermal properties and geometrical parameters, l_s is the sample thickness, and $\sigma_j = (1+i)\sqrt{\frac{a_j}{pf}}$, $j = g, s$, ($i=(-1)^{1/2}$ is the imaginary pure number), where f is the chopper frequency and α_j is the thermal diffusivity of the jth substance. The letter g refers to the gas inside the photoacoustic chamber and s refers to the absorber sample.

By expressing the Equation (1) in amplitude and phase form we obtain:

$$S_D = \frac{Y\sqrt{a_g a_s}}{2pf}\frac{1}{\sqrt{[\cos(x)\sinh(x)]^2 + [\sin(x)\cosh(x)]^2}}$$

$$\exp\left[i\left(-\frac{p}{2} - \arctan\left(\frac{\tan(x)}{\tanh(x)}\right)\right)\right] \qquad (2)$$

where $x=(f/f_c)^{1/2}$ and $f_c = a_s/(pl_s^2)$ is called the cut off frequency.

The photoacoustic phase lag has discontinuity points due to the tan(x) dependence, which are given at frequencies values given by the relation

$$f = (2n+1)^2\frac{p^2}{4}f_c \qquad (3)$$

where n is an integer number. In this way, these points of discontinuity are closely related with the cut off frequency. Consequently, the methodology proposed in this work consists in identifying experimentally the first discontinuity in the chopper frequency values (n=0 in Eq. 3) and, by using the Equation (3), to obtain the corresponding cut off frequency. From this parameter, the thermal diffusivity coefficient can be known.

III. Results and Discussion.

The method proposed previously was used in the measurement of the thermal diffusivity of a set of dental resins (Column 1 in Table I). The

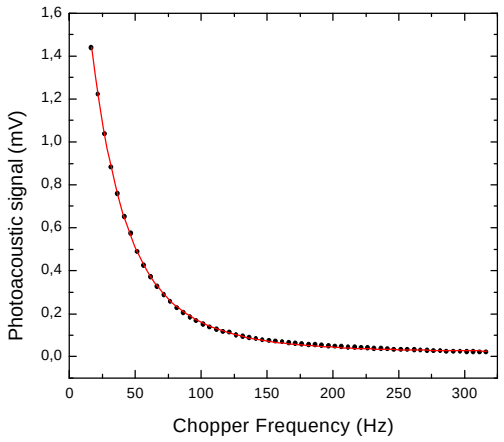

Fig. 1. Photoacoustic amplitude for Degufill LC dental resin. The continuous line corresponds to the best fitting to the amplitude given by Equation (2).

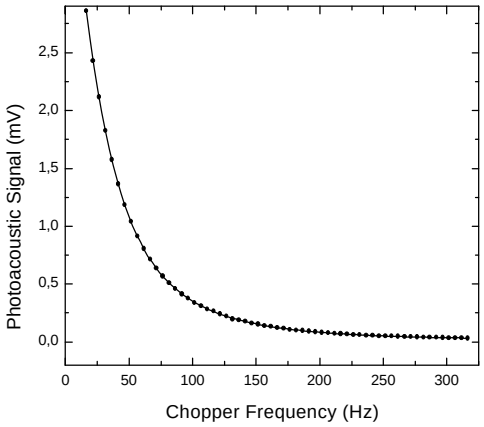

Fig. 2. Photoacoustic amplitude for Medental dental resin. The continuous line corresponds to the best fitting to the amplitude given by Equation (2).

resin samples were prepared in the shape of a disk with thickness between 100 and 200 microns (Table I for details). To satisfy the surface absorption regime, a piece of aluminum foil of 17 microns thickness was glued to the free sample surface using thermal paste.

In Figures 1 and 2 typical results of the signal amplitude for two of the studied dental resins are shown. The continuous line corresponds to the best fitting to the signal amplitude given by the equation (3). In the sixth column of Table I the thermal diffusivity values are shown. On the other hand, the photoacoustic phase lag versus

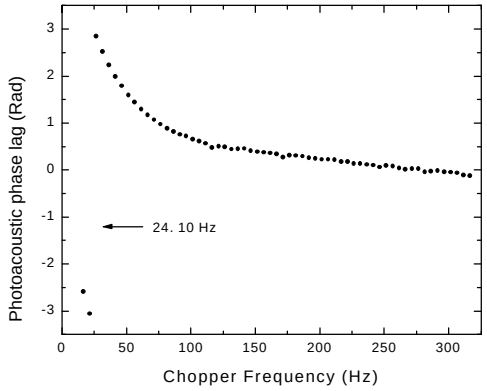

Fig. 3. Photoacoustic phase lag for Degufill LC dental resin where it is a discontinuity value in frequency as predicted by Equation (3).

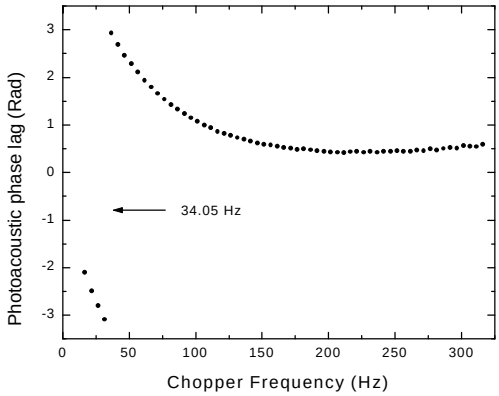

Fig. 4. Photoacoustic phase lag for Medental dental resin where it is a discontinuity value in frequency as predicted by Equation (3).

Table I. List of samples used in this work. The dental resins are named by their commercial names. α_{phase} refers to the thermal diffusion coefficient measured by looking in the phase phase lag discontinuity and α_{signal} refers to the diffusion coefficient obtained from the fitting of the photoacoustic amplitude signal.

Resin Sample	**Thickness (microns)**	***f*** **(Hz)**	f_c **(Hz)**	α_{phase} **(cm^2/s)**	α_{signal} **(cm^2/s)**
Degufill (auto)	191 ± 1.52	18.60 ± 2.41	7.54 ± 0.98	0.0086 ± 0.0011	0.0082 ± 0.0013
Medental	117 ± 6.85	34.05 ± 2.47	13.80 ±1.00	0.0059 ± 0.0004	0.0057 ± 0.0009
Degufill H	149 ± 4.83	19.06 ± 2.57	7.72 ± 1.04	0.0054 ± 0.0007	0.0058 ± 0.0016
Degufill LC	105 ± 3.65	24.10 ± 2.46	9.77 ± 1.00	0.0034 ± 0.0003	0.0034 ± 0.0002
3M	139 ± 6.06	19.18 ± 2.44	7.77 ± 0.99	0.0047 ± 0.0006	0.0041 ± 0.0003

chopper frequency of the same samples are shown in Figures 3 and 4. As predicted by Equation (3), it is found a chopper frequency value corresponding to a discontinuity point of the phase lag. By taking the middle point value between the initial and final points of the discontinuity, the corresponding *f* middle point value where this discontinuity take place is established (see third column of the Table I), and then, using the Equation (3) the corresponding cut off frequencies f_c (displayed in column 4th of Table I) and the thermal diffusivity values are obtained (column 5th of Table I). We therefore observe that by comparing the 5th and 6th columns of this table there is very close correlation between the values obtained using these two different methods. As a reference, the reported values for similar materials range from 0.00122 cm^2/s to 0.0066 cm^2/s [9] and the corresponding ones reported for enamel and dentine are 0.0042 cm^2/s and 0.0026 cm^2/s, respectively [10].

IV. Conclusions.

We have shown a new method to measure the thermal diffusion coefficient of samples by looking on the photoacoustic phase lag discontinuity. This new methodology has the advantage of being simpler than those reported in the literature. In principle, the technique is

applicable to all materials, assuming that the diffusion mechanism is the predominant. The precision of the measure depends only on the ability to identify the chopper frequency jump in the phase lag and, of course, the capacity to delimit it.

According to the equation 3 it is expected to appear other discontinuity points of the phase lag signal, although experimentally this is not the case. Disagreement between theory prediction and experimental results is attributed to the thermoelastic behaviour present in all samples. The thermoelastic contribution to the photoacoustic phase lag can not be neglected as in the case for the photoacoustic signal amplitude. This is the subject of our future work.

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