International Journal of Thermophysics, Vol. 24, No. 3, May 2003 (© 2003)

Investigation of the Thermal Diffusivity of Human Tooth Hard Tissue[1]

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Experiments of two kinds have been performed in which the heat diffusion effects in human tooth hard tissues have been investigated. The first one has been carried out on an incisor tooth as a whole with the use of a bath system. Experiments of the second kind have been done on slice specimens cut out of a tooth. A laser flash apparatus has been utilized. The time dependence of the temperature response has been measured using tiny thermocouples. The experimental data are then used to calculate the effective overall thermal diffusivity of the tooth structures as well as the thermal diffusivity of enamel and dentine alone. A discrepancy between the calculated results and literature data has been discussed.

KEY WORDS: dentine; enamel; laser dental therapy; laser flash method; semitransparent media: thermal diffusivity.

1. INTRODUCTION

In modern dentistry, as in whole medicine, heat effects and heat transfer phenomena are of great interest. There are at least two reasons for that. The first is that thermal loads are major risk factors for destruction of tooth structures which should be kept in mind, especially when planning heat or light treatment in dental therapy. The second is that the analysis of the temperature distribution could substantially help in diagnosis of many tooth and periodontal diseases. However, the problem of heat exchange in

[1] Paper presented at the Sixteenth European Conference on Thermophysical Properties, September 1–4, 2002, London, United Kingdom.

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dental structures lacks comprehensive understanding and still represents a most difficult task. It is mostly due to a combination of the complexity of a thermodynamic formulation of the problems, difficulties with analytical and numerical modeling and, last, but not least, the lack of precise and comprehensive experimental data concerning thermophysical properties of hard tooth tissues and dental materials.

The present work forms part of a research program concerned with an investigation of transient heat transfer in dental structures. Hypothermic effects and thermal loads in tooth exposed to thermal stimuli of different origins will be studied. For the case of a laser interaction, a very important issue is to differentiate between the effects of conductive and radiative heat transfer.

The aim of this study is to evaluate both the value of the effective overall thermal diffusivity of human tooth hard tissues as a whole and values of the thermal diffusivity for enamel and dentine alone. Two different kinds of experiments have been performed. The first has been done on an incisor tooth. The others were carried out on slice specimens cut out of a tooth. The experiments have been done in such a way that coupled conductive-radiative heat transfer effects could be neglected in the course of the thermal diffusivity calculations. The data provided in Ref. 1 are verified and complemented by the results of this study. This work is creating a basis for future theoretical analysis in this area.

2. Experimental

2.1. Effective Overall Thermal Diffusivity of a Tooth

Measurements of the effective overall thermal diffusivity of tooth structures were performed on an incisor tooth. The tooth had been extracted for therapeutic reasons and three thermocouples, each of 0.05 mm in diameter, were attached to the tooth. Omega K-type thermocouples were used. The thermocouple wires were encased in teflon tubes. Thermocouple junctions of about 0.1 mm in diameter were formed in a “V” shape by spark welding. The ends of the thermocouple wires were left uncovered for a length of about 1.0 to 1.5 mm.

X-ray macrophotographs of the tooth were taken after assembling the thermocouples on the tooth. Some of them are shown in Fig. 1. The spots at which the thermocouples were attached to the tooth are indicated in the pictures. Two main temperature sensors were attached to the front wall of a tooth crown: one outside (No. 1) and one inside the tooth chamber (No. 2). The third one was placed in a dental material. The dental material Tetric Ceram [2] was used for filling the hole that had been drilled through the back crown wall in order to attach thermocouple No. 2. Thermocouple No. 2 did not touch the filling. From X-ray pictures, characteristic distances were obtained for the thermal diffusivity calculations. Two additional thermocouples were used for the control temperature measurements.

During measurements the temperature changes were recorded while the tooth was subjected to alternate hot-cold baths or exposed to pulse laser radiation. The temperature signals were recorded through the NI4350 DAQ-Card and stored on a computer. The sampling rate was about 1 Hz. Typical results of the measurements are shown in Fig. 2. Two control thermocouples were employed for the bath temperature measurements (Fig. 2a).

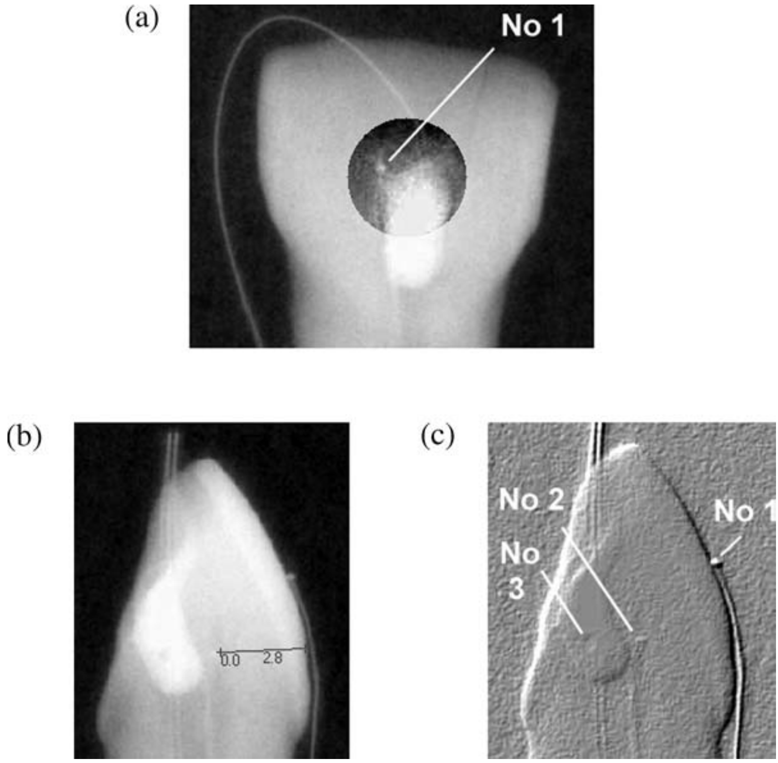
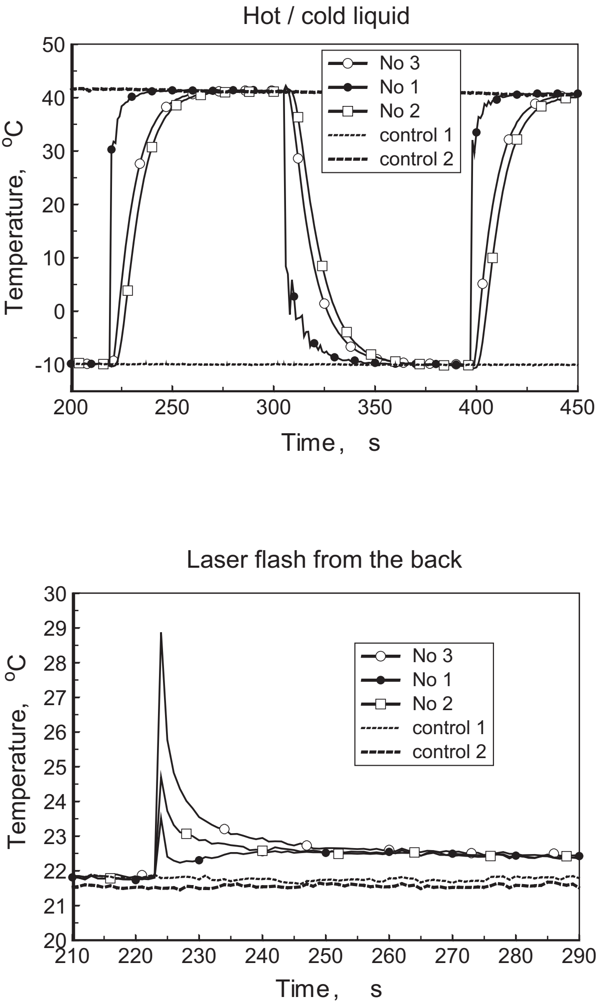


Fig. 1. X-ray macrophotographs of the tooth assembled with thermocouples: (a) front view, (b) side view with indication of distance from the inside thermocouple to the front surface of a tooth crown (about 2.8 mm), (c) relief image with indication of thermocouple positioning. The central picture (b) illustrates proportion between dimensions of an outer bright layer of enamel, which is about 0.8–1.0 mm thick, and dentine.

The experiments with a laser flash apparatus (Fig. 2b) demonstrated the crucial role of radiative heat transfer during the laser treatment of a tooth. However, the results of these tests were excluded from basic calculations and used only for qualitative analysis. Main calculations were based on the results from the alternate temperature bath experiments (Fig. 2a). During these measurements the ambient temperature of the tooth was cycled between a low value of −10, 0, or 10°C and a high value of about



(a)

(b)

Fig. 2. Typical results of measurements performed on a tooth subjected to (a) an alternate hot/cold bath and (b) exposed to a 1 μm pulse laser radiation.

45°C. The cold liquid bath was fed with ethanol from a low temperature thermostat. For the hot bath, water in a Dewar flask was employed. The temperature limits of the experiments were based on limits of previous investigations of specific heat [3].

2.2. Laser Flash Measurements of the Thermal Diffusivity of Tooth Structures

The thermal diffusivity of enamel and dentine was investigated in laser flash experiments. A typical apparatus for such experiments was used. The system is composed of a neodymium pulse laser, Riken Denshi TCCJ transient recorder, and a vacuum subsystem. The classical Parker method was modified to deal with difficulties that arose from the semitransparency of the investigated materials [4]. Whenever it was possible, the radiation through the sample was stopped by using a thin molybdenum foil attached to the front, irradiated surface of the sample. The idea of using the foil was taken from Ref. 5. The methodology of investigations was similar to that of dental material investigations [2].

The biological specimen slices were cut out of a premolar tooth along its length. The slices were about 1.2 to 1.5 mm thick. From these slices three test samples of different types were prepared. Each was in the shape of a small disk, 12 mm in diameter and about 1 mm thick which is, at least, ten times the thickness of molybdenum foil. The first sample was prepared from the whole slice specimen. The enamel-dentine structure of the cross section of the tooth was preserved as is shown in Fig. 3a (bright area). The voids were filled with Opticor Flow dental filling material. Two other samples were composed from separated specimens of dentine and enamel (Fig. 3b, c). These specimens were covered on the irradiated side with a thin, 0.1 mm molybdenum foil.

The temperature of both faces of the specimen was measured with two J-type thermocouples. The thermocouples were prepared from flat-rolled 0.05 mm wires. The first thermocouple was welded to the front surface covered with the molybdenum foil. The second one was glued to the back surface of a sample with a commercial adhesive.

After slicing the tooth, the specimens were stored in a physiological salt solution. The laser flash samples had been prepared a few days before measurements and then were stored at ambient conditions. Experiments were carried out in vacuum at a temperature slightly above room temperature (about 28°C). Two measurements were carried out on the first sample (Fig. 3a) first with the back thermocouple junction placed on the dentine surface and then with the hot junction on enamel. Two other measurements were performed on dentine (Fig. 3b) and enamel (Fig. 3c) compositions.

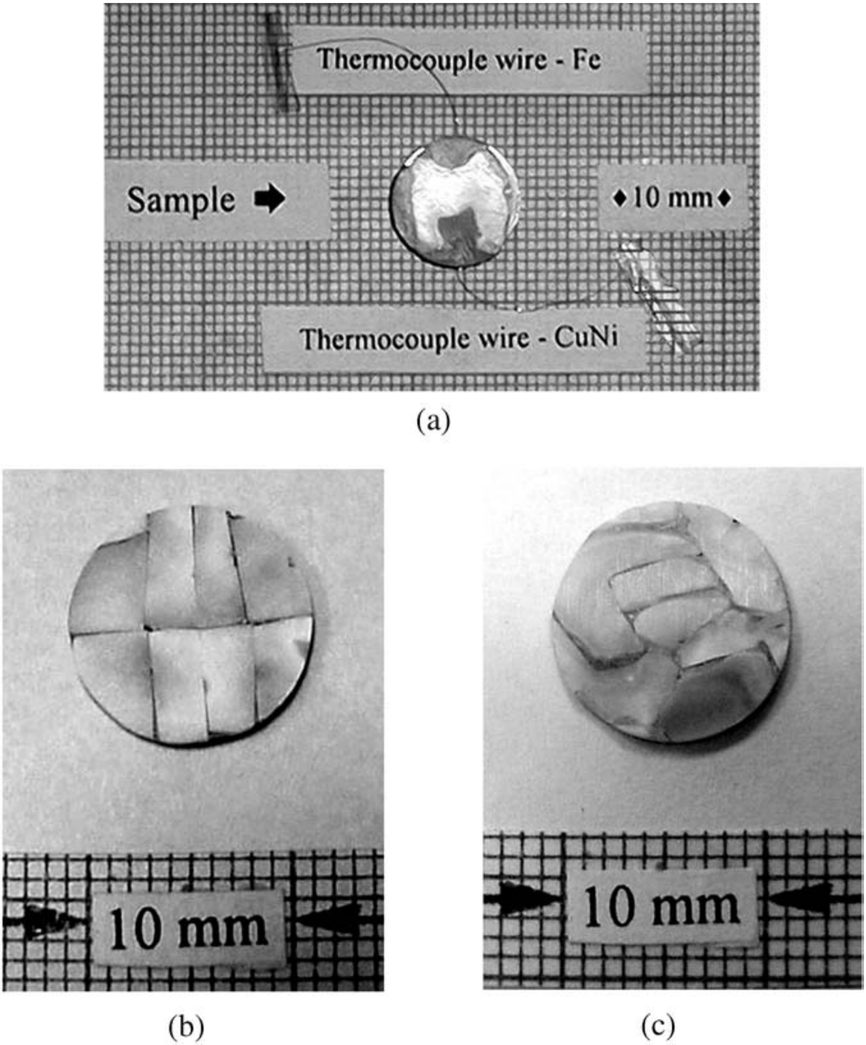


Fig. 3. Specimens for investigations of the thermal diffusivity: (a) a slice cross section of the tooth specimen, (b) a specimen composed from plates of dentine cut out from slices, and (c) an enamel specimen composed from irregular pieces.

During the experiment the sample was subjected to a one-sided burst of radiation energy. A transient thermoelectric signal, corresponding to the temperature difference between the front and rear surfaces, was recorded. The thermal diffusivity was obtained from computer-aided analysis of the recorded data.

3. RESULTS AND DISCUSSION

The effective overall thermal diffusivity of the whole tooth structure was obtained on the basis of the temperature histories from the bath experiments (Fig. 2a). The recorded signals were divided into subsequent heating and cooling protocols. After removing the short initial part, the temperature rise/fall curves $\Delta t(\tau)$ were fitted with a modified unit step response function,

$$\Delta t(\tau) = a(b - e^{-c\tau}) \tag{1}$$

where τ is the time and a, b, c are coefficients. Least-squares procedures were employed. Modification is based on introducing the parameter b which is not equal to 1. The difference between b and unity was used to indicate the quality of both the modeling and the approximations. Typical results of approximation are shown in Fig. 4. The results obtained for experiments of the same type, i.e., for heating or cooling stages, did not diverge between themselves in parameter c values by more than 3% independent of the temperature range of measurements. This concerns the results of similar, and close to 1, b values.

The thermal diffusivity was calculated from the coefficient c values. Simple analytical models of the heat conduction in an infinite parallel plate

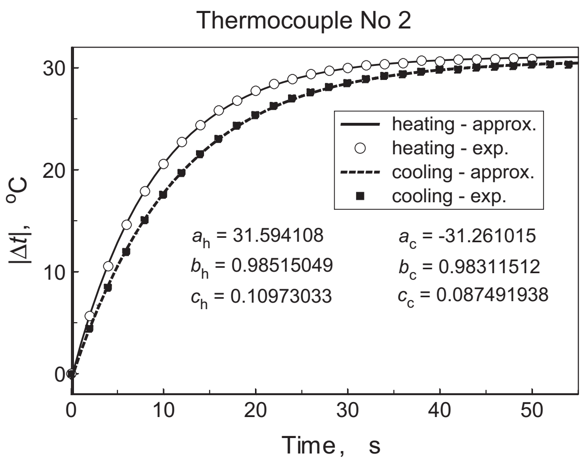


Fig. 4. Typical results of approximation of heating and cooling signals recorded in bath experiments. The picture illustrates results obtained for the part of data depicted in Fig. 2a (from 220 to 390 s). Absolute values with the starting point translated to zero abscissa value are shown. The "h" stands for heating, "c" for cooling.

("par"), infinite cylinder ("cyl"), and a sphere ("sph") were employed. It was assumed that the object (the tooth) of uniformly distributed temperature was being subjected to a sudden jump of the boundary temperature. The solutions of such problems are given in Ref. 6. From those solutions one can obtain, depending on the model used, the following formulae,

$$\kappa_{\mathrm{par}} = \frac{4cl^2}{\pi^2} \tag{2}$$

$$\kappa_{\mathrm{cyl}} = \frac{cl^2}{\beta_1^2} \tag{3}$$

$$\kappa_{\mathrm{sph}} = \frac{cl^2}{\pi^2} \tag{4}$$

where κ is the thermal diffusivity, l is a characteristic dimension (half width of a parallel plate, radius of a cylinder or a sphere), and the first root of an appropriate transcendental equation based on a Bessel function is denoted by $\beta_1 \cong 2.4048$ [6]. The exponential factor c from Eq. (1), present in Eqs. (2)–(4), stands for the inverse of a characteristic time of a transient heat conduction process. This means that the discussed formulae are valid in the time interval when higher harmonics of solutions given in Ref. 6 are negligibly small in comparison with the first ones. The results of calculations for $l = 2.8$ mm (see Fig. 1b) are listed in Table I.

The real value of the effective overall thermal diffusivity of tooth structures should be enclosed within limits determined by parallel and cylindrical models. Results of spherical modeling are included in order to get an impression of the range of possible changes. Due to a curved shape of the real object, κ_{par} slightly overestimates and κ_{cyl} underestimates the expected real values. The reason for such distinct differences between heating and cooling results is not clear. Analyzing Eqs. (2)–(4), one can notice that the results of calculations are sensitive to the characteristic

Table I. Results of Estimation of the Overall Thermal Diffusivity of Tooth Structures

Process	$\kappa_{\mathrm{par}} \times 10^7$ $(\mathrm{m^2 \cdot s^{-1}})$	$\kappa_{\mathrm{cyl}} \times 10^7$ $(\mathrm{m^2 \cdot s^{-1}})$	$\kappa_{\mathrm{sph}} \times 10^7$ $(\mathrm{m^2 \cdot s^{-1}})$
heating	3.49	1.49	0.87
cooling	2.78	1.19	0.69

dimension l value. Because of that, the results should be treated as qualitative. Precise estimation of the effective overall thermal diffusivity is possible but it requires further studies. The effects of the surface heat transfer phenomena should be thoroughly analyzed. In the present case this result was roughly estimated from the convective heat transfer analysis to be, in relative values, not greater than 5.5% for water (heating) experiments and 18% for ethanol experiments (cooling). These numbers define limits of underestimation of the searched parameter, i.e., thermal diffusivity.

For the case of laser flash measurements, processing of the experimental data was based on exponential curve fitting. Only certain parts of the recorded data were taken into account during numerical calculations. In these calculations a characteristic time τ_c was obtained. Next, the thermal diffusivity was derived from

$$\kappa = \frac{d^2}{\pi^2 \tau_c} \tag{5}$$

where d stands for the thickness of the disk specimen. If necessary, corrections for the influence of the molybdenum foil were applied afterwards [4]. The uncertainty in the thermal diffusivity evaluation procedure was estimated to be not greater than 10% in relative values. This value is mostly due to a small characteristic dimension—the specimen thickness. The results of calculations are listed in Table II.

Analyzing the data from Table II, one can easily notice inconsistencies between the results of the apparent thermal diffusivity and the thermal diffusivity of the dentine and enamel alone. The results of the apparent thermal diffusivity measurements were initially verified by numerical

Table II. Apparent Thermal Diffusivity and Thermal Diffusivity of Dentine and Enamel Calculated from Laser Flash Data

Specimen			
Slice cross section of the molar tooth (Fig. 3a)		Dentine composition (Fig. 3b)	Enamel composition (Fig. 3c)
$\kappa_{d,\,app} \times 10^7$ $(m^2 \cdot s^{-1})$	$\kappa_{e,\,app} \times 10^7$ $(m^2 \cdot s^{-1})$	$\kappa_d \times 10^7$ $(m^2 \cdot s^{-1})$	$\kappa_e \times 10^7$ $(m^2 \cdot s^{-1})$
2.16	4.09	1.92	2.27
$t = 28°C$			

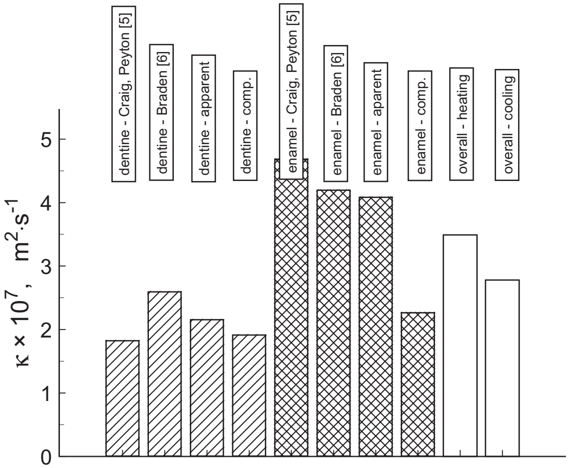


Fig. 5. Comparison between selected results of the thermal diffusivity of human tooth hard tissue investigations: dentine, first four bars; enamel, next three bars; effective overall from a parallel model, the last two bars.

modeling. From a simplified two-dimensional finite element analysis,[5] it appeared that the apparent thermal diffusivity could be underestimated by 25% for enamel and overestimated by 20% for dentine with reference to the assumed real values. In view of these results, the discrepancy is even stranger. The reason for that has not yet been determined. The most probable explanation is connected with the enamel specimen composition and preparation. A repeated thorough examination of the sample revealed the presence of dentine structures. A precise evaluation of dentine content is difficult but macroscopic inspection made possible a rough estimation of the dentine present from about 20 to about 35%. Nevertheless, the methodology of the laser flash experiments seems to be correct.

In general, the results of the thermal diffusivity investigations employing three different methods of the specimen preparation and treatment are within the literature data limits. Comparisons between them and some selected representative literature values from Refs. 7 and 8 are shown in Fig. 5. When commenting on this figure, it should be stressed that the previous thermal diffusivity data were obtained from the measured thermal conductivity values. In view of overestimation of the literature data for the

[5] The analysis was performed for a geometry of a cross section of the disk specimen. The enamel, dentine, and filling material sections were present in corresponding proportions but the axial symmetry was assumed. More precise three-dimensional calculations are in progress.

specific heat of tooth hard tissues (comp. [3]), the value of the thermal diffusivity provided in Ref. 8 seems to be underestimated.

From analysis of the obtained results, it appears that there are many problems that should be thoroughly studied in further investigations. In particular, the effect of moisture content on thermal characteristics needs an explanation as well as effects of specimen differences or temperature changes. In the present case the specimens were investigated in a dried state in order to make the results comparable. Some of the questions concern the methodology used. A very important issue is the problem of coupled conductive-radiative heat transfer, excluded from the present considerations, but very important from the point of view of prospective applications of the obtained results.

4. CONCLUSIONS

The work presented in this paper is part of a wider research program focusing on better understanding of heat exchange in dental structures. Knowledge of thermal properties is crucial for precise modeling and analysis of heat transfer phenomena. The limits for possible errors in that domain are very narrow. It is because of the low values of the hypothermia temperatures. Even a temperature exceeding the limit of 42.5°C damages tooth pulp [9]. Although the obtained results can not be accepted for a quantitative analysis of any kind, the same is true for the literature data. However, the present studies can be treated as a guide to the methodology of the thermal diffusivity of human tooth hard tissue measurements. Three independent methods have been used to study the thermal transport behavior of such structures. The measured values of the thermal diffusivity, in spite of the revealed discrepancy, are found to fall within the limits of the extremes of literature data. Further studies can provide more precise values of the thermal diffusivity, and some other problems could also be explored.

The present results contribute to a better understanding of findings of many *in vivo* and *in vitro* experiments which are now being carried out. In particular, the results of investigations of the thermal diffusivity complement results of microcalorimetric investigations of human tooth hard tissues [3] and create the basis for further systematic studies of the effect of age and personal differences on the thermal diffusivity.

ACKNOWLEDGMENT

This research is supported by the State Committee of Scientific Research of Poland, Grant 6P05E06621.

REFERENCES

1. W. J. O'Brien, *Dental Materials and Their Selection* (Quintessence Publ., Chicago, 1997).
2. A. J. Panas, J. Terpiłowski, J. Trykowski, P. Zaborowski, and S. Żmuda, *High Temp.–High Press.* **33**:581 (2001).
3. S. Żmuda, P. Zaborowski, and A. J. Panas, Microcalorimetric investigations of human tooth hard tissues in thermocycling, presented at 26th Int. Thermal Conductivity Conf., Cambridge, Massachusetts (2001).
4. J. Terpiłowski, "A Pulse Method of the Thermal Diffusivity Determination Applied to Materials Semitransparent for Laser Radiation," *Proc. 16th European Conf. Thermophys. Props.*, London (2002).
5. R. E. Taylor and K. D. Maglič, in *Compendium of Thermophysical Property Measurement Methods*, K. D. Maglić, A. Cezairliyan, and V. E. Peletsky, eds. (Plenum Press, New York, 1984), pp. 305–338.
6. H. S. Carlslaw and J. C. Jaeger, *Conduction of Heat in Solids* (Oxford University Press, London, 1959), pp. 100, 198, 234.
7. R. G. Craig and F. A. Peyton, *J. Dent. Res.* **40**:411 (1961).
8. M. Braden, *J. Dent. Res.* **43**:315 (1964).
9. M. Pohto and Schenin, *Acta Odontol.* **16**:303 (1958).