ELSEVIER

Nuclear Instruments and Methods in Physics Research A 480 (2002) 463–469

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

Direct measurements of the thermal conductivity of various pyrolytic graphite samples (PG,TPG) used as thermal dissipation agents in detector applications

C.A. Heusch[a], H.-G. Moser[b,*], A. Kholodenko[c]

[a] *Institute for Particle Physics, UCSC, 1156 High Street, Natural Science II, Santa Cruz, CA 95064, USA*
[b] *Max-Planck-Institut für Physik, Werner-Heisenberg-Institut, Föhringer Ring 6, D-80805 München, Germany*
[c] *IHEP, Popeda Str. 1, 142284 Protvino, Russia*

Received 21 July 2000; received in revised form 12 March 2001; accepted 7 April 2001

Abstract

We performed model measurements on heat conduction in graphite-based structures, using several configurations. We describe our method for the direct measurement of thermal conductivity both in-plane and out-of-plane, for TPG and PG samples. Our results for the in-plane thermal conductivity coefficient, K_{ab} were obtained with two different sets of boundary conditions; they are in good mutual agreement. Those for the transverse coefficient, K_c, differ by a significant factor from the values published by the producers of the material.

PACS: 44.10.+i

Keywords: Thermal conductivity; Pyrolytic graphite

1. Introduction

To assist power dissipation in high-density electronic devices, there has been an increasing demand for materials that are characterized by high thermal conductivity in the given directions only. Technical developments in the late 1950s [1] that permit the preparation of massive samples of pyrolytic carbon, opened the way for the production of highly oriented pyrolytic graphite (PG). The availability of annealed, even stress-annealed, samples of this material stimulated investigations on the structural, electronic, and thermal properties of graphite configurations. As a result of this research, further technological progress led to the commercial availability of highly anisotropic materials, many properties of which approximate those of ideal graphite.

The regular structure of such pyrolytic carbon-based materials and their high level of "in-plane" thermal conductivity open the way for their application in several fields [1]:

- as monochromators, filters, or analyzers of X-ray and neutron-optical elements;
- as proton polarization enhancers;
- as anisotropic absorbers;

*Corresponding author. Tel.: +49-89-32-354-371; fax: +49-89-32-26704.

E-mail address: moser@mppmu.mpg.de (H.-G. Moser).

0168-9002/02/$ - see front matter
PII: S0168-9002(01)01208-6

- for high-density (micro-)electronic readout and analysis assemblies as heat dissipaters.

In addition, this material offers low mass and a large radiation length ($X_0 \approx 190$ cm); it can therefore be used for the cooling of detector and electronic elements in tracking devices. In fact, thermal pyrolytic graphite (TPG) will be used in the ATLAS Semiconductor Tracker [2] where the heat dissipation of highly irradiated silicon detectors has to be effected optimally.

2. Measurement of the in-plane thermal conductivity, K_{ab}

The conventional method of measuring the thermal conductivity in a given material is the determination of a temperature profile along the direction of the energy flow under investigation. For a sample of uniform cross-section S and length L, the thermal power conducted per unit time is

$$W = K\frac{S}{L}\Delta T, \tag{1}$$

where K is the heat conduction coefficient, and ΔT the temperature difference between the two ends of a sample of length L. It is then straightforward to determine K as the appropriately scaled slope of a linear fit to the measured dependence of ΔT on W.

We performed two sets of model measurements. The first set was done inside a vacuum vessel at a residual gas pressure of $\sim 10^{-2}$ mbar, the second inside a polystyrene foam box at atmospheric air pressure; these assemblies were configured to minimize the effects of atmospheric and radiative heating, respectively.

The TPG bars used in both configurations measured $120 \times 12.5 \times 0.5$ mm^3. All temperature measurements described in this article were done with Pt100 thermal resistors, which displayed good linearity over the full range of our investigations.

2.1. Measuring K_{ab} inside a vacuum vessel

To avoid thermal conduction by the ambient atmosphere, we used the configuration shown in Fig. 1a, assembled inside an evacuated volume. A heating element consisting of resistive film was glued to one end of the TPG bar; the opposite end was connected to a massive copper heat sink, which, in turn, was cooled to -17°C by an alcohol cooling circuit. This heat sink was adjustable to different temperatures over a wide range. Sensor Pt1 measured the temperature just above the heat sink, while the other sensors traced the temperature profile of the TPG bar all the way to the heat source. The sensors and the heating element were glued to the TPG surface by special thermally conductive adhesive tape, whereas the heat sink was joined to the TPG by thermally conductive grease (DOW CORNING 340).

We display the principal results of our measurement in Fig. 1b; the solid line shows the thermal conductivity coefficient K_{ab} and its temperature dependence as advertised by the manufacturer[1] for TPG material; the points with error bars show our measured values for both the Advanced Ceramics (see footnote 1) and ATOMGRAPH[2] samples. They are considerably higher than those quoted for PG in Ref. [3], underscoring the value of the TPG configuration. Control measurements on standard materials convince us that the difference between our results and the producer's specification is not due to thermal radiation.

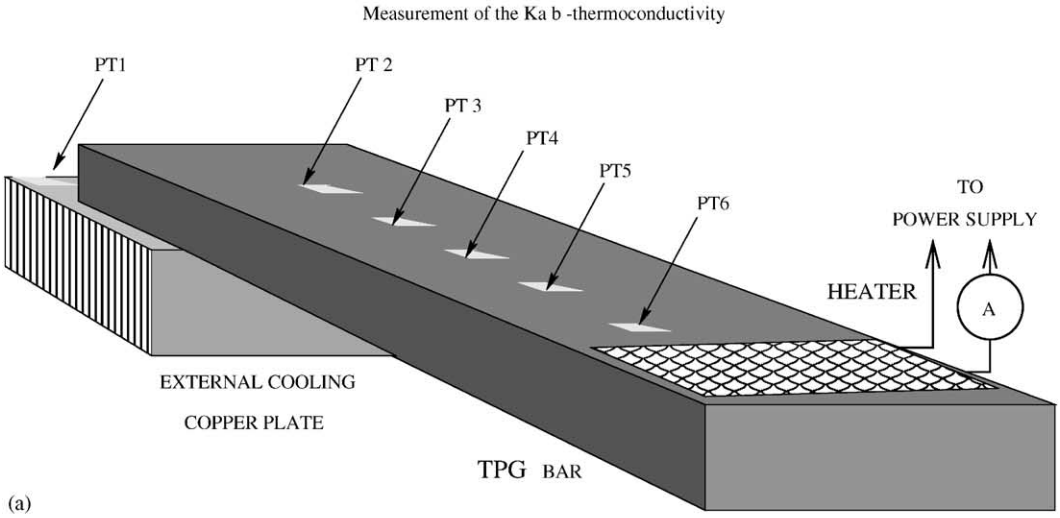
2.2. Measuring K_{ab} inside a polystyrene foam box at atmospheric pressure

Figs. 2a and b show the same TPG bar array between heat source and sink, with a few modifications made possible by its arrangement in atmospheric pressure, protected only by a polystyrene box; the array was configured such as to minimize the effects of thermal radiation. Further modifications were

- the addition of one Pt100 sensor for the measurement of the temperature profile;
- the use of thermally conductive grease for all connections between heat source, heat sink, Pt100 sensors, and the TPG bar;

[1] Advanced Ceramics Corporation, PO Box 94924, Cleveland, OH 44101-4924, USA.

[2] ATOMGRAPH, 2 Electrodnaya Str. 111524 Moscow, Russia.



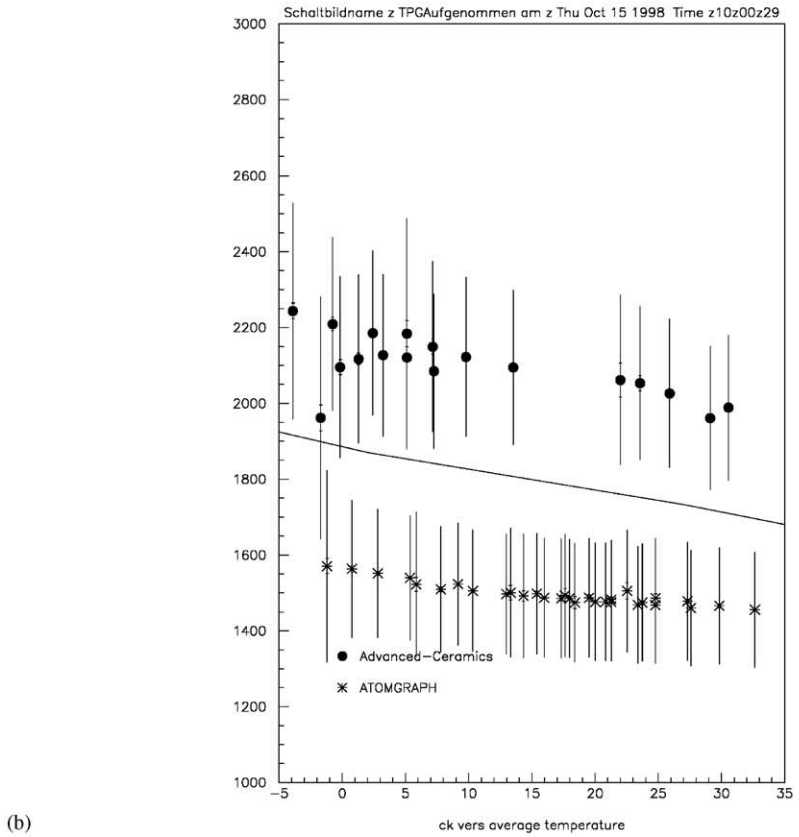


Fig. 1. (a) Schematic drawing of the setup for the measurement of the coefficient of thermal conductivity in-plane, K_{ab}, placed inside a vacuum vessel at a pressure of 10^{-2} mbar. (b) Results of the thermal in-plane conduction coefficient, K_{ab}, are shown for Advanced Ceramics and ATOMGRAPH samples. The solid line corresponds to the values specified by Advanced Ceramics Corporation.

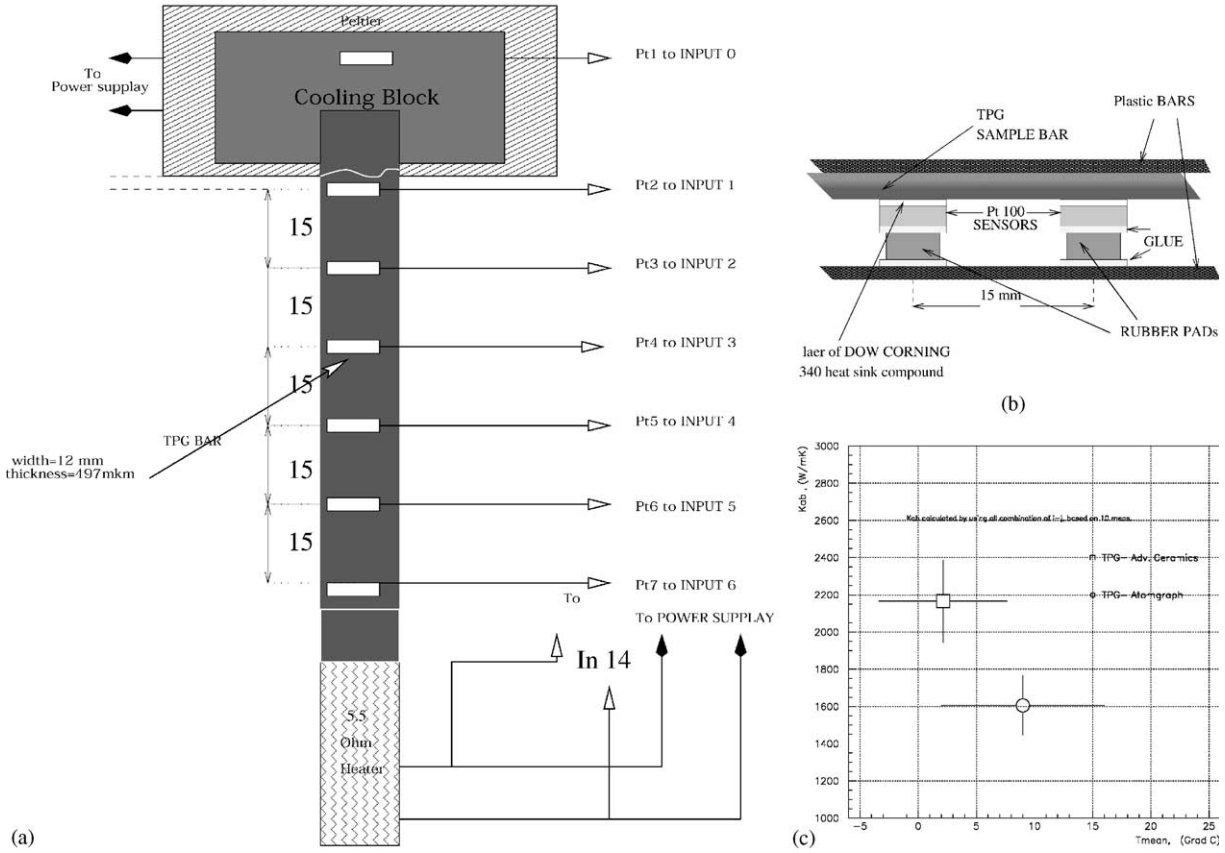


Fig. 2. (a) Schematic drawing of the setup. (b) Cross-section along the main TPG axis. (c) The coefficient of thermal conductivity in-plane, K_{ab}, for Advanced Ceramics and ATOMGRAPH samples. The measurements were performed inside a foam box in air at atmospheric pressure.

- also, the application of shims for adjustable mechanical pressure in the sensor joints attached to the TPG bars.
- The temperature of the circulated cooling fluid was raised to 0°C, to avoid all condensation of atmospheric moisture.

The results of this series of measurement, done at only one temperature for the coolant, are shown for TPG samples from the manufacturers mentioned above, in Fig. 2c. The horizontal error bars for the quoted values correspond to the temperature range of the bars during our measurements. Obviously, the measured values of the two coefficients are well compatible with our previous results from the vacuum-vessel configuration.

3. Measurement of the out-of-plane (transverse) thermal conduction, K_c

3.1. Experimental setup

To optimize our chances of obtaining reliable values for the transverse thermal conduction coefficients K_c, we tried out several different test setups before homing in on the design shown in Fig. 3a. The parameters we optimized in this

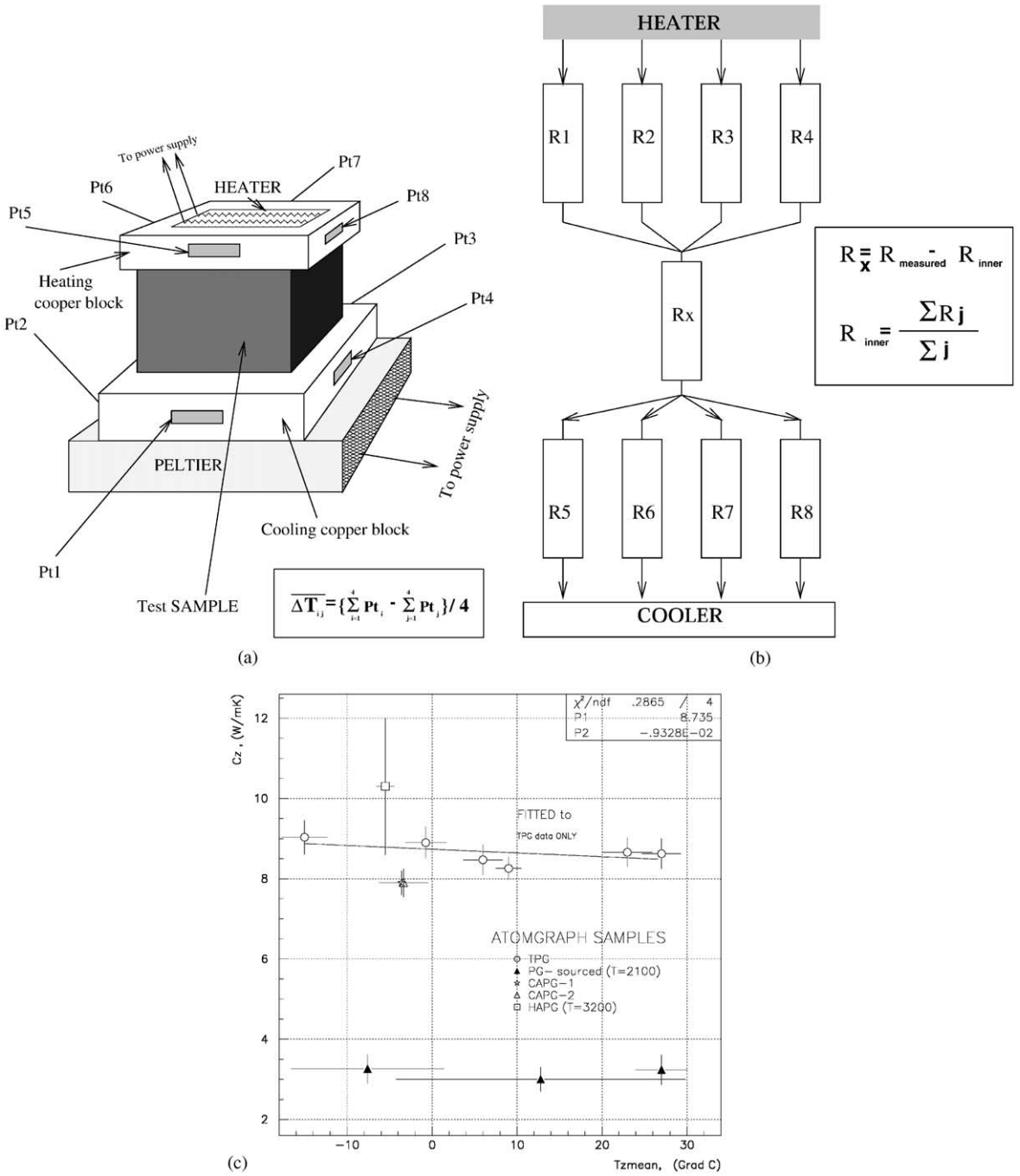


Fig. 3. (a) Schematic drawing of the setup for measuring the coefficient of transverse thermal conduction of the samples. (b) ''Equivalent'' electrical analog of the array in (a). (c) Transverse thermal conductivity, K_c: Measured values of thermal conductivity and its temperature dependence for various TPG and PG samples.

fashion, using bridge arrangements (Fig. 3b) well-established for precision measurement in electrical circuits, were the thicknesses of samples to be used, "inner resistances" of the circuits, and comparisons with test samples of known thermal conductivity. One of the complications in this preparatory stage was the need to have comparison samples of precisely equal thickness—not a trivial task for the various test substances.

The setup in Fig. 3a illustrates our final approach: not shown is a mechanical clamp that insures good thermal contact between heating element and TPG sample. For a reliable tracing of the temperatures, we used four pairs of thermal sensors (schematically shown, with the relevant analog parameters for an electric circuit, in Fig. 3b); they map out the temperatures on the four lateral surfaces of the various sample blocks, both on the heating side and on the side of the heat sink.

3.2. Results on transverse thermal conduction coefficients

We measured the transverse thermal conductivities of a number of different pyrolytic graphite materials (PG, TPG, CAPG, and HAPG), all from one manufacturer (see footnote 2). PG was sourced at about 2100°C, TPG is PG which has been annealed at 2900°C, HAPG has been annealed at higher temperatures ($\approx$3200°C), and CAPG is, in addition, compression-annealed (at 100 kg/cm^2); its principal application is for monochromators. The results are shown in detail in Table 1; they are plotted in Fig. 3c.

Our principal result is seen to be the fact that the coefficient K_c, quoted by industry sources to be about 25–30 W/mK (see footnote 1), is much smaller for all the PG samples measured, by at least a factor of 3. For comparison, our measured value for PG is precisely that quoted in Ref. [3, p. 57]. Given that there is no clear theoretical guidance on this issue, we regard our results as a significant input to a fuller understanding of the thermal conduction mechanism involved. A useful modeling of the underlying process, quite apart from the practical applicability, should also be able to explain the large difference between PG and TPG samples.

It is worth noting a secondary result: there is little if any temperature variation, over the small range measured, of the thermal conductivity.

4. Conclusions

Our measurements of the properties that govern out-of-plane thermal conduction in various pyrolytic graphite material samples indicate that they differ significantly from values advanced by their producers. This is significant not only for their efficient application as highly directional heat pipes in dense micro-electronic readout systems; also, it ought to stimulate interest in the physics of such extremely anisotropic heat conductors. As a reasonable next step, we plan to investigate the analogous behavior in the presence of strong magnetic fields: should thermal conduction in these graphites be a phenomenon based at least partially on electron mobility, electrical and

Table 1
Results of the transverse thermal conduction coefficient, K_c, for various samples of PG and TPG

Sample				T(°C)		K_c
Type	Dimension (mm)					(W/mK)
	x	y	z	Heater	Cooling	
PG	10	20	8	2.9	−4.1	$3.0^{+0.2}_{-0.3}$
TPG	10	20	8	1.9	−2.93	$8.9^{+0.4}_{-0.3}$
HAPG	10.0	20.0	2.5	−4.54	−6.55	$10.3^{+2.0}_{-1.3}$
CAPG(1)	16.2	13.2	7.5	2.21	−5.78	$7.9^{+0.3}_{-0.3}$
CAPG(2)	16.0	25	7.0	−0.34	−6.37	$7.9^{+0.4}_{-0.3}$

thermal conductivity should demonstrate a proportional effect ("Wiedemann–Franz law"). The presence of a strong magnetic field, such as we expect to have in essentially all vertex detector applications, should then lead to noticeably different results. If, on the other hand, heat conduction in our samples is based on phonon transfer alone, such as in ideal diamond crystals, there should be no difference of observed temperature profiles in the presence of a magnetic field.

Acknowledgements

We wish to acknowledge the kindness of Iris Abt and her group at MPI Munich, who put their laboratory equipment at our disposal for these measurements.

References

[1] A.V. Moore, Chem. Phys. Carbon 17 (1981).
[2] Inner Detector Technical Design Report, Vol. 1, ATLAS TDR 4, CERN/LHCC/97-16, 30 April 1997;
Inner Detector Technical Design Report, Vol. 2, ATLAS TDR 5, CERN/LHCC/97-17, 30 April 1997.
[3] H.O. Pierson, Handbook of Carbon, Graphite, Diamond and Fullerenes, Noyes, Park Ridge, NJ, 1993.