Journal of Testing and Evaluation, Vol. 41, No. 4, 2013
Available online at www.astm.org
doi:10.1520/JTE20120216

TECHNICAL NOTE

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Evaluation of Effective Thermal Conductivity for Mineral Cast Structural Materials Using Steady-State and Transient Methods

REFERENCE: Selvakumar, A. and Mohanram, P. V., "Evaluation of Effective Thermal Conductivity for Mineral Cast Structural Materials Using Steady-State and Transient Methods," *Journal of Testing and Evaluation*, Vol. 41, No. 4, 2013, pp. 1–7, doi:10.1520/JTE20120216. ISSN 0090-3973.

ABSTRACT: Thermal conductivity is a thermophysical property that represents the rate at which heat energy can be transported through the material. For any alternate material chosen for machine tool structures, the study of its thermal characteristics is imminent. Thermal conductivity is one major characteristic to be analysed. Mineral cast structures made of epoxy-granite are found to exhibit good mechanical properties, such as high stiffness and damping ratio. The material also has lesser weight, compared to conventional materials used for machine tool structures. Hence, these materials are emerging as an alternate to conventional cast iron machine tool structures. This study attempts to determine the effective thermal conductivity of epoxy granite material using steady-state and transient plane source (TPS) methods. The results obtained using the experimental methods are compared with geometrical models and the suitability of the methods is evaluated. It is observed that both methods are suitable for measuring effective thermal conductivity of two-phase materials. Compared to TPS method, the steady-state method is a slow and material-consuming technique but provides more accurate results. The effective thermal conductivity of the developed material is compared with some commercial polymer composites and observed that the developed material has greater thermal conductivity.

KEYWORDS: effective thermal conductivity, two-phase material, epoxy-granite, steady-state method, TPS method

Introduction

Traditionally, cast iron is the material used in machine tool structural fabrication because of its excellent mechanical and thermal properties. The inherent problems such as chattering detected in cast iron structures of advanced machine tools affect the tool life, machining integrity, and surface quality of the work piece and geometric accuracy [1]. Machine tools operating at high speeds generate heat in the spindle that is easily transported through the conventional structural materials, such as cast iron and steel, causing deflection of the components. The deflection of relative structural components because of thermal energy transport is a main reason for geometrical inaccuracy of products manufactured. Hence, alternate materials exhibiting good mechanical and thermal characteristics are under research for machine tool structures.

Composite materials were found to be suitable alternate materials for machine tool structures because of their excellent dynamic characteristics along with high damping ratio, lesser weight, and ease of manufacture. Fiber–matrix composites were found to be used in the manufacture of moveable components such as slides for CNC milling machines [2]. Stone-based metal–matrix composites were employed in the manufacture of machine tool supporting structures such as column, lathe bed, etc. A hybrid polymer–concrete bed fabricated using metal frame and polymer composite for a gantry type milling machine was found to have high damping ratio and stability at high-speed machining conditions [3]. An epoxy resin concrete bed was fabricated for an ultra precision bed of a CNC grinding machine using optimum composition of resin mixture that gives excellent mechanical properties [4].

Stone-based polymer–concrete machine tool structures were usually classified based on the type of polymer resin, such as polyester resin and epoxy resin, used for binding the aggregate materials [5]. They observed that the characteristics of these structures vary with the composition of ingredients in the mixture [6]. It was also detected that epoxy resin gives good binding properties and strength compared to polyester resin and are preferred in the manufacture of machine tool structures, irrespective of its high cost. Further, it is found that mineral cast structures fabricated using epoxy resin and granite particles exhibit a greater damping ratio and stiffness. Also, its suitability as alternate material for machine tool structures was tested [7,8].

Thermal energy transport through the structure is detected as another major cause for the positional error between the machining parts resulting in inaccurate products manufactured from it. Hence, alternate materials selected for the machine tool structures should be capable of overcoming thermal error propagation because of

Manuscript received July 2, 2012; accepted for publication February 7, 2013; published online May 23, 2013.

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heat energy developed during high-speed machining operations [9]. A high thermal conductivity for the material will enhance heat transfer from the structure. Hence, the study of thermal properties such as thermal conductivity is important for the alternate composite materials suggested for machine tool structures.

Techniques that were used to determine the effective thermal conductivities of two-phase materials can be classified as either steady-state methods or transient methods. In the steady-state technique, a steady temperature gradient will be build up over a known thickness of the sample. The major disadvantage of this technique is that it is a time-consuming technique and requires a large sample size. Transient techniques starts responding as and when the heat input signals are supplied to the sample. The transient plane source (TPS) technique is used reliably to find effective thermal conductivity of materials such as metal foams [10], fire-resistive materials [11], hydrating cement pastes [12], HVFA mortars and concrete materials [13], and insulation materials [14].

The thermal and mechanical characteristics of the material will vary with the composition of ingredients used in the mixture. Thermal conductivity of the material decreases with increase in epoxy resin content in the mixture. This is because the epoxy resin that has a very low thermal conductivity increases the interfacial resistance between the aggregate granite particles. This study attempts to determine the effective thermal conductivity of epoxy–granite material with a composition of ingredients that gives better mechanical properties to machine tool structures. Two experimental methods, the steady-state and TPS method, are used to obtain the results. The results obtained by these methods are analysed and compared with the values available in the literature to reach a conclusion. Also, the benefits and drawbacks of these methods in determining the effective thermal conductivity are also discussed.

Fabrication of Test Specimens

The mineral casting technique is used to fabricate the test specimens. From the literature, it is detected that a mixture with aggregate to resin in the ratio 88:12 provides favourable mechanical properties [4,5]. Also, the use of different particle sizes of aggregate material classified into coarse, medium, and fine particles increases compactness providing higher strength compared to uniform size materials. Hence, in this study, the granite used as an aggregate in the mixture are crushed and classified into three sizes according to sieve analysis as (i) coarse particle size ranging between 1.25–2.25 mm, (ii) medium-size particles ranging from 0.5–1.25 mm, and (iii) fine particles less than 0.5 mm. The coarse, medium, and fine particles are selected in the ratio 50:25:25 of the total weight of filler material, which constitute 88 % of the total weight of aggregate used in the mixture. The remaining 12 % by weight is the binder (matrix) material, a mixture of epoxy resin (LY 556) and 1 % by weight of resin mixture as hardener (HY 951). The test specimen is cured at room temperature for better results.

Two square plates of size 300 × 300 × 25 mm, as shown in Fig. 1 are fabricated using mineral cast techniques to match the size of the heater plates used in the experimental setup as per ASTM C177-97 [15], and ISO standards [16] are used for conducting steady-state analysis. A wooden mould with the required inner dimensions is used for fabricating the rest of the specimens. The aggregate and resin material selected in the pre-determined ratio are mixed thoroughly and poured into the wooden mould box attached to a concrete shaker. The shaker helps for compact packing of particles and removal of the air trapped between them.

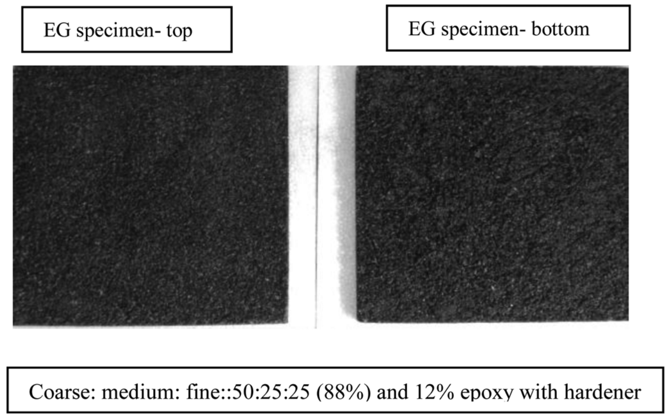


FIG. 1—*Epoxy granite (EG) test specimen for steady-state method.*

Two cylindrical blocks with radius 35 mm and thickness 12.80 mm are fabricated to determine the effective thermal conductivity of the material using a TPS method as shown in Fig. 2 [17,18]. To reduce the contact errors of the thermocouple, a 2 mm sheath is placed at the centre of the bottom block. The thermocouple is inserted in the sheath and its tip touches the heater.

The mechanical properties of the material are found out experimentally by fabricating separate specimens. The tensile test is carried out in an electronic type, TUE-CN-100G, universal testing machine, and the tensile strength is determined. For conducting the tensile test, a dog bone-shaped test specimen having dimensions, 60 × 60 × 18 mm in the grip and 200 × 50 × 18 mm in the test area is fabricated and subjected to tensile test. From the stress–strain curves obtained using win tensile software the Young's modulus is determined. A conventional hydraulically operated compression testing machine is used for conducting the compression test. The 75 × 75 × 75 mm size cubical test specimen is fabricated and the compression test is carried out. The density of the material is maintained the same for the mineral cast test specimens fabricated. The mechanical properties determined experimentally are shown in Table 1.

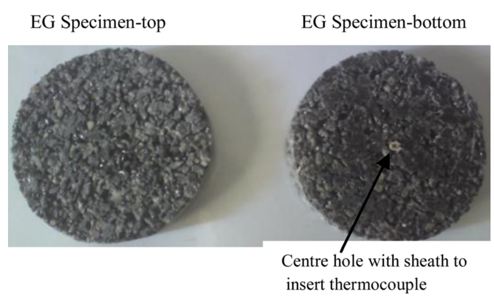


FIG. 2—*Test specimen for TPS method.*

TABLE 1—*Mechanical properties of epoxy granite material.*

Properties	Epoxy Granite
Density (kg/m)	2300
Young's modulus (GPa)	24
Compression strength (MPa)	51
Tensile strength (MPa)	6.3

Experimental Setup

Steady-State Method

The pictorial representation of the experimental setup and the photographic details of the stack in the apparatus are shown in Fig. 3. The apparatus is available in the fluid machinery lab and is used to determine the effective thermal conductivity of two-phase material using the steady-state method. The setup is designed similar to the specifications given by Karthikeyan and Reddy [19]. The uncertainty in measuring the thermal conductivity is determined as ±5.75 %. The apparatus accommodates the top and bottom part of the test specimen at the same time with symmetry across it. The test specimen is kept between hot and cold plates. The hot plate is embedded with a heating element and acts as the primary heater, supplying heat to the top and bottom part of the specimen. The heat input to the heater is given through an external DC supply.

A single phase, 230 V AC supply is used to provide heat input to secondary heaters embedded in the cold plate. The cold plate is maintained at a constant temperature during measurements by means of water-cooled coolant blocks kept above them. The whole stack consisting of hot plate, top and bottom part of specimen, cold plates, and coolant blocks are mounted on a supporting leg inside a rectangular box. The whole stack is completely covered with fiberglass wool having a density of 15–20 kg/m^3 and a thermal conductivity 0.03–0.04 W/mK, to reduce any lateral heat-transfer losses and to enhance steady one-dimensional heat-transfer flow between the plates. The temperature data are collected from the plates through K-type thermocouples connected to an external data-acquisition system (DAQ) with proportional integral derivative controllers (PID).

TPS Method

An experimental setup developed by Senthilkumar et al. [20] with a reliability of ±2.3 % is used to determine effective thermal conductivity of the material using the TPS method. The pictorial representation of the experimental setup is shown in Fig. 4.

The apparatus consists of:

(a) A sample container consisting of two cylindrical wooden blocks, which holds the test specimen. The inner surfaces of the containers are well insulated with glass wool to avoid lateral heat-transfer losses.

(b) A heater made up of Nichrome metal wire wound into the double spiral shape and well supported by a polymer film called "Kapton" is used. Kapton has a density of 1420 kg/m^3, thermal conductivity of 0.12 W/mK, and electrical resistivity of 100×10^6 Ω-m, gives good electrical insulation, and mechanical strength to the heating coil. The heater is sandwiched between the test specimens.

(c) An iron–constantan metallic, J-type thermocouple (273 to 973 K) is used to measure the temperature. The

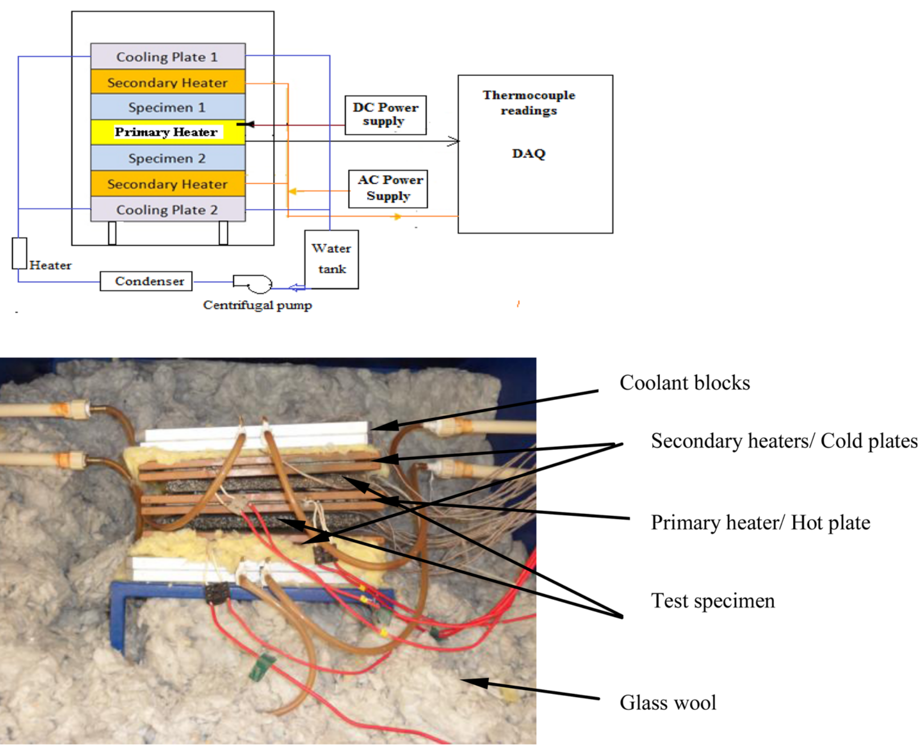
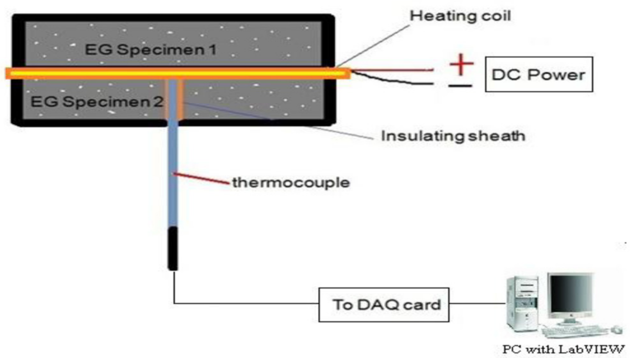


FIG. 3—*Experimental setup for steady-state method.*



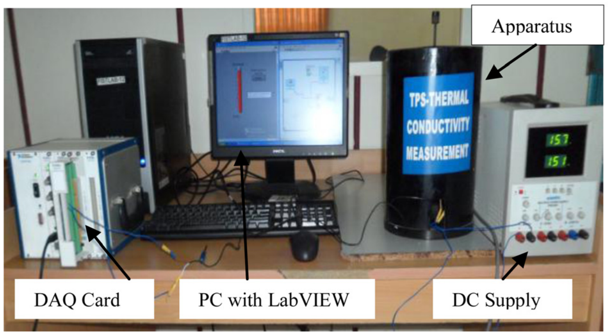


FIG. 4—*Experimental setup for TPS method.*

thermocouple is fixed firmly and its tip touches the middle of the spiral heater through a sheath at the center of the bottom sample. The sheath is provided between the thermocouple and the specimen to avoid any contact errors between them.

(d) The thermocouple is interfaced with a computer through an SCXI 1303 data-acquisition (DAQ) system that records the data on a computer directly with a minimum error of ±0.15 % as per the manufacturer specifications.

(e) LabVIEW software installed on the computer is programmed to collect the temperature data from the thermocouple and stores the data every 30 seconds.

(f) A PSD 3304 DC power supply is used to provide heat input to the heater.

Using the time and temperature data collected, a graph is plotted between ln (time) versus temperature. Using the slope of the curve plotted, the effective thermal conductivity is determined.

Results and Discussion

Steady-State Method

The apparatus designed to measure the thermal conductivity of low-density fibrous insulation materials and high-density insulation plates has been used to evaluate the effective thermal conductivity of the mineral cast epoxy granite material at 323 K having properties as given in Table 1. At steady-state conditions assuming one-dimensional heat transfer from the primary heater to the test specimens, the effective thermal conductivity is calculated for the material using the one-dimensional Fourier law [21] given by Eq 1.

$$P_0 = k_{\text{eff}} \cdot A \cdot \left[\frac{dT}{dx}\right] \tag{1}$$

where P_0 is heat supplied per plate (W), k_{eff} is effective thermal conductivity (W/mK), A is area of the test sample (m^2), dT is temperature difference between the hot and cold plates (K), and dx is thickness of the test specimen (m).

The effective thermal conductivity calculated from the experiment conducted at room temperature 301 K is given in Table 2. The average effective thermal conductivity for the material obtained is 2.1 ± 5.75 % (W/mK).

Transient Plane Source Method

The temperature measured by the thermocouple is noted down for every 30 seconds. The output from the LabVIEW program is used for thermal conductivity calculations. From the time (x) temperature (T) values are obtained, a graph is plotted between ln(x) versus T and the slope of the graph at the required temperature is found out.

The heat-conduction equation for an isotropic material independent of temperature is given by Eq 2 [21]:

$$\alpha \nabla^2 T + \frac{Q}{\rho c} = \frac{\partial T}{\partial t} \tag{2}$$

where α is the thermal diffusivity, Q (x,y,z,t) is the amount of heat released at (x,y,z and time, t) per unit volume, time $T(x,y,z,t)$ is the temperature at any point (x,y,z,t), and ρ and c are the density and specific heat of the material, respectively.

According to the transient plane source theory, based on which the apparatus is designed, for a disc-shaped sensor, the equation to determine effective thermal conductivity and diffusivity is derived from Eq 2 and is given in Eq 3 [22,23],

TABLE 2—*Effective thermal conductivity from experimental methods.*

	Steady-State Method			TPS Method		
Sl. No.	Heat Input (W)	ΔT (K)	Effective Thermal Conductivity, $k_{\text{eff}} \pm 5.75\%$ (W/mK)	Heat Input (W)	Slope	Effective Thermal Conductivity, $k_{\text{eff}} \pm 2.3\%$ (W/mK)
1	148.702	10	2.07	1	1.9145	2.68
2	152.112	10	2.11	0.99	1.9049	2.67
3	147.512	10	2.05	0.98	1.8830	2.67
4	151.608	10	2.11	1	1.8937	2.71
5	156.812	10	2.18	0.99	1.8881	2.69

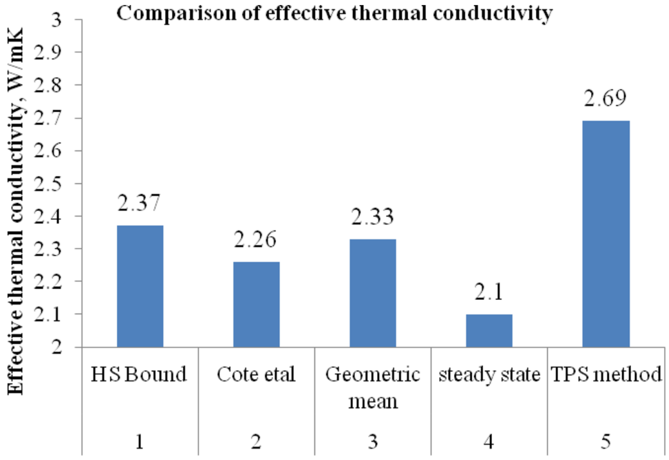


FIG. 5—*Error regions in TPS method.*

$$\Delta T_{\mathrm{ave}}(\tau) = \left[\frac{P_0}{\pi^{3/2} \cdot a \cdot k_{\mathrm{eff}}}\right] D(\tau) \tag{3}$$

where P_0 is total output power (W), k_{eff} is effective thermal conductivity of two-phase material (W/mK), a is radius of heating coil (m), and $D(\tau)$ is a dimensionless time-dependent function with time.

A computational straight line plot is made between the recorded temperature increase versus $D(\tau)$ that intercepts at ΔT_i. The slope given by Eq 4 is measured at experimental times much longer than Δt_i for accurate measurements.

$$\text{Slope} = \left[\frac{P_0}{\pi^{3/2} \cdot a \cdot k_{\mathrm{eff}}}\right] \tag{4}$$

Knowing the amount of heat supplied and the slope of the graph, the effective thermal conductivity is calculated.

The error region that is to be avoided while selecting the slope is shown in Fig. 5. The graph is an S-shaped curve with initial lag error and axial error regions. The initial lag error occurs because of the lag in temperature response as a result of the heat-transfer coefficient between the surface of heat source and testing material. The axial error occurs at higher temperatures at which the heat wave is absorbed or reflected by the testing material in axial direction. The slope of the curve, obtained after neglecting these error regions, is used to determine the thermal conductivity of the material. A trial and error method is adopted to determine the slope corresponding to the selected temperature, such that the values of thermal conductivity calculated from the slope is repeated within 2 % error limit [12,14].

The experiment is repeated five times and the effective thermal conductivity calculated are given in Table 2. The average value of effective thermal conductivity for the material is found to be $2.69 \pm 2.3\,\%$ (W/mK).

Theoretical Models

Three theoretical models given below are used to assess the experimental values of effective thermal conductivities:

(a) The Hashin-Shitrikman (H-S) bounds for thermal conductivity of two-phase material are calculated using Eqs 5 and 6 [12].

For $k_2 \geq k_1$

$$k_l = k_1 + \left\{\frac{x_2}{[(1/(k_2 - k_1)) + (x_1/3k_1)]}\right\} \tag{5}$$

$$k_u = k_2 + \left\{\frac{x_1}{[(1/(k_1 - k_2)) + (x_2/3k_2)]}\right\} \tag{6}$$

where k_1 and k_2 are the thermal conductivities of epoxy and granite materials, respectively, and x_1 and x_2 ($x_2 = 1 - x_1$) are the volume fraction of epoxy resin in the sample.
The upper and lower bounds are calculated by taking thermal conductivity for epoxy as 0.363 W/mK as per the data given by the manufacturer and for the granite as 3 W/mK.

(b) Correlation given by Cote et al. [24] is given in Eq 7:

$$k = \frac{(k_{2p} \cdot k_s - k_f)(1 - n) + k_f}{1 + (k_{2p} - 1)(1 - n)} \tag{7}$$

where k_{2p} is the fluid to solid thermal conductivity ratio given by

$$k_{2p} = 0.29\left(\frac{15k_f}{k_s}\right)^{\beta}$$

and k_f and k_s are the thermal conductivity of fluid and solid, respectively, and β is the empirical parameter accounting for structure effects on thermal conductivity.

(c) The geometric mean formula [24] is given by Eq 8:

$$k = (k_s)^{(1-n)} k_f^n \tag{8}$$

where n is the epoxy content in the mixture.

The effective thermal conductivity values obtained from the steady-state, TPS method, and from the geometric models are compared in Fig. 6.

Comparison of Test Methods

The effective thermal conductivity obtained from the steady-state method ($2.10 \pm 5.75\,\%$, W/mK) is 11.4 % less compared to HS bound average value, 7.1 % less compared to the value of Cote et al., and 9.9 % less compared to the geometric mean model. The percent error in effective thermal conductivity obtained from the

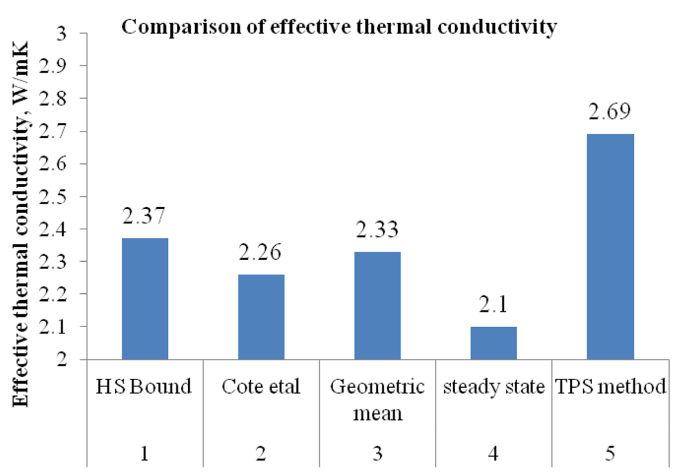


FIG. 6—*Comparison of thermal conductivity with other theoretical models.*

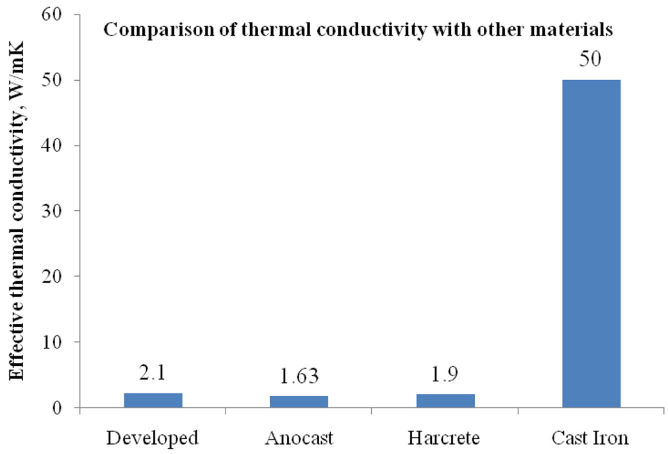


FIG. 7—*Comparison of thermal conductivities with other materials.*

steady-state method could be because of considerable lateral heat-transfer losses from the heater to the surroundings. These losses can be reduced by using a guarded plate around the stack [19].

The effective thermal conductivity determined using the TPS method (2.69 ± 2.3 %, W/mK) is 13.5 %, 19 %, and 15.5 % higher compared to HS bound, Cote et al., and geometric mean models, respectively. The difference in thermal conductivity could be because of considerable heat losses in the lateral direction.

The steady-state method and the transient plane source method are found to be useful in determining effective thermal conductivity for two-phase materials within the error limit. The steady-state method will give more accurate values if measures are taken to reduce the lateral heat-transfer losses. The steady-state method is found to be a more time- and material-consuming technique. The TPS technique is observed as a faster technique with a small size test material. The selection of slope is a tedious task and needs expertise to obtain the effective thermal conductivity within limits.

The lower value of thermal conductivity obtained from experimental methods for the developed material (2.1 W/mK) is compared with some of the manufacturers producing similar material and shown in Fig. 7. The thermal conductivity for the developed material is higher than Anocast's silica-filled epoxy polymer composite (1.63 W/mK) with 92 % silica and 8 % epoxy [25] and that of Hardinge's Harcrete [26].

It is required to conduct further studies to determine transport properties such as thermal diffusivity of the material to find the specific heat capacity of the epoxy granite material through experiments.

Conclusions

The steady-state and TPS methods are found to be useful reliable methods in determining effective thermal conductivity for two-phase materials. The effective thermal conductivity of the epoxy granite is found to vary in the range 2–3 W/mK, that is much less than that of conventional cast iron (50 W/mK) and closer to other commercial polymer composites like Anocast's silica filled polymer concrete (1.63 W/mK) and Hardinge's Harcrete (1.9 W/mK). The high thermal conductivity of the epoxy granite material compared to other polymer concrete materials will permit more energy transport through the material-reducing thermal error caused because of structural deflections between machine tool components. Compared to the TPS method, the steady-state method gives more accurate results though it is a slow, time-consuming technique. The accuracy of the steady state-method can be further increased by adopting suitable methods to reduce the lateral heat-transfer losses.

Acknowledgments

The experimental setup is supported by the Fluid Mechanics Lab, Department of Mechanical Engineering, PSG College of Technology, Coimbatore, Tamil Nadu, India.

References

[1] Siddhpura, M. and Paurobally, R., "A Review of Chatter Vibration Research in Turning," *Int. J. Machine Tools Manuf.*, Vol. 61, 2012, pp. 27–47.

[2] Lee, D. G., Suh, J. D., Kim, H. S., and Kim, J. M., "Design and Manufacture of Composite High Speed Machine Tool Structures," *Comp. Sci. Technol.*," Vol. 64, 2004, pp. 1523–1530.

[3] Suh, J. D. and Lee, D. G., "Design and Manufacture of Hybrid Polymer Concrete Bed for High-Speed CNC Milling Machine," *Int. J. Mech. Mater. Des.*, Vol. 4, 2008, pp. 113–121.

[4] Kim, H. S., Park, K. Y., and Lee, D. G., "A Study on the Epoxy Resin Concrete for the Ultra-Precision Machine Tool Bed," *J. Mater. Proc. Technol.*, Vol. 48, 1995, pp. 649–655.

[5] Mani, P., Gupta, A. K., and Krishnamoorthy, S., "Comparative Study of Epoxy and Polyester Resin-Based Polymer Concretes," *Int. J. Adhes. Adhes.*, Vol. 7(3), 1987, pp. 157–163.

[6] Orak, S., "Investigation of Vibration Damping on Polymer Concrete With Polymer Resin," *Cement Concrete Res.*, Vol. 30, 2000, pp. 171–174.

[7] Piratelli-Filho, A. and Shimabukuro, F., "Characterisation of Compression Strength of Granite-Epoxy Composites Using Design of Experiments," *Mater. Res.*, Vol. 11(4), 2008, pp. 399–404.

[8] Piratelli-Filho, A. and Neto, F. L., "Behaviour of Granite Epoxy Beams Subjected to Mechanical Vibrations," *Mater. Res.*, Vol. 13(4), 2010, pp. 497–503.

[9] Chen, J. S., "A Study of Thermally Induced Machine Tool Errors in Real Cutting Conditions," *Int. J. Tools Manuf.*, Vol. 36(12), 1996, pp. 1401–1411.

[10] Rodriguez-Perez, M. A., Reglero, J. A., Lehmhus, D., Wichmann, M., de Saja, J. A., and Fernandez, A., "The Transient Plane Source Technique (TPS) to Measure Thermal Conductivity and Its Potential as a Tool to Detect in-Homogeneities in Metal Foams," International Conference on Advanced Metallic Materials, Smolenice, Slovakia, Nov 5–7, 2003, pp. 253–257.

[11] Bentz, D. P., "Combination of Transient Plane Source and Slug Calorimeter Measurements to Estimate Thermal Properties of Fire Resistive Materials," *J. Test. Eval.*, Vol. 35(3), 2007, pp. 1–5.

[12] Bentz, D. P., "Transient Plane Source Measurements of the Thermal Properties of Hydrating Cement Pastes," *Mater. Struct.*, Vol. 40, 2007, pp. 1073–1080.

[13] Bentz, D. P., Peltz, M. A., Herrera, A. D., Valdez, P., and Juarez, C. A., "Thermal Properties of High Volume Flyash Mortars and Concretes," *J. Build. Phys.*, Vol. 34(3), 2011, pp. 263–275.

[14] Al-Ajlan, S. A., "Measurements of Thermal Properties of Insulation Materials by Using Transient Plane Source Technique," *Appl. Therm. Eng.*, Vol. 26, 2006, pp. 2184–2191.

[15] ASTM C177, 1997, "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transition Properties by Means of the Guarded Hot Plate Apparatus," *Annual Book of ASTM Standards*, Vol. 4-06, ASTM International, West Conshohocken, PA, pp. 21–42.

[16] ISO 8302, 1991, "Thermal Insulation—Determination of Steady-State Area Thermal Resistance and Related Properties—Guarded Hot Plate Apparatus," International Organization for Standardization, Geneva, Switzerland.

[17] Naito, K., Inaba, H., and Noda, Y., "Technical Report: Measurement of Thermal Conductivity and Diffusivity by Means of Scanning Temperature Method," *J. Nucl. Sci. Technol.*, Vol. 13(9), 1976, pp. 508–516.

[18] Senthilkumar, A. P., Karthikeyan, P., Prabhuraja, V., and Selvakumar, B., "Experimental Comparison Study between Line Heat Source and Plane Heat Source Method to Estimate the Thermal Conductivity of Two-Phase Materials," *Int. J. Eng.*, Vol. 10(1), 2012, pp. 239–242.

[19] Karthikeyan, P. and Reddy, K. S., "Absolute Steady-State Thermal Conductivity Measurement of Insulation Materials Using Square Guarded Hot Plate Apparatus," *J. Energy, Heat Mass Trans.*, Vol. 30, 2008, pp. 273–286.

[20] Senthilkumar, A. P., Prabhuraja, V., and Karthikeyan, P., "Estimation of Effective Thermal Conductivity of Two Phase Materials Using Line Heat Source Method," *J. Sci. Ind. Res.*, Vol. 69, 2010, pp. 872–878.

[21] Incropera, F. P. and Dewitt, D. P., *Fundamentals of Heat and Mass Transfer*, 5th ed., Wiley, Singapore, 2005.

[22] Nandi, A. K., Cingi, C., Datta, S., and Orkus, J., "Experimental Investigation on Equivalent Properties of Particle Reinforced Silicone Rubber: Improvement of Soft Tooling Process," *J. Reinf. Plast. Comp.*, Vol. 30(17), 2011, pp. 1429–1444.

[23] Suleiman, B. M., *Advances in Composite Materials—Eco-Design and Analysis*, InTech, New York, 2011, pp. 625–642.

[24] Cote, J., Fillion, M. H., and Konrad, J. M., "Estimating Hydraulic and Thermal Conductivities of Crushed Granite Using Porosity and Equivalent Particle Size," *J. Geotech. Geo-Environ. Eng.*, Vol. 137, 2011, pp. 834–842.

[25] "MatWeb Material Property Data," 2013, http://www.matweb.com (Last accessed 4 Feb 2013).

[26] Kushnir, E. F., Patel, M. R., and Sheehan, T. M., "Material Consideration in Optimization of Machine Tool Structure," *Proceedings of 2001 ASME International Mechanical Engineering and Exposition*, New York, Nov 11–16, 2001, pp. 1–12.