International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 6 (2018) pp. 3784-3788
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Comparison of Thermal Conductivity Experimental Results of SIC_P/AL_2O_3 Ceramic Matrix Composites with Mathematical Modeling

Dr. Malkapuram Devaiah[1]

[1]Department of Mechanical Engineering, Geethanjali College of Engineering and Technology,
Cheeryal (V), Keesara (M), Medchal Dist. 501301, Telangana, India.
Corresponding Author

Abstract

DIMOX processed SiC_p/Al_2O_3 Ceramic Matrix Composites of dimensions measuring 70 × 70 × 20, in mm with varying SiC volume fraction. The experimental result of $SiCp/Al_2O_3$ composites such as thermal conductivity property is compared with Mathematical models predictions.

In this paper, different mathematical model predictions such as Rule-of-mixture for heat flow parallel to layers (parallel ROM), Rule-of-mixture for heat flow parallel to layers (normal ROM) and Maxwell's model are used to determine the thermal conductivity property values of SiC_p/Al_2O_3 composites with varying SiC volume fraction in the range of 0.35 to 0.43, the results of mathematical model predictions are compared with experimental values of DIMOX processed SiC_p/Al_2O_3 composites with different volume fractions of SiC. The experimental results of SiC_p/Al_2O_3 have relatively good agreement with the model prediction of normal Rule-of Mixture (ROM).

Keywords: Ceramic Matrix Composites, Al_2O_3, SiC, Mathematical models, thermal Conductivity.

INTRODUCTION

Ceramics have excellent strength-to-weight ratio when compared to advanced metals and alloys. These attractive properties can also be maintained to extremely high temperature, which make them a sole choice for high temperature applications. A variety of structural applications of ceramic materials ranging from high temperature gas turbines and adiabatic diesel engines to cutting tools and other wear-resistant parts. In each of the said applications, beneficial properties of ceramics such as high stiffness, strength and hardness, low density, and good resistance to corrosion, oxidation, and wear at high temperatures have been explored. With the ever-increasing performance requirements of engineering materials, the properties of monolithic materials are pushed to their limits. Monolithic ceramics possess high strength but lack the fracture toughness, required in many applications, such as components in jet engines. Ceramic materials have properties that make them ideal candidates for many elevated temperature applications such as heat exchangers and turbine engines components. Due to the refractory nature of ceramics, they are, at times, the sole selection for a material that may probably satisfy the foremost hard-to-please necessities significantly at high temperatures. In addition to giving high melting or decomposition temperatures, several ceramics posses different enticing options like low density, warm temperature strength, high hardness and resistance to creep deformation, thermochemical stability and lack of reactivity in-tuned with different materials and varied atmospheres, and, last, however not least, high wear resistance

In this paper, validation of SiC_p/Al_2O_3 composites fabrication through directed metal oxidation process, and its mechanical and physical properties was modeled which had been experimentally tested and reported by devaiah *et al*. [7]. This is followed by a comparison of the finite element with experimental results on SiC_p/Al_2O_3 composites fabrication through directed metal oxidation process in the following study.

A.S. Nagelberg *et al*. studied thermal conductivity of SiC particulate reinforced alumina matrix composites fabricated by directed metal oxidation process. The conductivity of the composites varies between 70 $W/m.^0K$ - 20 $W/m.^0K$ for temperatures 25°C to 1000°C. They also, reported the thermal conductivity of 2-D Nicalon/alumina composites produced by directed metal oxidation process. The conductivity of the composites varies between 8.7 $W/m.^0K$ to 5.5 $W/m.^0K$, for temperatures between 100°C to 1200°C [1]. M. Belmonte *et al*. report thermal conductivity of Al_2O_3/20 vol.% SiC composites prepared by hot pressing at 1500°C as a function of SiC grain size. The thermal conductivity was measured by the laser flash method was falls in the range of 17.10 to 31.0 $W/m.^0K$ at room temperature to 500°C [2]. L. Fabbri *et al.* reported that the thermal conductivity of Al_2O_3/SiC_w composites is slightly greater than pure Al_2O_3, and the highest value reported for Al_2O_3 -30 vol. % SiC_w composites at levels of 40 $W/m.^0K$ [3]. Marianne. I.K Collin *et al.* indicated thermal conductivity of Al_2O_3 -30 vol. % SiC_w prepared by hot pressing process in a protective atmosphere of pressure 25 MPa and temperature of 1850°C for 60 min. the conductivity was falls in the range of 24 - 34 $W/m.^0K$ [4]. Rafael Barea *et al.* studied thermal conductivity of hot pressed 0 - 30 vol.% of SiC/Al_2O_3 platelet composites. The conductivity measured as a function of the platelet content was varying in the range of 42 - 49 $W/m.^0K$ [5]. In the present work, the thermal conductivity of directed metal oxidation processed SiC particulate reinforced Al_2O_3 matrix composites is evaluated as a function of SiC volume fraction. The thermal conductivity of the SiC particulates has been estimated from the composite data and compared to published values for SiC.

EXPERIMENTAL WORK

Thermal conductivity is a physical property of a substance and characterizes the ability of the substance to transfer heat. It determines the quantity of heat flowing per unit of time per unit area at a temperature drop of 1°C per unit length. Thermal conductivity of materials can be measured using either a direct (steady state) or a transient approach. A steady-state technique was used for the thermal conductivity measurements. The technique employs a Comparative – Guarded-Axial Heat Flow system as shown in Figure 3.21, to determine the thermal conductivity of a sample using a variation of ASTM 1225-99 [6]. In this approach, a specimen of unknown thermal conductivity is sandwiched between two materials with known thermal conductivities. By applying heat in the direction perpendicular to the material interfaces and measuring the temperature along the length of the three materials, the heat flow, q, may be inferred and used to determine the thermal conductivity of an unknown specimen since:

$$q = -kA\frac{\Delta T}{\Delta x}$$

$$\lambda_S = \frac{(q_{top} + q_{bottom}) \cdot (Z_4 - Z_3)}{2 \cdot (T_4 - T_3)}$$

λ_M (T) = Conductivity of meter bars as a function of T;

λ_M top = Conductivity of top bar ;

λ_M bm = Conductivity of bottom bar ;

λ_S (T) = Conductivity of specimen ;

$\lambda_{S(1)}$ (T) = Conductivity of specimen ;

λ_I (T) = Conductivity of insulation;

r_A = Specimen radius ;

r_B = Guard cylinder inner radius;

T_g (Z) = Guard temperature as a function of position.

Where q is the conducted thermal power (W), k is the thermal conductivity (W/m K), A is the cross-sectional area that the heat flows through (m^2), and $\Delta T/\Delta x$ is the temperature gradient (K/m) over the distance that heat flow is measured. In the approach used for this work, the temperature difference across a fixed, known distance of the substrate was measured using an IR microscope. This, in conjunction with the known thermal conductivity of the substrate material and equation (2) was used to calculate q; the thermal conductivity of the ceramic material could then be determined by measuring $\Delta T/\Delta x$ across the thickness of the ceramic. The observed variation in the coefficient of thermal expansion was further compared with experimental results available in the literature and also the experimental results are examined with mathematical models.

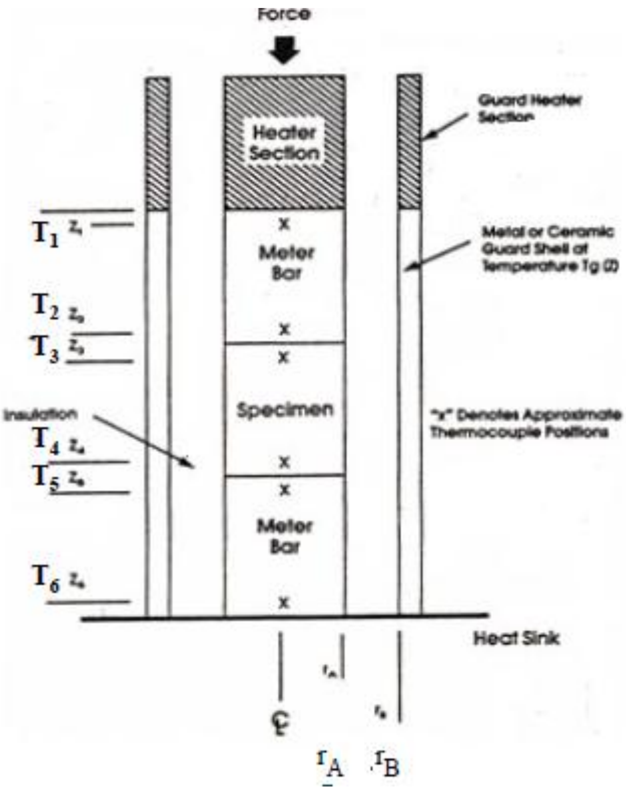

Figure 1: Schematic of a comparative – Guarded-Axial Heat Flow System (ASTM standards 1999, E 1225, P.437).

RESULTS AND DISCUSSION

In the present work, SiC_p/Al_2O_3 composites with different volume fractions were prepared by directed metal oxidation process. This was comprised of two steps namely preparation of SiC preforms with different volume fraction and appropriate heat treatment schedule to aid formation of Al_2O_3 matrix as figure 1. The volume fraction of SiC was varied by using SiC particulates of different grit sizes namely # 100, # 120 and # 220 [7],. The SiC_p/Al_2O_3 composites fabrication as mentioned in [7], the thermal conductivity property from experimental work are compared with Mathematical models predictions.

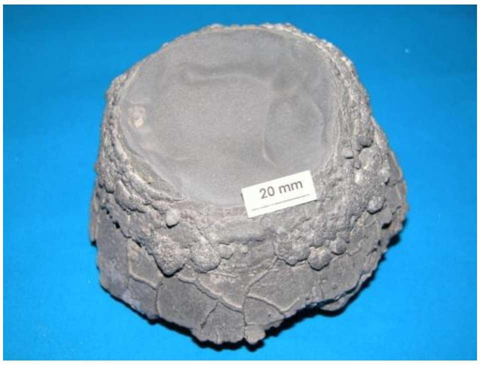

Figure 1: A large specimen of SiC_p/Al_2O_3 composite prepared by directed metal oxidation process in a conical shape. We note that the SiC_p/Al_2O_3 composite thus obtained has the shape of the mould.

In the present work, it was aimed to study the physical properties of SiC_p/Al_2O_3 ceramic matrix composites with different volume fractions of SiC_p. SiC_p/Al_2O_3 ceramic matrix composites in their as-prepared condition with different shapes are shown in Figure 1. From the figure it can be observed that the composite has grown almost to the dimensions of the containers used. Moreover, the dimensions of the composite material fabricated by the DIMOX process in this work are large enough to facilitate measurements of various physical and mechanical properties. The growth of the composite was found to be complete with a hollow left back in the metal reservoir. Thus, it can be said that the processing schedule employed in the present work was successful in the fabrication of bulk SiC_p/Al_2O_3 ceramic matrix composites. It is necessary to ensure that the material has a minimum amount of defects/voids formed as a consequence of the processing technique. Before proceeding further to evaluate various physical properties of SiC_p/Al_2O_3 composites such as coefficient of thermal expansion (α), ultrasonic velocity (V) and thermal conductivity (λ), the material was evaluated for its density and porosity.

3.1. Thermal Conductivity

Thermal conductivity of SiC_p/Al_2O_3 matrix composites was obtained from measurements of Comparative Guarded-Axial Heat Flow System. Figure 2 shows specimens measuring 25 mm diameter and 5 mm thick which were machined out of a block of ceramic matrix composite, used for thermal conductivity measurement. Resulting thermal conductivity values are listed in Table 1.

Figure 2: Samples used for thermal conductivity measurements

Table 1. Average thermal conductivity of SiC_p/Al_2O_3 ceramic matrix composites

Label	SiC Volume Fraction	Thermal Conductivity (W/m.^{0}K)
B1	0.35	25
B2	0.40	29
B3	0.43	35

Figure 3 depicts the thermal conductivity versus temperature plots for the SiC reinforced Al_2O_3 matrix composites tested on the Comparative Guarded-Axial Heat Flow System at all temperatures between 50°C – 300°C. For each composite, the thermal conductivity slightly decreases with temperature. The thermal conductivity values are found to be in the range of 25 W/m.^{0}K - 35 W/m.^{0}K for SiC volume fractions between 0.35 – 0.43.

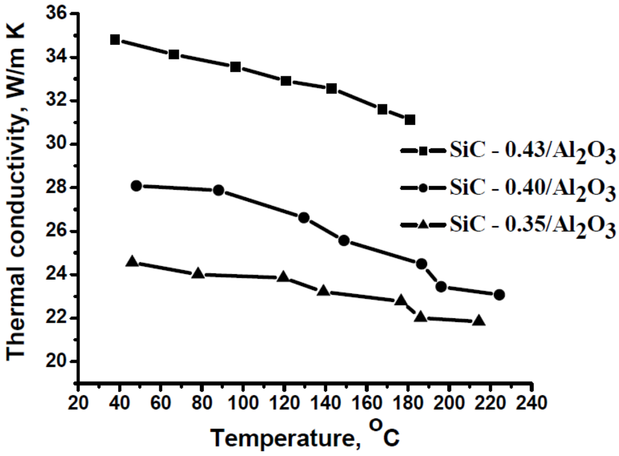

Figure 3: Variation in Thermal Conductivity of SiC_p/Al_2O_3 ceramic matrix composite as a function of temperature

The thermal conductivity of SiC/Al_2O_3 increases as a function of SiC volume fractions as shown in Figure 4. A maximum K value of 35 W/m.^{0}K is reached at room temperature for SiC volume fraction 0.43.

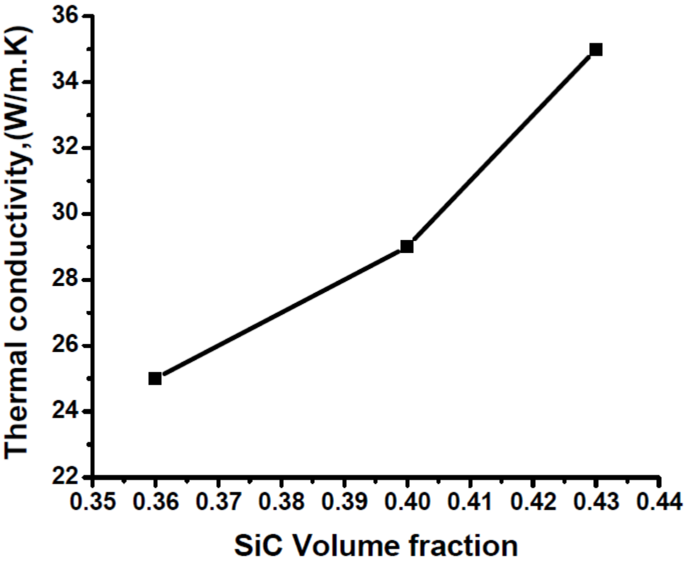

Figure 4 Variation in Thermal Conductivity of SiC_p/Al_2O_3 ceramic matrix composite as a function of SiC volume fraction

A.S. Nagelberg *et al*. studied thermal conductivity of SiC particulate reinforced alumina matrix composites fabricated by directed metal oxidation process. The conductivity of the composites varies between 70 W/m.^{0}K to 20 W/m.^{0}K for temperatures 25^{o}C to 1000^{o}C. They also reported the thermal conductivity of 2-D Nicalon/alumina composites produced by directed metal oxidation process. The conductivity of the composites varies between 8.7 W/m.^{0}K to 5.5 W/m.^{0}K, for temperatures between 100^{o}C - 1200^{o}C [1].

M. Belmonte *et al*. report thermal conductivity of Al_2O_3/20vol.% SiC composites prepared by hot pressing at 1500^{o}C as a function of SiC grain size. The thermal conductivity was measured by the laser flash method and falls in the range of 17.10 - 31.0 W/m.^{0}K from room temperature to 500^{o}C [2]. L. Fabbri *et al.* reported that the thermal conductivity of Al_2O_3/SiC_w composites is slightly greater than that of pure Al_2O_3, and the highest value reported for Al_2O_3 - 30 vol. % SiC_w composites was 40 W/m.^{0}K [3]. Rafael Barea *et al*. studied thermal conductivity of hot pressed 0 - 30 vol. % of SiC / Al_2O_3 platelet composites. The conductivity measured as a function of the platelet content varied in the range of 42 - 49 W/m.^{0}K [5]. Room temperature thermal conductivity values are also in agreement with data found in literature for SiC_p reinforced Al_2O_3 matrix composites (17.10 - 70 W/m.^{0}K) [4, 8] and SiC_w/ Al_2O_3 matrix composites(24 - 34 W/m.^{0}K, 40 W/m.^{0}K) [2, 9], other Al_2O_3 based composites (42 - 49 W/m.^{0}K) [10];. The high thermal conductivity of 70 W/m.^{0}K at room temperature was reported by A.S. Nagelberg for SiC reinforced alumina composites with 48 vol. % of SiC and 13 vol. % of metal in the composite and than used #500 SiC. In the present work the highest value of conductivity is 35 W/m.^{0}K for V_f: 0.43, and used coarser SiC particulates as reinforcement. The thermal conductivity increases as volume fraction increases. A low value of thermal conductivity in the present work as compared to the inventor is due to lowest metal content, coarser SiC particulates or both.

The composites exhibited low coefficient of thermal expansion ranging between 5.81 – 5.0 x 10^{-6} /K and Young's modulus levels ranging between 207 and 262 GPa for SiC volume fraction between 0.35 and 0.43. The lower thermal expansion coefficient, low density, high modulus and relatively high thermal conductivity due to the presence of aluminum channels can make the material attractive for electronic packaging, and can competitive with the currently used KOVAR (CTE ~ 5.2 ppm/^{o}C, density ~ 8100 kg/m^3, thermal conductivity ~11-17 W/m.^{0}K) in some applications.

Validation of Experimental Results with Mathematical Modeling

The purpose of this paper is to compare experimental results on SiC_p/Al_2O_3 composites discussed in [7] with Mathematical models predictions. The Finite Element Method (FEM) is used for studying some of the problems. With the advancement of computers, finite element analysis [11] has become one of the most important tools available to an engineer for design. The finite element method is one of the most general procedures for solving complex analysis problems. For performing finite element analysis the material is considered to be isotropic in nature and the boundary conditions and load conditions applied are similar to those obtained in the experiments. Comparisons were made with the experimental results on the SiC_p/Al_2O_3 composites with different volume fractions of SiC.

Thermal Conductivity

The experimental data for thermal conductivity, accompanied by mathematical model predictions from earlier works in this direction are shown in Figure 5. Widely used models [12 - 13] for the prediction of thermal conductivity are listed in Table 2. Maxwell's model describes the behavior of composites consisting of the matrix randomly distributed and randomly sized spherical particles. The cube model considers the cermets as a set of square columns, some of which consist of metal and ceramic phases and others consist only of the metal phase. Columns that have metal-ceramic interfaces are taken as non-conductive. The experimental results for SiC_p/Al_2O_3 have relatively good agreement with the model prediction of normal ROM as shown in Figure 5.

Table 2. Model predictions for Thermal Conductivity of composite materials

Name of the Model	Model	Equation No.	Ref.
Rule-of-mixture for heat flow parallel to layers (parallel ROM)	$\lambda_c = \lambda_m V_m + \lambda_d V_d$	**5.11**	12
Rule-of-mixture for heat flow normal to layers (normal ROM)	$\lambda_c = \dfrac{\lambda_m \lambda_d}{\lambda_m V_d + \lambda_d V_m}$	**5.12**	13
Maxwell's model	$\lambda_c = \dfrac{2(1-V_d)+\lambda_d(1+2V_d)}{(2+V_d)+\lambda_d(1-V_d)}.$	**5.13**	14

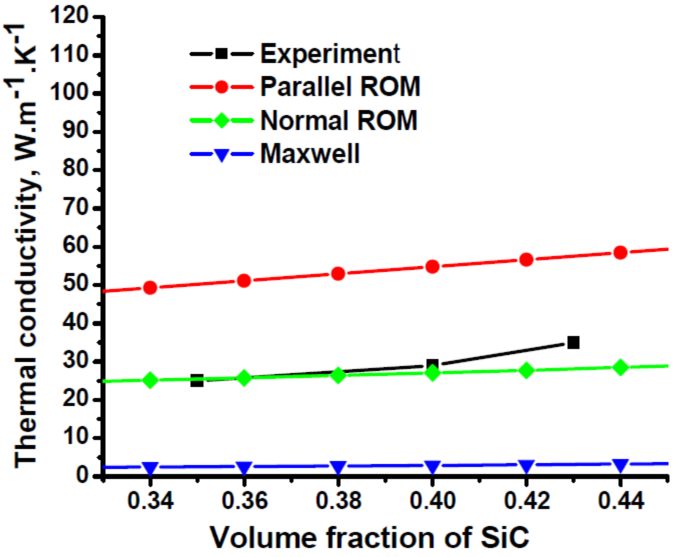

Figure 5: Comparison of the experimental results with models predictions for thermal conductivity of composite systems. Normal ROM models give good agreement with experiments.

CONCLUSIONS

The lower thermal expansion coefficient, low density, high modulus and possible high thermal conductivity due to the presence of aluminum channels can make the material attractive as an electronic packaging material, and competitive with the currently used KOVAR (CTE ~ 5.2 ppm/°C, density ~ 8100 kg/m^3, thermal conductivity ~11-17 W/m.^{0}K).

The thermal conductivity was found to be in the range of 25 W/ m.K - 35 W/ m. K for SiC volume fraction between 0.35 and 0.43. Finite element analysis has been used to calculate some of the properties of the composites and they are compared with the experimental values.

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