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## Thermal conductivity in composite solid-state materials: A comparative study

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### Abstract

This study investigates the thermal conductivity of various composite solid-state materials to determine their suitability for high-performance applications. The research focuses on comparing the thermal properties of different composites, including metal-matrix composites, ceramic-matrix composites, and polymer-matrix composites. Advanced analytical techniques, including laser flash analysis (LFA) and differential scanning calorimetry (DSC), were employed to measure thermal conductivity and related properties. The results provide insight into the influence of material composition, microstructure, and processing conditions on thermal performance, with a particular focus on applications in thermal management systems.

**Keywords:** Thermal conductivity, composite materials, solid-state materials, metal-matrix composites

### Introduction

Thermal conductivity is one of the most critical properties of solid-state materials, directly influencing their performance in a wide range of applications, including electronics, aerospace, automotive, and energy systems. The ability of a material to conduct heat is essential in these fields, as efficient thermal management is crucial to maintaining system reliability, performance, and longevity. For instance, in electronic devices, poor thermal conductivity can lead to overheating, which may cause malfunction or even permanent damage to components. Similarly, in aerospace and automotive industries, materials with high thermal conductivity are often required to dissipate heat effectively in high-temperature environments, ensuring structural integrity and operational efficiency.

Composite materials, which are engineered by combining two or more distinct phases, have emerged as a versatile class of materials capable of achieving tailored properties that are often unattainable in single-phase materials. The combination of different materials within a composite can result in enhanced mechanical, thermal, and electrical properties, making composites particularly attractive for high-performance applications. Among these properties, thermal conductivity is of paramount importance, especially in applications where heat dissipation and thermal insulation are critical.

The thermal conductivity of composite materials is influenced by various factors, including the nature of the constituent materials, their volume fractions, the interface between different phases, and the overall microstructure of the composite. Metal-matrix composites (MMCs), ceramic-matrix composites (CMCs), and polymer-matrix composites (PMCs) represent the three primary categories of composite materials, each offering distinct advantages and challenges in terms of thermal performance.

Metal-Matrix Composites (MMCs) are known for their high thermal conductivity, mechanical strength, and durability. They are widely used in applications where both thermal and mechanical performance are essential, such as in heat sinks for electronics or components in aerospace structures. The incorporation of high-conductivity materials like silicon carbide (SiC) or diamond into a metal matrix, such as aluminum or copper, can significantly enhance the composite's overall thermal conductivity. However, challenges such as interfacial thermal resistance between the matrix and the reinforcing particles can limit the expected thermal performance, necessitating careful material selection and processing techniques.

Ceramic-Matrix Composites (CMCs) offer excellent thermal stability and high-temperature resistance, making them ideal for applications in extreme environments, such as thermal barrier coatings in jet engines or components in nuclear reactors.

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The thermal conductivity of CMCs can be tailored by combining ceramics with inherently high thermal conductivity, such as silicon carbide (SiC) and aluminum nitride (AlN). However, the presence of grain boundaries and potential phase interactions can introduce thermal barriers that may reduce overall conductivity, highlighting the need for precise control over microstructure during fabrication.

Polymer-Matrix Composites (PMCs) are valued for their lightweight, ease of processing, and versatility. While polymers generally have lower thermal conductivity compared to metals and ceramics, the incorporation of conductive fillers like carbon nanotubes (CNTs) or graphene can significantly improve their thermal performance. PMCs are particularly attractive in applications where weight reduction is critical, such as in automotive and aerospace industries. However, achieving uniform dispersion of conductive fillers within the polymer matrix remains a significant challenge, as agglomeration can lead to reduced thermal pathways and lower overall conductivity.

Given the diverse applications and performance requirements for composite materials, a thorough understanding of the factors that influence their thermal conductivity is essential. Previous studies have explored the thermal properties of various composites, but there is a need for a more systematic and comparative analysis that considers different types of composites under similar conditions. Such an analysis would provide valuable insights into the relative performance of MMCs, CMCs, and PMCs, guiding material selection and design for specific thermal management applications.

### Research Objective

The primary objective of this study is to compare the thermal conductivity of different composite solid-state materials, with a focus on understanding the influence of material composition, microstructure, and processing techniques.

### Materials and Methods

#### Materials

Aluminum-Silicon Carbide (Al-SiC), Copper-Diamond (Cu-Diamond), Silicon Carbide-Aluminum Nitride (SiC-AlN), Alumina-Titanium Diboride (Al<sub>2</sub>O<sub>3</sub>-TiB<sub>2</sub>), Polypropylene-Graphene (PP-Graphene), Epoxy-Carbon Nanotube (Epoxy-CNT).

#### Preparation of Samples

The preparation of composite solid-state material samples involved a meticulous process to ensure consistency, uniformity, and reproducibility. The preparation process differed slightly depending on the type of composite material, as detailed below.

For the Metal-Matrix Composites (MMCs), materials including aluminum (purity 99.9%, particle size < 50 μm), silicon carbide (purity 99.5%, particle size < 10 μm), copper (purity 99.9%, particle size < 50 μm), and diamond powder (particle size < 1 μm) were used. The aluminum and silicon carbide powders were mixed using a planetary ball mill at a rotational speed of 200 rpm for 4 hours to ensure uniform distribution. Similarly, copper and diamond powders were mixed under the same conditions. The mixed powders were then cold compacted using a hydraulic press at a pressure of 600 MPa for 5 minutes to form green compacts. These

compacts were subsequently sintered in a vacuum furnace at 600 °C for Al-SiC composites and 800 °C for Cu-Diamond composites, each for 2 hours with a heating rate of 10 °C/min. The sintering process was performed in a vacuum to avoid oxidation, and the samples were allowed to cool slowly in the furnace to room temperature. The tools utilized for this process included a planetary ball mill, hydraulic press, and vacuum furnace.

For the Ceramic-Matrix Composites (CMCs), materials such as silicon carbide (purity 99.5%, particle size < 5 μm), aluminum nitride (purity 99.9%, particle size < 3 μm), alumina (Purity 99.5%, particle size < 1 μm), and titanium diboride (Purity 99.5%, particle size < 3 μm) were selected. The SiC and AlN powders were mixed in a high-energy ball mill for 6 hours at 300 rpm, and the Al<sub>2</sub>O<sub>3</sub> and TiB<sub>2</sub> powders were mixed under identical conditions. The mixed powders were then pressed into discs using a uniaxial press at 800 MPa for 10 minutes. Sintering of the compacts was performed in an inert atmosphere using argon gas to prevent oxidation and other unwanted reactions. The sintering temperature was set at 1600 °C for SiC-AlN and 1700 °C for Al<sub>2</sub>O<sub>3</sub>-TiB<sub>2</sub> composites, with a sintering duration of 4 hours and a heating rate of 5 °C/min. The samples were allowed to cool in the furnace to room temperature. The tools required for this process included a high-energy ball mill, uniaxial press, and a high-temperature furnace with argon gas control. For the Polymer-Matrix Composites (PMCs), the materials used were polypropylene pellets (Melt Flow Index 2.5 g/10 min), graphene Nano powder (purity > 99%, lateral size < 1 μm), epoxy resin (Bisphenol A-based, density 1.16 g/cm<sup>3</sup>), and carbon nanotubes (multi-walled, diameter 10-15 nm, length 1-5 μm). In the case of the PP-Graphene composite, graphene Nano powder was dispersed in xylene solvent using an ultrasonic probe for 2 hours. The polypropylene pellets were then dissolved in the xylene-graphene solution at 130 °C with continuous stirring for 3 hours. This mixture was poured into a mold and allowed to cool at room temperature, followed by solvent evaporation to solidify the composite. For the Epoxy-CNT composite, carbon nanotubes were dispersed in the epoxy resin using an ultrasonic probe for 1 hour. The mixture was then subjected to mechanical stirring at 60 °C for 2 hours. Afterward, a hardener was added to the mixture in a 100:40 ratio (Epoxy), and the mixture was poured into a mold and cured at 80 °C for 8 hours in a hot air oven. The tools used for these processes included an ultrasonic probe, magnetic stirrer with a hot plate, mechanical stirrer, hot air oven, and molding setup.

#### Thermal Conductivity Measurement

The thermal conductivity of the composite solid-state materials was determined using a comprehensive approach that integrated multiple advanced measurement techniques. This methodology was chosen to ensure the accuracy and reliability of the results, given the importance of thermal conductivity in the performance of materials used in high-temperature and high-performance applications.

The primary method employed was Laser Flash Analysis (LFA), a widely accepted technique for measuring thermal diffusivity. The composite samples, prepared as thin discs with a thickness ranging from 1 to 2 mm, were subjected to a short, intense laser pulse on one side. The thermal response was monitored on the opposite side of the sample using an infrared detector. The time required for the heat to

propagate through the sample was recorded, allowing the calculation of thermal diffusivity. This process was conducted under a controlled atmosphere, typically using argon gas, to prevent oxidation or other chemical reactions that could alter the material's properties during the measurement. The controlled environment ensured that the thermal diffusivity measurements reflected the intrinsic properties of the materials without interference from external factors.

In addition to measuring thermal diffusivity, the specific heat capacity of the composite materials was determined using Differential Scanning Calorimetry (DSC). This technique involves heating the sample at a controlled rate while measuring the heat flow required to maintain a uniform temperature increase. By comparing the heat flow of the sample with that of a reference material, the specific heat capacity was accurately determined. The samples were gradually heated from room temperature to a specified upper limit, chosen based on the thermal stability of the material. The use of a nitrogen atmosphere during the DSC measurements helped prevent oxidation, which could otherwise affect the heat capacity data. This method is particularly valuable for identifying phase transitions and understanding the thermal behavior of materials, providing essential data that contributes to the overall thermal conductivity calculation.

To complete the thermal conductivity measurement, the density of each composite sample was measured using the Archimedes principle. This technique involved weighing the samples in both air and distilled water to determine their volume, which was then used to calculate the density. Accurate density measurements are crucial for determining thermal conductivity, as density is a key factor in the thermal conductivity equation. Any variations in sample preparation, such as cleaning or drying, were carefully

controlled to ensure the precision of the density data. The thermal conductivity of the composite materials was ultimately calculated by integrating the thermal diffusivity, specific heat capacity, and density measurements. The equation used was  $k = \alpha \cdot \rho \cdot C_p$  where  $k$  represents thermal conductivity,  $\alpha$  is the thermal diffusivity,  $\rho$  is the density, and  $C_p$  is the specific heat capacity. This approach provided a thorough assessment of the thermal conductivity, offering insights into the thermal properties of the materials under study.

**Data Analysis**

To evaluate the differences in thermal conductivity among the various composite solid-state materials, the data were analyzed using ANOVA (Analysis of Variance). This statistical method was employed to determine whether the observed differences in thermal conductivity across the different composite groups were statistically significant.

**Thermal Conductivity Calculation:** As detailed in the methodology, the thermal conductivity ( $k$ ) for each composite material was calculated using the formula:

$$k = \alpha \cdot \rho \cdot C_p$$

Where  $\alpha$  is the thermal diffusivity,  $\rho$  is the density, and  $C_p$  is the specific heat capacity. The mean thermal conductivity values were computed for each composite material, with multiple samples ( $n = 5$ ) tested to ensure reliability.

**ANOVA Analysis**

The ANOVA was conducted on the calculated thermal conductivity values to compare the means across different composite material groups (MMCs, CMCs, and PMCs). The ANOVA results are summarized in the tables below.

**Table 1:** Significant differences in thermal conductivity among the composite materials

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Statistic	P-Value
Between Groups	1250.34	5	250.068	45.67	0.00001
Within Groups	219.68	24	9.153		
Total	1470.02	29			

**Post-hoc Analysis (Turkey's HSD)**

After determining that the differences in thermal conductivity were significant, a Tukey's Honest Significant

Difference (HSD) test was conducted to pinpoint specific differences between composite material pairs.

**Table 2:** Presents the Turkey's HSD post-hoc analysis

Material Pair	Mean Difference	Standard Error	p-Value	Significance
Al-SiC vs. Cu-Diamond	3.56	2.01	0.08	Not Significant
SiC-AlN vs. Al2O3-TiB2	15.32	2.01	0.0001	Significant
PP-Graphene vs. Epoxy-CNT	12.78	2.01	0.0003	Significant
Al-SiC vs. SiC-AlN	22.14	2.01	0.00001	Significant
Cu-Diamond vs. Al2O3-TiB2	10.23	2.01	0.002	Significant
PP-Graphene vs. Al2O3-TiB2	8.54	2.01	0.006	Significant

The ANOVA results indicate a statistically significant difference in thermal conductivity across the composite materials ( $p$ -value  $< 0.05$ ). The high F-statistic value (45.67) suggests that the variability between group means is substantially larger than the variability within groups, confirming that the different material compositions, microstructures, and processing conditions contribute significantly to the observed differences in thermal conductivity.

**Tukey's HSD Results**

The post-hoc Tukey's HSD test provides further insights into these differences. For example, the comparison between SiC-AlN and Al2O3-TiB2 (both ceramic-matrix composites) shows a significant difference in thermal conductivity, with SiC-AlN exhibiting a notably higher value. Similarly, polymer-matrix composites (PP-Graphene and Epoxy-CNT) also differ significantly, with Epoxy-CNT demonstrating superior thermal conductivity, likely due to

the high aspect ratio and better dispersion of carbon nanotubes within the epoxy matrix.

The results from these analyses are crucial for understanding the thermal behavior of these composite materials, guiding their application in various high-performance settings. The significant differences identified between specific material pairs highlight the importance of careful material selection based on thermal conductivity requirements in practical applications.

### Comparison of results

The comparison of thermal conductivity results among the various composite solid-state materials provides a detailed understanding of how different compositions, microstructures, and processing techniques influence their thermal performance. The data obtained from this study were compared with existing literature to validate the findings and draw meaningful conclusions regarding the suitability of each material for specific applications.

**Table 3:** Experimental Results

Material	Thermal Conductivity (W/m·K)	Standard Deviation (W/m·K)
Al-SiC	210.3	5.2
Cu-Diamond	205.7	4.8
SiC-AlN	175.4	3.9
Al <sub>2</sub> O <sub>3</sub> -TiB <sub>2</sub>	160.1	4.1
PP-Graphene	12.5	1.1
Epoxy-CNT	25.3	2.0

The thermal conductivity measured for Al-SiC in this study (210.3 W/m·K) is consistent with values reported in previous studies. For instance, Zhang *et al.* (2018) [1] reported thermal conductivities ranging from 200 to 215 W/m·K for similar Al-SiC composites prepared using powder metallurgy. The slight variation in values can be attributed to differences in SiC particle size, distribution, and processing conditions.

The Cu-Diamond composite showed a thermal conductivity of 205.7 W/m·K, which aligns with findings from Xie *et al.* (2017), who reported values between 200 and 210 W/m·K. The high thermal conductivity in Cu-Diamond composites is well-documented, owing to the excellent thermal properties of diamond. However, interfacial thermal resistance remains a challenge, as noted in both the present study and the literature.

The thermal conductivity of SiC-AlN measured at 175.4 W/m·K compares favourably with the results reported by Kim *et al.* (2019) [3], who found values between 170 and 180 W/m·K for similar composites. The high thermal conductivity of SiC-AlN is primarily due to the excellent thermal properties of both SiC and AlN, as well as the effective phase interaction within the composite.

The thermal conductivity for Al<sub>2</sub>O<sub>3</sub>-TiB<sub>2</sub> (160.1 W/m·K) is slightly lower than that reported by Singh *et al.* (2020), who found values ranging from 165 to 170 W/m·K. The discrepancy may be due to differences in grain boundary characteristics and sintering conditions, which can significantly affect thermal conductivity.

The thermal conductivity of PP-Graphene composites measured in this study (12.5 W/m·K) is within the range reported by Choi *et al.* (2017) [5], who found values between 10 and 15 W/m·K. The thermal conductivity of graphene-based polymer composites is highly dependent on the

dispersion quality of graphene within the polymer matrix. The present study's results align well with these findings, indicating a moderate level of graphene dispersion.

The measured thermal conductivity of Epoxy-CNT composites (25.3 W/m·K) is slightly higher than the values reported by Park *et al.* (2018) [6], who found a range of 20 to 24 W/m·K. This difference may be attributed to the improved dispersion of CNTs in the epoxy matrix achieved through ultrasonic treatment in the present study, enhancing the thermal conductivity.

The statistical analysis, specifically the ANOVA and post-hoc Tukey's HSD tests, confirmed the significance of the observed differences in thermal conductivity among the composite materials studied. The F-statistic value of 45.67 and the associated p-value of 0.00001 indicate that the differences in thermal conductivity are statistically significant. These findings are consistent with previous studies that have also reported significant variability in thermal conductivity based on composite material composition and processing conditions.

For example, Zhang *et al.* (2018) [1] reported significant differences in thermal conductivity between Al-SiC and other MMCs, similar to the findings of this study. Likewise, Kim *et al.* (2019) [3] observed significant differences between SiC-AlN and other ceramic composites, aligning with the results presented here. The statistical validation provided by the ANOVA and post-hoc tests in this study supports the broader body of research in the field, reinforcing the reliability of the findings.

### Discussion

The study aimed to explore and compare the thermal conductivity of various composite solid-state materials, focusing on Metal-Matrix Composites (MMCs), Ceramic-Matrix Composites (CMCs), and Polymer-Matrix Composites (PMCs). Through a combination of advanced measurement techniques and rigorous statistical analysis, the research provides a comprehensive understanding of how different material compositions, microstructures, and processing techniques impact thermal conductivity.

The results indicate that metal-matrix composites, particularly Al-SiC, exhibit the highest thermal conductivity among the materials studied. The measured thermal conductivity of Al-SiC was 210.3 W/m·K, which aligns well with existing literature and highlights its suitability for applications requiring efficient heat dissipation, such as in electronics and aerospace industries. The high thermal conductivity is attributed to the intrinsic properties of silicon carbide and its effective distribution within the aluminum matrix, minimizing thermal barriers and maximizing heat transfer.

The Cu-Diamond composite, another metal-matrix material, also demonstrated high thermal conductivity (205.7 W/m·K), slightly lower than Al-SiC. This result is consistent with previous studies, which have identified interfacial thermal resistance as a limiting factor in Cu-Diamond composites. Despite this, the composite remains a strong candidate for high-performance applications where superior thermal management is required.

Ceramic-matrix composites exhibited lower thermal conductivity compared to metal-matrix composites, with SiC-AlN showing the highest value among CMCs at 175.4 W/m·K. This result is significant given the ceramic materials' inherent thermal stability and resistance to high

temperatures, making SiC-AlN suitable for applications in harsh environments where metals might fail. The Al<sub>2</sub>O<sub>3</sub>-TiB<sub>2</sub> composite, while still a good thermal conductor (160.1 W/m·K), performed less effectively than SiC-AlN, likely due to differences in microstructural features such as grain boundaries, which can impede heat flow.

Polymer-matrix composites, as expected, exhibited the lowest thermal conductivity among the materials tested. However, the results are still noteworthy, particularly for Epoxy-CNT composites, which achieved a thermal conductivity of 25.3 W/m·K. This value, although lower than metal and ceramic counterparts, represents a significant enhancement over typical polymers, attributed to the effective dispersion of carbon nanotubes within the epoxy matrix. The PP-Graphene composite showed a lower thermal conductivity (12.5 W/m·K), which could be due to challenges in achieving a uniform dispersion of graphene within the polymer, leading to agglomeration and reduced thermal pathways.

The statistical analysis, including ANOVA and post-hoc Turkey's HSD tests, provided robust validation of the observed differences in thermal conductivity among the composite materials. The ANOVA results confirmed that the variations in thermal conductivity are statistically significant, with a p-value of 0.00001 indicating that the differences are not due to random variation but are indeed meaningful and attributable to the materials' properties and processing methods.

While the study provides comprehensive insights into the thermal conductivity of composite materials, there are some limitations that should be acknowledged. The study focused on a limited number of composite types, and future research could explore a broader range of materials, including emerging composites with novel filler materials. Additionally, the study primarily measured thermal conductivity at room temperature, whereas real-world applications may involve varying temperatures. Future studies could investigate the thermal conductivity of these materials across a broader temperature range to better simulate operating conditions.

Furthermore, while the study employed advanced measurement techniques, the potential effects of microstructural features such as grain boundaries, porosity, and phase distribution on thermal conductivity could be explored in greater depth. Advanced imaging and modeling techniques could be used to better understand these microstructural influences and optimize composite design for enhanced thermal performance.

## Conclusion

This study provides a detailed comparison of the thermal conductivity of various composite solid-state materials, offering valuable insights for material selection in thermal management applications. The results demonstrate that MMCs, particularly Al-SiC, offer the highest thermal conductivity, making them suitable for high-performance applications. CMCs like SiC-AlN also show excellent thermal performance, especially at high temperatures, while PMCs provide a balance between thermal conductivity and other desirable properties such as weight and flexibility. The consistency of these findings with existing literature and the robust statistical validation underscore the importance of this research in guiding the development and application of composite materials in various industrial sectors. Future

research should build on these findings, exploring new materials and conditions to further enhance our understanding of thermal conductivity in composites.

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