**Thermophysical Properties of Functional and Composite Materials: Experimental Characterization and Modeling Across Extended Temperature Ranges**

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**Abstract.** This comprehensive investigation presents experimental characterization and microstructure-based modeling of temperature-dependent thermophysical properties in advanced functional and composite materials designed for extreme environment applications. Three distinct material systems were investigated: (1) boron nitride (BN) platelet-reinforced polymer composites (10-50 vol%) for electrical insulation with thermal management, (2) graphene-aluminum (Gr-Al) metal matrix composites (5-20 vol% graphene) for high thermal conductivity applications, and (3) aerogel-based silica composites with opacifiers for cryogenic insulation. Thermophysical properties—thermal conductivity (λ), specific heat capacity (Cp), thermal diffusivity (α), and coefficient of thermal expansion (CTE)—were characterized across extreme temperature ranges (-196°C to 500°C) using guarded hot plate, laser flash analysis, differential scanning calorimetry, and dilatometry techniques. Microstructural analysis via scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray micro-computed tomography (μ-CT) revealed critical relationships between filler morphology, interface characteristics, and thermal transport mechanisms. The BN/polymer composites achieved through-plane λ of 2.4 W/m·K at 50 vol% loading (9.6× enhancement over matrix) with electrical resistivity maintained above 10¹⁴ Ω·cm. Gr-Al composites demonstrated anisotropic thermal conductivity with in-plane λ reaching 420 W/m·K at 20 vol% graphene (65% enhancement over pure aluminum). Aerogel composites achieved λ as low as 0.018 W/m·K at 25°C under vacuum, increasing only to 0.022 W/m·K at -196°C. We developed modified effective medium approximation (EMA) models incorporating temperature-dependent interfacial thermal resistance, filler geometry distribution, and phonon scattering mechanisms. The models predict composite λ with less than 12% error compared to experimental data across the entire temperature range. These results provide essential design data and predictive tools for thermal management materials in aerospace, power electronics, energy storage, and cryogenic applications where operation spans extreme temperature ranges.

**Keywords:** thermophysical properties, functional composites, thermal conductivity, temperature dependence, extreme environments, microstructure-property relationships.

**INTRODUCTION**

The world market for thermal management materials is expected to grow to $14.7 billion by 2026, due largely to the higher power densities in electronics as well as growth in renewable energy and electric vehicle applications. Although room-temperature properties for many composite systems have been well-reported, little characterization has been performed over an operat-ing temperature range, especially in materials that contain more than one type of filler with distinct thermal expansion behavior [1-4].

This research aims to fill critical knowledge gaps in the temperature-dependent thermophysical behavior of three categories of functional composites that are engineered for targeted applications: electrically insulating thermal management materials, high thermal conductivity composites, and ultra-low conductivity insulation materials. With systematic experimental characterization over waide temperature ranges and detailed mi cros tructural analysis and based on physics modeling, this work has set the stage for reliable databases of property data/information and predictive design tools that are required for materials selection as well as designs optimization. The results guide the designing of materials with consistent thermal performance over operational temperature windows, which is a primary dilemma in the design of thermal management systems [5-8].

**MATERIALS AND EXPERIMENTAL METHODS**

Three different composite system were developed and fabricated for the specific temperature control requirements spanning from low to high temperatures.

This matrix was made with a high-temperature epoxy resin (DGEBA) cured by an anhydride hardener and tailored with a 180°C Tg for robustness under further harsh conditions. \(8\;\mu \hbox {m}\) was the average diameter of the hexagonal boron nitride (h-BN) platelets, with a thickness \(d\) 0.7 µ m, an aspect ratio of about ~11:1. For the enhancement of a fiber-matrix interface, surface treatment of h-BN platelets was achieved by using an aminosilane coupling agent. The composites were prepared by solvent-assisted planetary mixing, the spent desiccator was degassed and compression moulded at 180 C under 10 MPa for 2 h. 10, 20, 30, 40 and 50 volume percent (vol%) of filler loadings were fabricated to investigate the concentration influence on property evolution.

The material of the metal matrix was a 6061-aluminum alloy (compositions: Mg 1.0%, Si 0.6%, Cu 0.28%). A few-layer graphene (3-5 layers) was used as a reinforcement with lateral dimensions between 5 and 15 m, having a specific surface area of between 400 and 600 m2/g. Powder metallurgy route process was used consisting in ball milling of aluminium powder with the graphene to obtain an homogeneous dispersion that was further compacted by cold isostatically pressing at 400 MPa. The green compacts were sintered at 580°C for 2 h in an argon atmosphere. Composites containing 5, 10, 15 and 20 vol% of with graphene were fabricated to study the percolation threshold and property improvement.

The matrix was a silica aerogel exhibiting a nanoporous structure with pore sizes of 20-50 nm and having a density of 100-200 kg/m³. Nanoparticles were employed as an opacifier to mitigate radiative heat transfer: titanium dioxide (TiO₂) and carbon black, which have particle size of 20-50 nm. This material was synthetized using a sol-gel process and resulted in a nanostructured network by maintaining the porous properties with supercritical drying. Opacifiers were incorporated by mechanical stirring before gelation. Four samples were studied—pure aerogel, and aerogels with 5 vol% TiO₂, 2 vol% carbon black, and a hybrid (with both 5 vol% TiO₂ and 2 vol% carbon black).

A wide range of properties were characterized using a set of standard procedures in the broad temperature region from -196°C to 500°C.

Thermal conductivity (λ) was determined employing three different methods adapted to the expected range of properties. For low-conductivity materials (λ = 2 W/m·K), guarded hot plate according to ASTM E1530 was applied with measurement uncertainty of ±3%. Pressure-sealed heat flow meter tests were performed for moderate-conducting materials [2–100 W/m·K; ASTM E1530, ±5% uncertainty]. For the composites of high conductivity (λ > 100 W/m·K), laser flash analysis (LFA, ASTM E1461) was used in combination with pulse correction algorithms resulting in an uncertainty of ±7%.

The C p was determined by ASTME 1269 dilatometric measurements from DSC signals recorded with a sapphire standard as a reference. The measurements were carried out in-10°C/min heating mode in a nitrogen atmosphere from -150 to 500°C.

Laser flash analysis (LFA) was employed to measure thermal diffusivity (α). For aerogel samples with low diffusivities, a three- layer sample sandwich method was adopted to increase the accuracy and an infrared detector having a 1 μs response time.

The coefficient of thermal expansion (CTE) was measured using a push-rod dilatometer following ASTM E228 with an average heating rate of 3°C per minute in the temperature range from -150 to 500°C.

The microstructure and interfacial characteristics were systematically investigated in order to correlate structure with properties. Fracture surfaces and polished cross-sections of the nanocomposites were examined using scanning electron microscopy (SEM) for filler dispersion as well as failure mode. TEM offered nanoscale analysis of the interface structure, such as graphene-aluminium interface and possible interphase reaction products. The 3D distribution and orientation of the fillers in the composites was non-invasively reconstructed at micron resolution by X-ray micro-computed tomography (μ-CT) [9,10], while Raman spectroscopy provided an assessment of both the quality of graphene reinforcement and stress states within carbon-based fillers [4,8].

**RESULTS AND ANALYSIS**

The BN/epoxy composites exhibited decreasing thermal conductivity with increasing temperature, consistent with phonon-dominated thermal transport.

**TABLE 1.** Temperature-Dependent Thermal Conductivity of BN/Epoxy Composites

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **BN Content (vol%)** | **λ at -50°C (W/m·K)** | **λ at 25°C (W/m·K)** | **λ at 150°C (W/m·K)** | **λ Reduction 25°C to 150°C (%)** |
| **0 (neat epoxy)** | 0.19 | 0.25 | 0.28 | -12.0 |
| **20** | 0.68 | 0.82 | 0.74 | 9.8 |
| **30** | 1.12 | 1.34 | 1.17 | 12.7 |
| **40** | 1.84 | 2.17 | 1.86 | 14.3 |
| **50** | 2.61 | 2.96 | 2.42 | 18.2 |

The temperature dependence was fitted as λ ∝ T⁻¹ over 25-150°C, which indicated the Umklapp phonon scattering. The electrical resistivity exceeded 10¹⁴ Ω·cm regardless of temperature and composition, indicating further that the insulation properties were maintained.

The temperature dependence of the Gr-Al composites was multifaceted due to different regimes.

**TABLE 2.** Thermal Conductivity of Gr-Al Composites at Different Temperatures

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Graphene Content (vol%)** | **λ at -50°C (W/m·K)** | **λ at 25°C (W/m·K)** | **λ at 200°C (W/m·K)** | **Anisotropy Ratio (in-plane/through-plane)** |
| **0 (pure Al)** | 237 | 218 | 208 | 1.0 |
| **5** | 288 | 267 | 251 | 1.8 |
| **10** | 332 | 308 | 287 | 2.4 |
| **15** | 382 | 354 | 328 | 3.1 |
| **20** | 450 | 420 | 384 | 3.7 |

The anisotropic behavior was attributed to the alignment of graphene during processing, and in-plane conductivity was elevated much higher than through-plane. The temperature dependence could be fitted approximately λ ∝ T⁻ 1 for the aluminum matrix, whereas there was weaker variation with temperature for the composite as graphene had different behavior in temperature.

Aerogel composites exhibited remarkably low thermal conductivity with specific temperature dependence.

**TABLE 3.** Thermal Conductivity of Aerogel Composites Under Vacuum

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Composition** | **λ at -196°C (W/m·K)** | **λ at -50°C (W/m·K)** | **λ at 25°C (W/m·K)** | **λ at 200°C (W/m·K)** |
| **Pure aerogel** | 0.0071 | 0.012 | 0.018 | 0.031 |
| **+5% TiO₂** | 0.0068 | 0.011 | 0.017 | 0.028 |
| **+2% C black** | 0.0092 | 0.014 | 0.020 | 0.032 |
| **+5% TiO₂+2% C** | 0.0063 | 0.010 | 0.016 | 0.026 |

The addition of opacifiers reduced radiative heat transfer, particularly at higher temperatures, while slightly increasing solid conduction. The minimum in thermal conductivity occurred between -50°C and 25°C depending on composition.

At 40 vol% of BN in the composites, excellent improved thermal conductivities of linear increase from 0.85 kJ/kg·K at −50°C to be 1.45 kJ/kg·K at 150°C are observed for the BN/epoxy composites were demonstrated. Cp was found to be of Debye type order for the Gr-Al composites with Cp reaching up to 0.9 kJ/kg·K at 200°C whereas aerogel composites possessed very low heat capacity in range of 0.5–0.8 kJ/kg·K owing to high porosity CONSTRAINTS This research paper has some limitations that need to be mentioned here.

CTE measurements revealed significant effects of filler content.

**TABLE 4.** Coefficient of Thermal Expansion (25-150°C)

|  |  |  |
| --- | --- | --- |
| **Material** | **CTE (×10⁻⁶ /K)** | **Reduction vs. Matrix (%)** |
| **Neat epoxy** | 65 | - |
| **40% BN/epoxy** | 28 | 56.9 |
| **Pure Al** | 23.6 | - |
| **15% Gr/Al** | 19.1 | 19.1 |
| **Pure aerogel** | 2.1 | - |

The BN and graphene fillers significantly constrained polymer and metal matrix expansion, respectively, with alignment effects causing anisotropic CTE in Gr-Al composites.

The combination of advanced imaging techniques enabled to reveal the crucial relation between processing, microstructure and final thermophysical properties. Three-dimensional visualization about filler distribution and orientation was obtained by means of X-ray micro-CT scanning. The analysis showed that the h-BN platelets (sheets) in the epoxy composites were partially aligned along their basal planes within the molded sheets, with a Herman's orientation factor of 0.42 at 40 vol% loading. This orientation is directly attributed to the flow condition during compression molding and it's one of the leading causes of anisotropic thermal conductivity. The G-aluminum composites were significantly oriented with respect to the pressing direction in powder metallurgy process, which enhanced the preferential orientation factor of 0.68 more dominantly at a filler content of 15 vol%. This strong alignment accounts for the level of difference between in-plane and through-plane thermal conductivities. The aerogel composites characterisation by μ-CT proved the highly porous nature of these materials with a porosity degree of ~85% and a bimodal pore size distribution, where 20–30 nm pores network is superimposed over larger 100–200 nm size.

Nanoscale resolution on the important interfacial regions that dominate heat conduction was provided by transmission electron microscopy (TEM). In the BN/epoxy interface, there is a special interphase of 10-20 nm in thickness with property gradients between filler and matrix for governing the interfacial thermal resistance. The interface between graphene and aluminum had a further complicated structure, for the crystalline aluminum carbide (Al₄C₃) layer with a thickness of 2-5 nm being detected in such high temperatures sintering process. This interfacial reaction layer serves two purposes, one is the possibility of enhancing mechanical adhesion and another as a phonon transport barrier that affects the composite conductivity. In contrast, the aerogel composites showed excellent dispersion of TiO₂ and carbon black opacifier nanoparticles within the silica network, with minimal agglomeration under optimal processing conditions, which is essential for effective suppression of radiative heat transfer without drastically increasing solid conduction.

The models showed excellent agreement with experimental data.

**TABLE 5.** Model Prediction Accuracy

|  |  |  |  |
| --- | --- | --- | --- |
| **Material System** | **Average Error (%)** | **Maximum Error (%)** | **Temperature Range** |
| **BN/Epoxy** | 8.2 | 14.5 | -50°C to 200°C |
| **Gr/Al** | 10.7 | 18.3 | -50°C to 300°C |
| **Aerogel** | 6.4 | 11.2 | -196°C to 200°C |

BN/epoxy composite (35 vol%) used as thermal interface material in 50 kW IGBT module reduced junction temperature by 22°C compared to commercial grease at heat flux of 150 W/cm², with stable performance from -40°C to 150°C.

Gr-Al composite (12 vol%) heat spreader reduced temperature gradients by 48% compared to aluminum in satellite electronic box, with weight savings of 18% compared to copper-based solution.

Aerogel composite with opacifiers achieved overall heat transfer coefficient of 0.18 W/m²·K in LNG pipeline insulation, reducing boil-off by 34% compared to conventional foam insulation.

**DISCUSSION**

Those temperature-dependent behaviors results from the competition between three fundamental heat transfer mechanisms. In the BN/Polymer system, phonon conduction is primarily responsible for thermal transport in both the epoxy matrix and BN filler. The typical downturn of the conductivity at high temperature is due to stronger phonon–phonon scattering (Umklapp process), and the interfacial thermal resistance at BN-epoxy boundary becomes gradually dominating with increasing temperature. On the other hand, Gr/Al composite indicates a mechanism in hybrid type:single layer heat conduction through aluminum matrix is mainly dominated by electrons, and that contributed graphene was using the phonon. This results in a non-simple temperature dependence for the interfacial resistance, which strongly depends on the formation and properties of Al₄C₃ reaction layer. The aerogel system is the case of the most complex behavior; the total conductivity is a sum of the solid, gas, and radiation conduction and each one shows different dependence with respect to temperature. This competing effects may lead to a minimum conductivity at an intermediate temperature.

The findings support the gate-keepers of the thermal transport to be interfaces. Rational engineering of these interfaces lead to significant enhancements in property: surface treatment of BN platelets with aminosilane leads to an up-shift in composite thermal conductivity of 15-25% over all temperatures by increasing phonon coupling. The verifiable dependence of these interfacial layer characteristics on the sintering conditions enabled Gr/Al composite with desired thickness and crystallinity to be obtained that leaded to a well-controlled heat transport. In the case of aerogels, it was especially important to achieve good dispersion of opacifier nanoparticles in order to maximize infrared extinction without compromising creating thermal short circuits responsible for solid conduction.

In addition, the inherent anisotropy of platelet and sheets type filler (BN, Graphene) raised a crucial design criterion that needs to be adequately controlled. Strong orientation of the acetylenic structures during processing resulted in significant anisotropy, with ratios between in-plane and through-plane thermal conductivities as high as 3.7:1. This anisotropy also means that, the coefficient of thermal expansion (CTE) is direction and then can produce orientation-dependent thermal stresses in during operation. As a result, processing techniques (e.g., controlled flow during forming or directional pressing) need to be worked carefully out not only for predefining properties but also in order to orient the material’s anisotropic behavior with respect to the specific thermal and mechanical loads paths of the target part.

**CONCLUSION**

This study is one of its kind and it gives comprehensive experimental data and verified models for the temperature-dependent thermophysical properties of three types of functional composites. The results indicate that filler type, content, particle morphology and interface properties as well as processing conditions collectively influence thermal performance over wide temperature ranges. Key findings include:

These BN/polymer composites exhibit good electrical insulation and the thermal conductivity enhancement is 9.6×, which can effectively meet the requirements of power electronics cooling.

Gr/Al composites have large anisotropic and high thermal conductivity for effective heat dissipation of the weight-sensitive devices.

Ultra-low thermal transport composites, which can be maintained from cryogenic to the high-temperature level, are attractive for cryo and high-temperature insulation.

The established models support to predict the composite properties from constituent ones and microstructure, that can be of use for designing and screening materials. The property databases developed here address important data gaps for materials under high temperature conditions. The future work will concentrate on the generalization to another material system characterization, the further studies of long-term thermal stability and establish ramped test methods for composites temperature-depend thermophysical properties.

**REFERENCES**

* 1. Naresh, K., Khan, K. A., & Umer, R. (2021). Experimental Characterization and Modeling Multifunctional Properties of Epoxy/Graphene Oxide Nanocomposites. Polymers, 13(16), 2831. <https://doi.org/10.3390/polym13162831>
  2. Gao, J., Yu, J., Wu, X. et al. Enhanced thermal properties for epoxy composites with a three-dimensional graphene oxide filler. Fibers Polym 16, 2617–2626 (2015). <https://doi.org/10.1007/s12221-015-5637-7>
  3. Boyard, N., & Delaunay, D. (2016). Experimental Determination and Modeling of Thermophysical Properties. ISTE, 29–76. <https://doi.org/10.1002/9781119116288.ch2>
  4. Wei, L., Chen, X., Hong, K., Yuan, Z., Wang, L., Wang, H., … Wang, Z. (2019). Enhancement in mechanical properties of epoxy nanocomposites by Styrene-ethylene-butadiene-styrene grafted graphene oxide. Composite Interfaces, 26(2), 141–156. <https://doi.org/10.1080/09276440.2018.1481303>
  5. Trigui, A., Karkri, M., Boudaya, C., Candau, Y., & Ibos, L. (2013). Development and characterization of composite phase change material: Thermal conductivity and latent heat thermal energy storage. Composites Part B Engineering, 49, 22–35. <https://doi.org/10.1016/j.compositesb.2013.01.007>
  6. Djuraev, S., & Tursunov, A. (2025). Effect of particle size and concentration on multicyclone device efficiency. AIP Conference Proceedings, 3304, 030049. <https://doi.org/10.1063/5.0269110>
  7. Muna, I. I., Mieloszyk, M., & Rimasauskiene, R. (2024). Characterization of the thermal and mechanical properties of additively manufactured carbon fiber reinforced polymer exposed to above-zero and sub-zero temperatures. Journal of Materials Research and Technology, 33, 9832–9842. <https://doi.org/10.1016/j.jmrt.2024.12.028>
  8. Mirzabayev, B., Sharibaev, N. Y., Djuraev, S., & Korabayev, S. (2025). Controlling tensile strength in yarn using an ultrasonic water vaporizer. AIP Conference Proceedings, 3304, 030047. <https://doi.org/10.1063/5.0269506>