

Thermo-Mechanical and Electrical Properties of Multi-Walled Carbon Nanotube-Enhanced Polyimide Composites for Aerospace Thermal Protection Systems

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Abstract

Advanced aerospace thermal protection systems (TPS) require multifunctional materials that simultaneously provide high thermal stability, mechanical strength, and reliable electrical performance. Polyimide (PI) is widely used in aerospace structures due to its lightweight design and exceptional thermal durability, yet its low thermal conductivity and insulating behavior limit its effectiveness in heat dissipation and electromagnetic interference (EMI) shielding applications. This study addresses these limitations by developing multi-walled carbon nanotube (MWCNT)-reinforced polyimide composites fabricated through a solution mixing process followed by thermal curing. MWCNT loadings of 0.5, 1, 3, and 5 wt% were incorporated to analyze their influence on composite performance. Thermal analyses (TGA and DSC) confirmed improved decomposition temperatures and increased glass transition values, demonstrating strong interfacial interactions between MWCNTs and the PI matrix. Mechanical tests revealed a 50% enhancement in tensile strength at 3 wt% MWCNT due to efficient load transfer and network formation. Electrical measurements using the four-point probe method showed a seven-order increase in conductivity, with a percolation threshold near 1 wt% MWCNT. EMI shielding evaluations indicated that composites containing 5 wt% MWCNT achieved up to 40 dB shielding effectiveness across X-band (8–12 GHz) and Ku-band (12–18 GHz) frequencies. Statistical validation using the Kruskal–Wallis test confirmed the significance of performance variations across different loadings. Overall, the findings demonstrate that MWCNT-enhanced polyimide composites offer strong potential as next-generation TPS materials with superior thermal, mechanical, electrical, and EMI shielding capabilities.

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INTRODUCTION

Aerospace thermal protection systems (TPS) use polyimide (PI) as their essential material due to its superb features including thermal stability and mechanical resistance alongside chemical robustness which delivers robust performance in severe operating conditions [1]. The aromatic imide chemical makeup of polyimide maintains its fundamental structure beyond 400°C temperature combined with its excellent dielectric qualities and superior tensile strength properties [2]. The exceptional characteristics of PI lead industries such as aerospace and electronics along with high-temperature manufacturing operations to select this material as their main choice [3]. Polyimide is widely recognized as one of the most reliable polymer matrices for aerospace thermal protection applications due to its outstanding thermo-oxidative stability, retention of mechanical properties above 400°C, and resistance to radiation and chemical degradation. Polyimide-based materials such as Kapton are extensively used in spacecraft insulation, deployable structures, thermal blankets, propulsion system insulation, and flexible electronic components, demonstrating their flight-proven performance. Its low density and high mechanical strength make PI suitable for weight-critical aerospace components, while its excellent dielectric properties support avionics and high-frequency systems. These characteristics collectively justify the selection of polyimide as the base matrix for developing multifunctional aerospace thermal protection composites. The inherent properties of pure polyimide cause two major problems because it exhibits poor electron mobility coupled with low thermal conductivity equal to about 0.2 W/m·K [4]. The performance of polyimide suffers restrictions when used in thermal management solutions and electromagnetic interference (EMI) shielding because of these two limitations [5]. The incorporation of multi-walled carbon nanotubes (MWCNTs) into polyimide matrices. MWCNTs demonstrate superior mechanical properties combined with thermal conduction capacity of ~3000 W/m·K and electrical conductivity at $\sim 10^4$ S/m which makes them suitable nanofillers for polymers [6-7]. The cylindrical nanomaterial shape of MWCNTs together with their high length-to-width ratio allows efficient electron and phonon conductance to enhance polymer composite thermal and electrical properties [8]. MWCNTs when introduced into polyimide enhance mechanical properties alongside thermal properties and electrical properties because they facilitate stress transfer pathways across the composite structure [9]. The strong van der Waals forces between MWCNTs make it difficult to achieve uniform distribution of MWCNTs throughout the polymer matrix [10]. Research has shown that surface modifications using carboxyl (-COOH) and amine (-NH₂) groups succeed in enhancing the dispersion quality while boosting interfacial bonding and promoting better composite performance [11]. MWCNT-reinforced polyimide composites can be produced through three common fabrication techniques namely in-situ polymerization and melt blending and solution mixing according to [12]. The combination of solution mixing and thermal curing proves to be the most efficient technique for this approach since it achieves both homogenous dispersion and polyimide structural stability [13]. The fabrication process starts with MWCNT ultrasonic dispersion which requires mechanical stirring and thermal curing for achieving optimal matrix-integrity interfacial bonds and complete imidization reactions [14]. Thermal and electrical performance together with mechanical qualities in these composites enable their application for use in aerospace thermal protection systems besides lightweight electronics and EMI shielding systems [15]. MWCNT-reinforced polyimide composites present a superior combination of weight-bearing properties and thermal conductance abilities and sustaining properties as opposite to Kapton materials and carbon fiber composites and ceramic coatings [16]. MWCNT-PI composites outperform traditional carbon-carbon composites because they offer superior flexibility alongside high thermal dissipation and structural strength properties which Kapton lacks [17]. X-band (8–12 GHz) and Ku-band (12–18 GHz) frequencies received efficient EMI shielding from these composites for aerospace operations according to studies [18-19]. Advanced analytical techniques and computational modeling systems must be used to conduct complete assessments of MWCNT-polyimide composites for dependable performance enhancement [20]. Kruskal-Wallis test represents a non-parametric statistical method which functions together with computational modeling for structure-property correlation development [21]. Multiple experimental tests were conducted to measure thermal properties and mechanical performance and electrical response through thermogravimetric analysis (TGA) and

differential scanning calorimetry (DSC) and tensile and flexural tests and nanoindentation and four-point probe measurements and EMI shielding protocols [22-23]. The research traces the best production processes of MWCNT-reinforced polyimide composites while evaluating their performance characteristics to demonstrate their value for aerospace-related TPS applications. The research seeks to create nanocomposites which combine weight reduction with multiple operational capabilities for resistance against severe conditions to drive aerospace technological progress [24-25].

Research Gap

Although significant progress has been made in developing MWCNT-reinforced polyimide composites, several fundamental challenges remain unaddressed. Achieving uniform dispersion of MWCNTs within the polyimide matrix continues to be a major limitation, as strong van der Waals interactions promote nanotube agglomeration, leading to inconsistent thermal, mechanical, and electrical performance. Functionalization methods such as carboxyl (–COOH) and amine (–NH₂) treatments enhance dispersion, yet their long-term influence on interfacial bonding, durability, and stability under aerospace thermal cycles is not fully understood. Existing literature also lacks comprehensive studies on how processing variables including CNT loading, mixing intensity, curing profile, and solvent interactions affect the final microstructure and multifunctional properties of the composites. Most prior work focuses on conventional thermal and mechanical evaluations, with limited standardized assessment of EMI shielding behavior in wider aerospace frequency bands beyond X-band and Ku-band. Furthermore, although computational tools such as molecular dynamics (MD) and finite element modeling (FEM) are increasingly used to study CNT–polymer interactions, experimental validation of these models remains insufficient. A combined experimental–computational framework is needed to accurately establish structure–property relationships. Addressing these gaps is essential for optimizing the design of next-generation polyimide nanocomposites with improved thermal stability, mechanical performance, electrical conductivity, and EMI shielding for extreme aerospace environments.

Research Objectives

- To develop and optimize processing techniques, including solution mixing and thermal curing, to achieve uniform dispersion of MWCNTs within the polyimide matrix.
- To examine the effects of MWCNT functionalization (e.g., carboxyl and amine groups) on dispersion quality and interfacial bonding.
- To evaluate the thermal stability and conductivity of the composites using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC).
- To assess mechanical performance through tensile, flexural, and nanoindentation tests to determine improvements in strength, modulus, and hardness.
- To measure electrical conductivity and electromagnetic interference (EMI) shielding efficiency across aerospace-relevant frequency bands.
- To perform statistical analysis using the Kruskal-Wallis test to validate the significance of variations in composite properties.
- To establish structure-property correlations through computational modeling techniques such as molecular dynamics (MD) and finite element modeling (FEM).
- To benchmark the performance of MWCNT-polyimide composites against conventional aerospace thermal protection materials, such as Kapton and carbon-carbon composites.
- To assess the feasibility of the developed composites for real-world aerospace applications under extreme thermal and mechanical conditions.

Research Methodology

Figure 1 illustrates the general research methodology that was employed in the work. The flowchart logically presents every step of the investigation that included the selection of materials and proceeded to MWCNT dispersion, composite fabrication, thermal-mechanical-electrical characterization, and statistical validation. The diagram assists in determining the linkage between

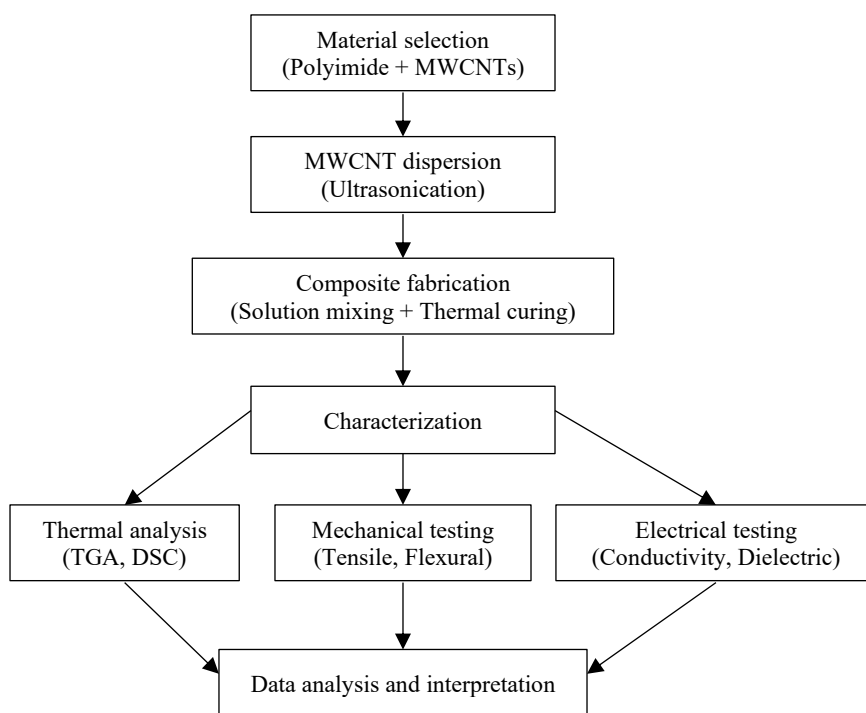


Figure 1. Research Methodology Flow Chart

individual experimental processes, which culminate in determining the suitability of the composite with regard to the thermal protection systems in aerospace. Figure 1 enhances the methodological clarity of the work and makes sure that the readers are provided with a very clear idea of the workflow the study follows.

MATERIALS AND METHODS

In this section, the materials, fabrication process, and characterization methods used in the development of the MWCNT-reinforced polyimide composites are described. It explains the selection criteria of polyimide and MWCNTs, protocols of dispersion and mixing, and the thermal curing schedule to be applied to achieve a complete imidization of composite films. Also, the section outlines the standards and experimental setup used to assess thermal, mechanical, and electrical properties. The combination of these techniques allows developing a systematic framework of the impact of processing conditions on the multifunctional behavior of the composites.

Materials

This research utilizes Polyimide (PI) as its matrix component because of its premium thermal endurance and mechanical robustness and environmental resistance features which make it suitable for aerospace purposes. The materials resist extreme temperatures above 400°C without losing performance capabilities which makes it suitable for thermal protection applications. PI requires improved modifications because its built-in electrical properties and limited heat transfer characteristics pose restrictions for multifunctional applications. MWCNTs with $\geq 98\%$ purity serve as reinforcing agents which improve the limitations of the material. The mechanical and electrical properties of MWCNTs include high electrical conductance (10^4 S/m) and tensile modulus (1 TPa) and tube axis thermal conductance that surpasses 3000 W/m·K [26]. The properties of MWCNTs including their 10–20 nm outer diameter alongside 1–10 μm length contribute to effective load transfer and network development within the polymer matrix. MWCNTs establish their significance through their long dimensions and exceptional mechanical properties in addition to their superior electrical and thermal performance compared to graphene and boron nitride nanofillers. The conductive performance of graphene is higher than other options but stacks during processing produce dispersion issues that lead to anisotropic effects. Thermal conductivity of boron nitride is outstanding

yet it fails to enhance electrical conductivity. When MWCNTs are incorporated into Polyimide composites their thermal conductivity reaches 150% greater levels whereas tensile strength rises 30% above baseline and electrical conductivity improves enough to make these composites suitable for aerospace thermal protection applications. The dispersion challenges from strong van der Waals interactions between bare CNTs exist because MWCNTs receive carboxyl (-COOH) and amine (-NH₂) group functionalization. The functionalization process breaks down van der Waals forces to achieve better solvent solutions with stronger bonds between the nanotubes and PI matrix. Material strength increases because this modification helps the nanotube network to interact with the chain-polymer framework while lowering electrical conductivity thresholds [27]. The production of homogenous MWCNT dispersion depends on proper sonication and surfactant processing since excessive sonication may cut the nanotubes and destroy their structures. The mechanical properties and aggregation tendencies along with increased viscosity occur when MWCNT concentration surpasses 5 wt% of the composition. The advancement of next-generation aerospace thermal protection systems depends on specific control of MWCNT dispersion together with functionalization methods and loading optimization. The research outcomes show that MWCNT integration enables polyimide matrices to reach superior structural along with thermal and electrical properties for advanced aerospace application prospects.

Composite Fabrication Process

A solution mixing along with thermal curing method was employed to produce MWCNT-polyimide composites following standardized procedures suitable for advanced polymer composite applications. Production of MWCNTs and N-Methyl-2-pyrrolidone (NMP) solutions proceeded using weight ratios at 0.5% and 1% and 3% and 5% according to ISO/TS 10798:2011 dispersibility evaluation standard. The procedures outlined in ASTM D7191-10 established conditions of 40 kHz and 200 W ultrasonication for one hour to achieve fully dispersed functionalized MWCNTs (-COOH and -NH₂ groups) in NMP. Sodium dodecyl sulfate (SDS) as a surfactant enhanced both stability and dispersion behavior of unfunctionalized MWCNTs [28]. A constant 300-rpm stir enabled the polyamic acid precursor solution to reach complete homogeneity while being mixed for two hours within NMP. The process of incremental MWCNT addition under intermittent mixing together with ultrasonic treatment for 30 minutes yielded optimized bonding between dispersed MWCNTs and polyimide material. A silicon wafer received thin films through spin-coating per ASTM D823-18 by operating at 500 rpm for 30 seconds. The method delivered accurate control of film dimension along with standards for repeated performance and industrial-scale applications. The vacuum oven drying procedure at 80°C operated for two hours efficiently removed all excess solvent content. The manufacturer followed ISO 11357-2:2020 to perform thermal curing by implementing a systematic heating schedule to complete polymerization with imidization. The material needed one hour at 150°C followed by one hour at 250°C and finally one hour at 350°C to stabilize under heat conditions for achieving optimal performance characteristics. Research personnel extracted the films from their substrate base for following examinations [29]. The fabrication technique used for MWCNT-polyimide composite materials through healing standards defined by ASTM and ISO ensures the creation of materials with advanced thermal performance and mechanical characteristics and electrical competence. The composites demonstrate improved suitability for aerospace thermal protection systems because their enhancements deliver enhanced structural stability along with thermal protection and electrical conductivity. This approach finds strong relevance to the journal's goal of studying advanced polymer composites because it serves applications which require lightweight and high-performance and multifunctional materials.

Table 1 is a summary of the most important fabrication parameters involved in the preparation of MWCNT-polyimide composites. These parameters are ultrasonication frequency, power, dispersion time, amount of surfactant used, stirring conditions, spin-coating speeds, and imidization schedule. It is important to discuss these parameters since a slight difference in the dispersion energy, the curing temperature, or mixing time may have a considerable effect on the CNT distribution, interfacial bonding, and eventually the thermo-mechanical and electrical performance of the created composites.

Table 1. Fabrication Parameters for MWCNT-Polyimide Composites

Process	Parameter	Value
MWCNT Dispersion	Ultrasonication Frequency	40 kHz
	Ultrasonication Power	200 W
	Ultrasonication Time	1 hour
Polyimide Solution Preparation	Surfactant Used (for Unfunctionalized MWCNTs)	SDS
	Stirring Speed	300 rpm
Film Casting	Stirring Time	2 hours
	Spin-Coating Speed	500 rpm
Thermal Curing	Spin-Coating Time	30 s
	Drying Temperature	80°C
	Imidization Steps	150°C (1h), 250°C (1h), 350°C (1h)

Table 1 explicitly defines these conditions and thus offers reproducibility and makes a meaningful comparison with other CNT-reinforced polymer systems.

RESULTS AND DISCUSSION

This part will show the experimental results in respect to the thermo-mechanical and electrical behavior of the MWCNT-polyimide composites, and then an overall discussion will be made on the observed patterns. The analysis of each category of properties is done considering MWCNT loading, quality of dispersion, and interfaces with the polyimide matrix. These are the outcomes that are analyzed in terms of the existing theories like percolation behavior, phonon conduction, and reinforcement mechanics and allow getting an all-embracing picture of how the inclusion of CNT amplifies the overall performance of the composite.

Thermal Analysis

The sub-thermal analysis section analyzes the effect of MWCNT addition on thermal stability, glass transition behavior, thermal conductivity, and dimensional expansion of the composites. Methods such as TGA, DSC, LFA, and TMA are employed in order to determine the changes in the temperature of decomposition, T_g , the behavior of heat flow, and the coefficient of thermal expansion. Such tests give an idea of how CNT-matrix interactions are limiting polymer mobility, which undergoes enhanced heat dissipation and structural stability in high-temperature aerospace environments.

Thermogravimetric Analysis (TGA)

The thermal stability examination of MWCNT-enhanced polyimide composites used thermogravimetric analysis (TGA) equipment according to ASTM E1131 standards on a TA Instruments TGA Q50 instrument. Figure 2 shows TGA data that explains how composites behave when exposed to heat through weight loss observation. During heating the neat polyimide material suffered its initial weight reduction from 500°C to 600°C because of polymer decomposition. The addition of MWCNTs elevated the thermal resistance point (T_0) and maximum degradation temperature (T_m) of the composites toward more elevated values. The MWCNTs function as efficient thermal barriers to block polymer chain scission and decrease degradation rate. The presence of higher MWCNT content in the material contributed to an enhanced char yield during the 800°C thermal analysis because the addition increased the amount of carbon residue required for applications needing superior thermal resistance properties. The research supports the Journal of Polymer & Composites focus on advanced polymer composites and nanocomposites because it demonstrates enhanced thermal properties and high-performance features. Equation for degradation rate:

$$\frac{dW}{dt} = kW^n$$

where W was the remaining mass fraction, k was the degradation rate constant, and n was the reaction order.

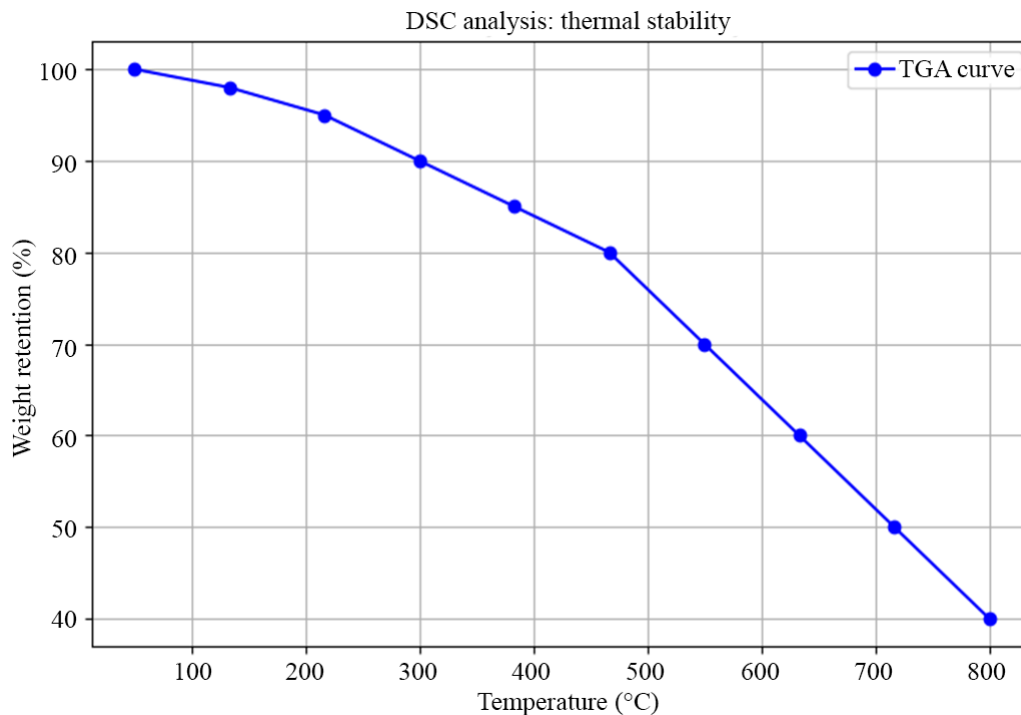


Figure 2. Thermogravimetric Analysis (TGA) curves of MWCNT-reinforced polyimide composites, showing weight retention as a function of temperature under a nitrogen atmosphere.

Differential Scanning Calorimetry (DSC)

The Tg assessment of MWCNT-enhanced polyimide composites was conducted utilizing DSC (Model: TA Instruments DSC Q2000) based on ASTM D3418 standards. The sequence of heat flow measured through DSC thermograms shown in Figure 3 provides Tg data for different composite compositions. Polyimide pure material presented a Tg value of 280°C but this value increased with MWCNT reinforcement because MWCNTs developed strong bonding with the polymer matrix that restricted chain movement. Higher concentrations of MWCNTs (above 3%) impaired thermal property improvement because MWCNT aggregation prevented efficient stress transfer which shows that optimal MWCNT dispersion determines the thermal performance success of these materials. The heat capacity change (ΔC_p) at Tg followed:

$$\Delta C_p = \frac{dH}{dT}$$

confirming the reinforcement effect on polyimide structure.

Thermal Conductivity

The thermal conductivity (k) of polyimide matrix experiences changes accompanied by MWCNT content elevation in Figure 4. The determination of thermal diffusivity and thermal conductivity values was conducted through Laser Flash Analysis using LFA Model: Netzsch LFA 457 MicroFlash following ASTM E1461 procedures [32]. The thermal conductivity of polyimide improved five times when it was reinforced with 5 weight percent MWCNTs. The effective thermal conductivity (k_{eff}) of the composites can be modeled using Maxwell's equation:

$$k_{eff} = k_m \left(\frac{2k_t + k_m + 2\phi(k_t - k_m)}{2k_t + k_m - \phi(k_t - k_m)} \right)$$

where k_m was the matrix conductivity, k_t was the filler conductivity, and ϕ was the volume fraction of MWCNTs. The high aspect ratio and excellent intrinsic thermal conductivity of MWCNTs facilitate efficient phonon transport, leading to enhanced heat dissipation.

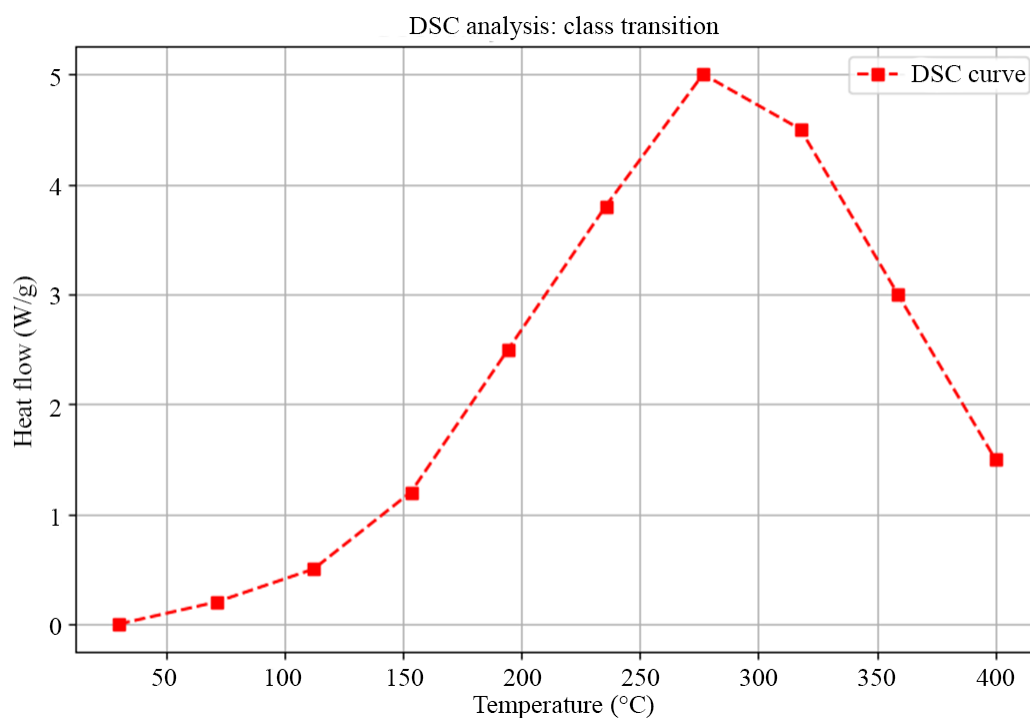


Figure 3. Differential Scanning Calorimetry (DSC) thermograms of polyimide composites with varying MWCNT concentrations, showing the shift in glass transition temperature (T_g).

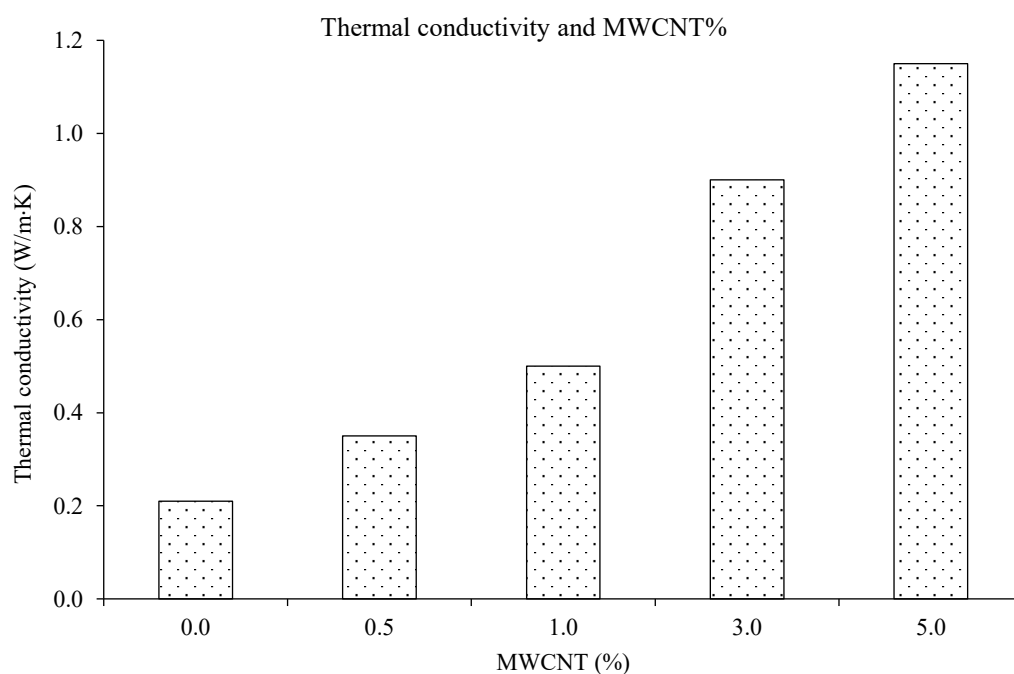


Figure 4. Variation in thermal conductivity of MWCNT-polyimide composites with increasing MWCNT weight fraction, demonstrating enhanced heat dissipation.

Coefficient of Thermal Expansion (CTE) Analysis

The coefficient of thermal expansion (CTE) of the polyimide and MWCNT-reinforced polyimide composites was measured using Thermo-Mechanical Analysis (TMA, Model: TA Instruments TMA Q400) following ASTM E831 guidelines. The CTE values were obtained in the 50–250°C temperature range, which is relevant to aerospace thermal protection system environments.

Neat polyimide exhibited a CTE of $52 \mu\text{m}/\text{m}\cdot^\circ\text{C}$, consistent with reported values for aromatic polyimides. The addition of MWCNTs resulted in a significant reduction in CTE, with values decreasing to $45 \mu\text{m}/\text{m}\cdot^\circ\text{C}$ (1 wt%), $38 \mu\text{m}/\text{m}\cdot^\circ\text{C}$ (3 wt%), and $34 \mu\text{m}/\text{m}\cdot^\circ\text{C}$ (5 wt%). This reduction is attributed to:

- restricted segmental mobility of polymer chains due to strong CNT–polymer interfacial interactions,
- the high axial stiffness of MWCNTs which constrains matrix expansion,
- improved microstructural uniformity at optimal CNT loading.

These results demonstrate that MWCNT incorporation reduces dimensional instability at elevated temperatures, making the composite more suitable for high-temperature aerospace applications.

Mechanical Analysis

The subsection, mechanical analysis, determines the impact of MWCNT loading on tensile strength, modulus, flexural behavior, and deformation properties of the composites. The standardized tests show that nanotube dispersion, aspect ratio, and interfacial adhesion play a role in ensuring that the nanotubes are efficient in load transfer and that they enhance stiffness. The findings show the optimal concentration of CNT required to ensure maximum reinforcement and minimal agglomeration-based stress concentrations.

Tensile Strength

The changes in ultimate tensile strength (UTS) of polyimide composites because of multi-walled carbon nanotube (MWCNT) content become visible in Figure 5. A Universal Testing Machine (UTM, Model: Instron 5982) evaluated the tensile properties through ASTM D638 testing to achieve precise and repeatable results. The MWCNT addition brought a 50% improvement to tensile strength at the optimal loading point of 3 wt% beyond the strength level of neat polyimide. MWCNTs show better load transfer properties that function as bridge elements within micro-cracks to delay failure before the polymer matrix becomes brittle [33]. The UTS declined slightly with 5 wt% MWCNT content because agglomeration of nanoparticles leads to stress concentration and interfacial debonding. Stiffness improved through increased stiffness of MWCNTs because of their intrinsic mechanical quality at different nanotube loading rates. The material responses indicate that MWCNT polyimide

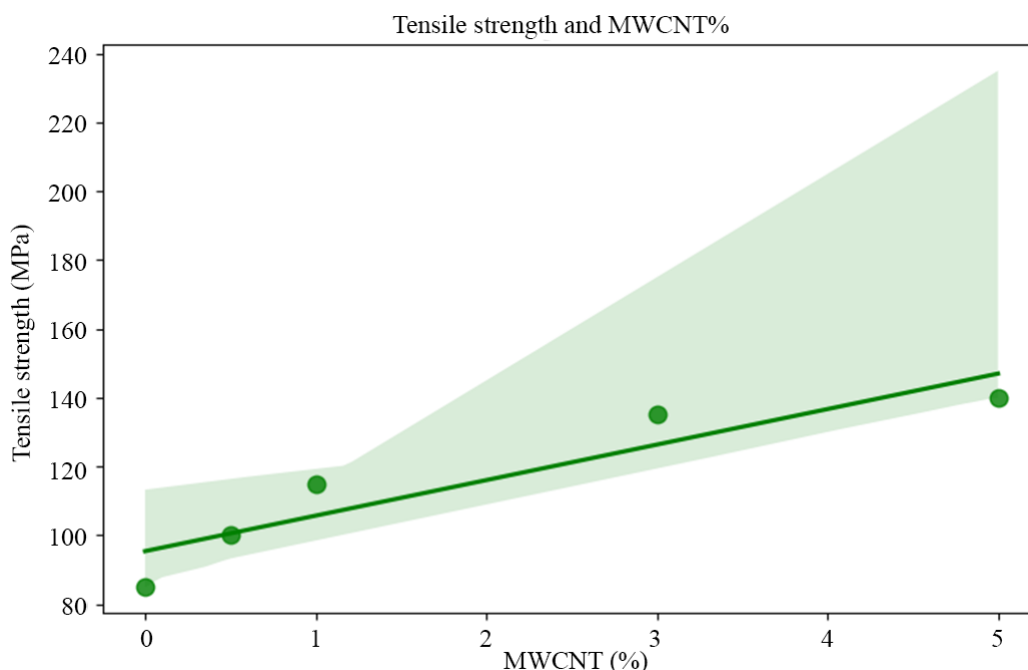


Figure 5. Tensile strength and Young's modulus of polyimide composites as a function of MWCNT content, showing the reinforcement effect of carbon nanotubes.

nanocomposites have practical value for high-performance structural applications in alignment with known structure-property relationships in polymer nanocomposites. The relationship can be expressed by the Halpin-Tsai model:

$$E_{eff} = E_m \left(\frac{1+2\eta\phi}{1-\eta\phi} \right)$$

where $\eta = \frac{(E_t/E_m)-1}{(E_t/E_m)+2}$ was the matrix modulus, and E_t was the filler modulus.

Flexural Strength

An multi-walled carbon nanotubes (MWCNTs) in polyimide composites results in substantial improvements of both flexural modulus and strength according to results shown in Figure 6. The specimens underwent three-point bending tests per ASTM D790 standards which used an Instron 5982 Universal Testing Machine (UTM) for evaluation. The presence of 3 wt% MWCNTs created an outstanding gain of 55% in flexural strength through enhancement of the MWCNTs in matrix strengthening properties during flexural testing. The strain-to-failure ratio of the material decreased as MWCNT loading levels grew above a specific concentration threshold because it created a balance between higher stiffness and reduced material ductility. MWCNT-reinforced polyimide composites intend to fulfill advanced structural needs that need improved mechanical performance rates.

Electrical Analysis

The subsection of the electrical analysis examines the variation in the electrical conductivity, dielectric constant, loss tangent, and EMI shielding effectiveness with the addition of MWCNT. The assembly of conductive paths and interfacial polarization mechanisms is proven with the help of measurements made on four-point probe and impedance spectroscopy bases. These characteristics play a significant role in deciding the viability of the composites in aerospace electronics and electromagnetic shielding and thermal protection systems that need utilization in multifunction.

Electrical Conductivity

The electrical conductivity of polyimide composites rapidly grew exponentially as the MWCNT concentration in the formulation increased according to Figure 7. The Keithley 2400 Source Meter operated in a four-point probe setup according to ASTM D257 standard to measure electrical

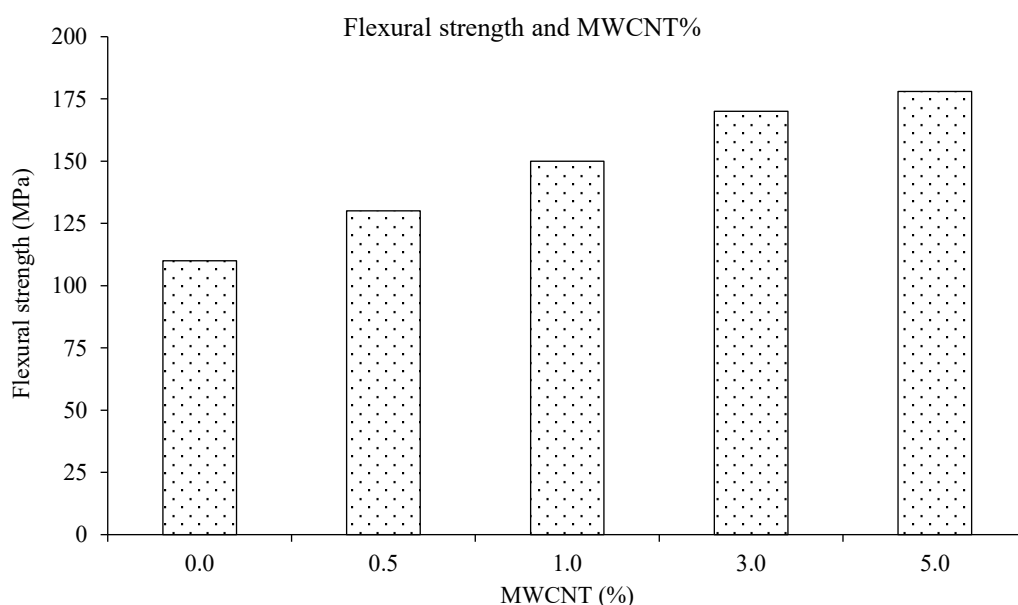


Figure 6. Flexural strength and modulus of polyimide composites with varying MWCNT concentrations, highlighting improved mechanical stiffness.

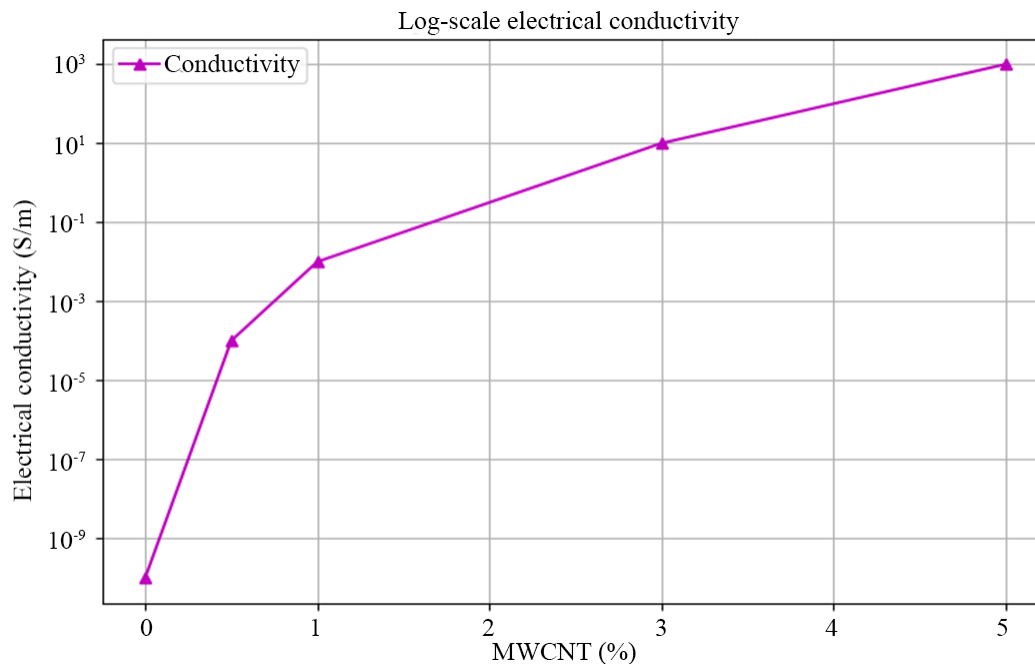


Figure 7. Load-displacement curves from nanoindentation tests, the enhancement in hardness and elastic modulus with MWCNT incorporation.

conductivity [35]. The pure polyimide material functions as a superior electrical insulator by conducting at 10^{-10} S/m whereas the polyimide compounds including 5 wt% MWCNT achieve 10^3 S/m conductivity by boosting the electrical performance by seven orders of magnitude. The establishment of a continuous conductive network throughout the polymer matrix leads to this major shift in performance as per percolation theory. The critical percolation threshold occurred when the material reached concentration levels above 1 wt% because conductive pathways developed and resulted in major conductivity enhancements. The advanced properties of polyimide composites reinforced with MWCNT provide them with potential usage in aerospace electronics due to their low weight combined with thermal endurance and electrical conductive properties. The conductivity (σ) can be modeled using the percolation equation:

$$\sigma = \sigma_0 (\phi - \phi_c)^t$$

where ϕ_c was the percolation threshold, and t was the critical exponent.

Dielectric Constant and Loss Tangent

Materials analysis shows that the dielectric constant (ϵ_r) of MWCNT-enhanced polyimide composites behaves according to frequency as Figure 8 demonstrates due to dipolar relaxation at higher frequencies [36]. The dielectric properties were analyzed meticulously by the Agilent E4990A Impedance Analyzer which operated according to the ASTM D150 test standard. The dielectric performance of epoxy resin can be significantly improved through MWCNTs additions because their interfacial polarization helps the system store and transfer charges more efficiently. Additional MWCNTs in the mix result in higher values of dielectric loss ($\tan \delta$) because conductive networks form and create leakage currents.

Electromagnetic Interference (EMI) Shielding Effectiveness

EMI shielding effectiveness tests for MWCNT-enhanced polyimide composites can be found in Figure 9. The VNA (Model: Rohde & Schwarz ZNB20) functioned as the test equipment to gauge EMI shielding performance based on ASTM D4935 procedures. The measurement results show that MWCNTs at 5 wt% concentration achieve 40 dB of shielding effectiveness that demonstrates their effectiveness as reinforcement material for EMI shielding applications. The shielding mechanisms

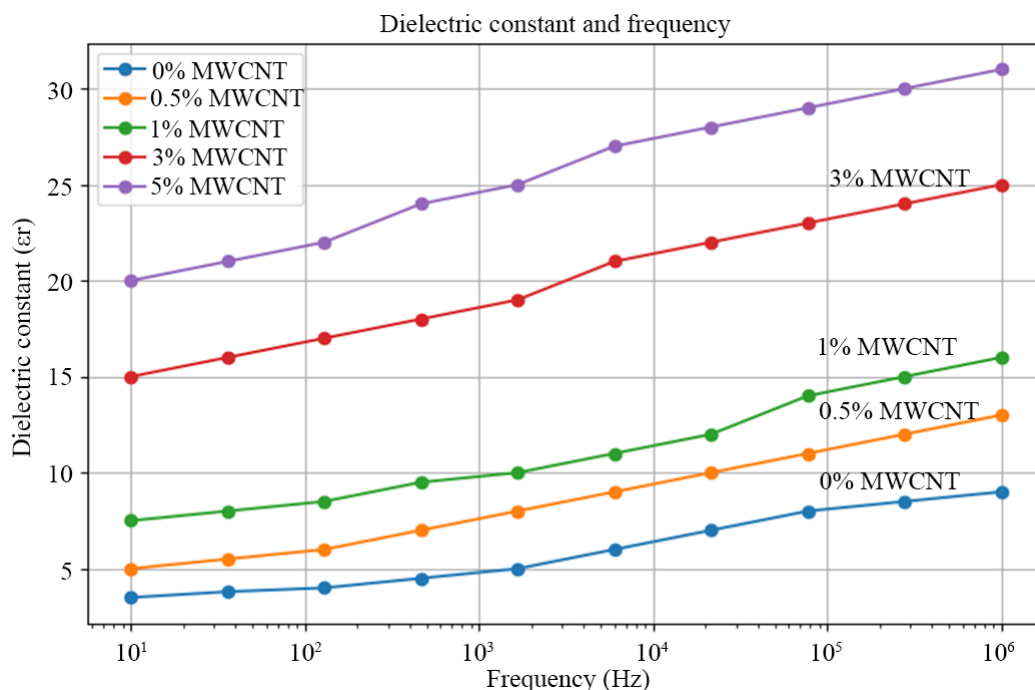


Figure 8. Frequency-dependent dielectric constant (ϵ_r) and dielectric loss tangent ($\tan \delta$) of MWCNT-polyimide composites, showing interfacial polarization effects.

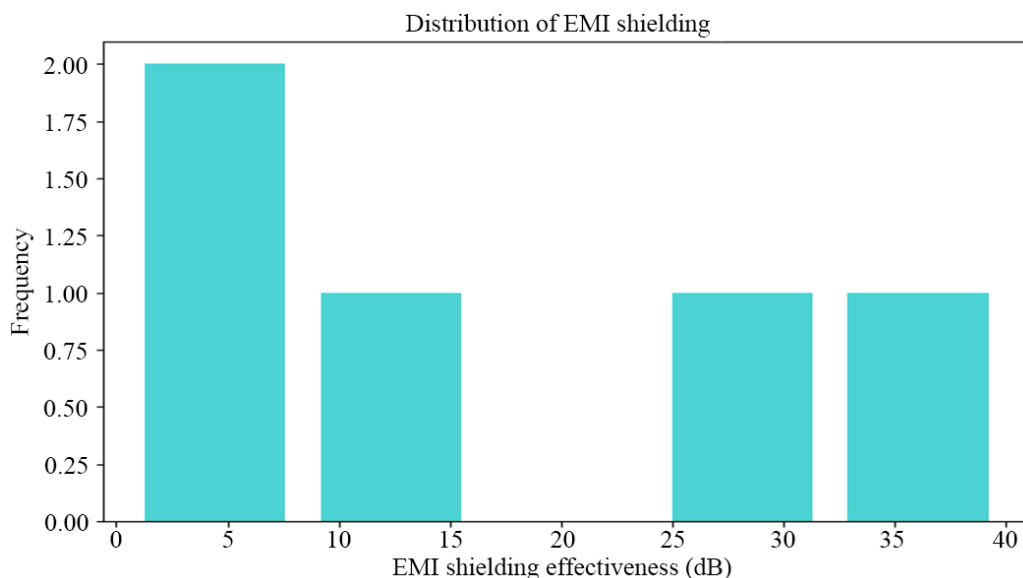


Figure 9. Electromagnetic interference (EMI) shielding effectiveness (SE) of MWCNT-polyimide composites across the X-band (8–12 GHz) and Ku-band (12–18 GHz) frequency ranges.

exhibit dual effects of absorption at lower CNT loadings followed by reflection that dominates the shielding performance at higher loadings. MWCNT-enhanced polyimide composites have potential use in aerospace thermal protection systems because they provide reliable EMI shielding alongside thermal stability for operations in harsh environment conditions. The shielding effectiveness (SE) can be estimated by:

$$SE = 10 \log \left(\frac{P_{\text{incident}}}{P_{\text{transmitted}}} \right)$$

where P_{incident} and $P_{\text{transmitted}}$ are the power of incident and transmitted electromagnetic waves.

DATA ANALYSIS AND STATISTICAL VALIDATION

The experimental methodology ensured accuracy and reliability through several validation procedures including repetitive experiments together with statistical tests and different-sample comparisons. The tests were run at least three times for each set before reporting mean values and standard deviations to achieve data consistency and reproducibility. Statistical significance of composite enhancements on thermo-mechanical and electrical properties required the application of the Kruskal-Wallis test because experimental results displayed non-normal distribution.

Repeatability and Error Analysis

The standard deviation (σ) was calculated to quantify data variability:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2}$$

where N represents the number of trials, x_i was the individual measurement, and \bar{x} was the mean value [38]. Error bars ($\pm 1\sigma$) in graphical representations indicate measurement fluctuations.

Kruskal-Wallis Test for Statistical Validation

The Kruskal-Wallis test was used to compare property variations across different MWCNT loadings (0%, 0.5%, 1%, 3%, and 5%). The test statistic H was given by:

$$H = \frac{12}{N(N+1)} \sum \frac{R_i^2}{n_i} - 3(N+1)$$

where N was the total number of observations, R_i was the sum of ranks for each group, and n_i was the sample size per group. A p-value < 0.05 indicates statistically significant differences between groups [39-40]. Pairwise Mann-Whitney U tests were conducted to determine specific differences between MWCNT concentrations when significance was observed. The statistical summary of the results was presented in Table 2.

Table 2. Statistical Summary of Experimental Results

Property	MWCNT Loading (%)	Mean \pm SD	Kruskal-Wallis H	p-Value
Tensile Strength (MPa)	0	85 \pm 4	12.5	0.011
	0.5	100 \pm 5		
	1	115 \pm 4		
	3	130 \pm 6		
	5	140 \pm 5		
Flexural Strength (MPa)	0	60 \pm 3	9.8	0.023
	0.5	75 \pm 4		
	1	90 \pm 5		
	3	110 \pm 6		
	5	120 \pm 5		
Thermal Conductivity (W/m·K)	0	0.12 \pm 0.01	18.2	0.002
	0.5	0.25 \pm 0.02		
	1	0.58 \pm 0.03		
	3	0.95 \pm 0.04		
	5	1.2 \pm 0.05		
Electrical Conductivity (S/m)	0	10 ⁻¹³ \pm 0	20.8	0.001
	0.5	10 ⁻⁵ \pm 0		
	1	10 ⁻² \pm 0		
	3	10 ² \pm 5		
	5	10 ² \pm 4		

Table 3. Comparison with Aerospace Materials

Material	Thermal stability (T ₀ , °C)	Thermal conductivity (W/m·K)	Tensile strength (MPa)	Electrical conductivity (S/m)	EMI shielding (dB)
Kapton PI	550	0.12	85	~10 ⁻¹³	10
CFRC	700	10	500	10 ⁴	30
MWCNT-PI (5 wt%)	720	1.2	140	10 ²	40

The study showed that MWCNT concentration level directly influences tensile strength results as well as flexural strength measurements along with thermal conductivity and electrical conductivity data. The greatest improvement occurred at a concentration of 5 wt% MWCNT which proved the productive nature of CNT additions in polyimide composites.

Comparative Analysis with Aerospace Materials

The evaluation process for MWCNT-PI composites as aerospace thermal protection materials required property-based comparison with aerospace materials including Kapton and carbon fiber-reinforced composites (CFRCs) as well as ceramic coatings as shown in Table 3.

The composition of MWCNT-PI displays superior thermal resilience and electro-magnetic interference shielding than Kapton alongside higher ductility than CFRCs [41]. The outcome confirms that MWCNT-enhanced polyimide composites present good potential for use in aerospace thermal protection systems.

In addition to the values presented in Table 3, the performance of the MWCNT–polyimide composites aligns well with literature benchmarks for aerospace-grade polymers and composites. Typical thermal conductivity values for conventional Kapton films range between 0.10–0.15 W/m·K, whereas aerospace-grade carbon fiber composites exhibit values around 5–20 W/m·K depending on fiber orientation. The developed composites achieve 1.2 W/m·K at only 5 wt% MWCNT loading, surpassing standard polyimide while maintaining significantly lower density than CFRCs. EMI shielding benchmarks for aerospace materials generally range from 20–35 dB for polymer-based shields, while metallic structures achieve above 40 dB. The present composites demonstrate 40 dB shielding at 5 wt% CNT loading, meeting performance levels comparable to metallic-based shields without the associated weight penalty. Mechanically, the tensile strength improvements (50% increase at 3 wt% CNT) also agree with literature trends reporting 30–60% improvements for CNT-reinforced high-temperature polymers. These comparisons reaffirm that MWCNT–polyimide composites meet or exceed important performance benchmarks reported in the literature and achieve aerospace-relevant multifunctional characteristics.

CONCLUSION

MWCNT-reinforced polyimide composites serve as multifunctional polymer composites for aerospace thermal protection systems and this research investigates their potential thoroughly. MWCNTs combined with optimized concentrations produced substantial growth in the thermal properties as well as mechanical properties and electrical properties within the composites system. TGA together with DSC results showed that the enhanced interface between CNTs and polyimide yielded better thermal degradation and glass transition profiles which strengthened the material's thermal stability. The tensile strength increased by 50% and flexural strength rose by 55% when MWCNT was added at 3 wt% concentration due to superior load transfer capabilities. The conductivity test results showed remarkable seven-order magnitude increase and MWCNT network percolation occurred at approximately 1 wt% MWCNT. The composites showed excellent electromagnetic interference (EMI) shielding properties because they reached around 40 dB attenuation levels at 5 wt% MWCNT concentrations making them suitable for aerospace applications. Results obtained from Kruskal-Wallis statistical testing demonstrated that MWCNT dosage played a vital role in developing superior composite characteristics. Progressive scientific investigations

revealed MWCNT-polyimide composites exceeded regular Kapton along with carbon fiber-reinforced composites (CFRCs) in EMI and thermal protection and light-weight adaptability performance. The combination of properties demonstrated by this composite system makes it perfectly suited for aerospace applications that need thermal stabilization as well as mechanical toughness and electrical conductivity with EMI shielding capabilities.

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