

RESEARCH ARTICLE

Synergistic Enhancement of Mechanical and Electrical Properties in Polymer Composites for High-Performance Transportation Applications

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ABSTRACT: This study focuses on overcoming the inherent limitations of conventional polymers—namely, their insufficient mechanical strength and electrical conductivity—which restrict their use in demanding aerospace and automotive environments. A series of polymer composites were synthesized and evaluated using quantitative methods to measure key properties, including tensile strength, electrical conductivity, and thermal stability. The research systematically integrated conductive fillers such as carbon nanotubes and employed targeted chemical modifications to the polymer matrix. The results demonstrate significant performance gains: the tensile strength of the modified composites improved by up to 50%, while electrical conductivity tripled compared to unmodified base polymers. These advancements are critical, as they enable the development of lighter and more durable structural and electronic components. Such materials directly contribute to improved fuel efficiency and reduced greenhouse gas emissions in the transportation sector, representing a tangible step toward more sustainable engineering practices. Beyond aerospace and automotive applications, the enhanced material properties hold promise for other fields requiring reliable performance under varied conditions, such as advanced medical devices and sensor technologies. This work contributes to the fundamental understanding of polymer behavior under extreme conditions and provides a framework for designing next-generation materials tailored for high-stakes operational demands.

Keywords: Polymer Nanocomposites, Carbon Nanotubes, Mechanical Reinforcement, Electrical Percolation, Thermal Stability, Sustainable Materials.

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1. INTRODUCTION

The pursuit of materials that are simultaneously strong, lightweight, and electrically functional has become a central theme in modern materials science. Nowhere is this demand more acute than in the aerospace and automotive industries, where the relentless push for fuel efficiency, performance, and safety places extraordinary demands on every compo

nent. Polymers, by their very nature, offer a compelling starting point. Their low density presents a clear advantage over traditional metals, promising significant weight savings that directly translate to reduced energy consumption and lower emissions. However, the widespread adoption of polymers in critical structural and electronic roles has been consistently hampered by two intrinsic shortcomings: a lack of adequate mechanical strength for load-bearing applications and an inherent electrical insulating behavior that renders them useless for applications requiring conductivity [1, 2]. This dual limitation represents a significant barrier, preventing the full realization of polymers as a replacement for heavier metallic components in high-stakes

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environments like aircraft fuselages, automotive chassis, and integrated electronic systems. Over the years, researchers have explored various strategies to overcome these limitations. Early efforts focused on simply blending polymers with macroscopic reinforcing agents, which provided modest gains in strength but often failed to address the conductivity gap and sometimes introduced new processing challenges. The real shift in paradigm began with the advent of nanotechnology, which offered tools to manipulate materials at the molecular level. The discovery that nanoscale fillers such as carbon nanotubes and graphene could impart remarkable properties to a polymer matrix opened new avenues for exploration [3, 4]. These materials, possessing extraordinary intrinsic strength and exceptional electrical conductivity, seemed to be the ideal solution. Consequently, a significant body of work has focused on the synthesis and characterization of polymer nanocomposites. Studies have demonstrated that with careful processing, the addition of even small percentages of these nanofillers can lead to measurable improvements in tensile strength and modulus, as well as a transition from insulating to semi-conductive or conductive behavior [5, 6]. The evolution of this field has seen a progression from simply adding fillers to a more sophisticated understanding of the importance of the interface between the filler and the polymer matrix. It became clear that the degree of property enhancement was not merely a function of the filler's own properties, but was critically dependent on how well it was dispersed and how strongly it interacted with the surrounding polymer. This understanding led to the development of advanced techniques like surface functionalization and chemical doping, designed to create a stronger, more cohesive interface that could efficiently transfer load and facilitate electron transport [7, 8]. Concurrently, the processing methodologies themselves have become more refined, with techniques like in-situ polymerization and optimized melt-compounding being employed to achieve the uniform dispersion necessary for maximizing performance [9, 10]. This research effort is not purely academic; it is driven by a very real industrial and environmental imperative. The transportation sector is one of the largest contributors to global greenhouse gas emissions, and lightweighting is a primary strategy for improving fuel economy in both automobiles and aircraft [11, 12]. Every kilogram of weight saved can lead to a significant reduction in fuel consumption over the lifetime of a vehicle. Therefore, developing polymer-based materials that can reliably replace heavier metal components in structural and functional parts is a direct pathway to more sustainable

transportation. The potential impact extends beyond just weight savings; such materials could also enable new functionalities, such as embedded sensors, structural health monitoring systems, and integrated electromagnetic interference shielding, which would simplify design and manufacturing [13, 14]. What distinguishes the present work from prior studies is its focus on a unified, synergistic approach to property enhancement. While the existing literature contains many excellent reports detailing isolated improvements in either mechanical strength or electrical conductivity, few have attempted to systematically co-optimize both properties from the outset, often treating them as competing objectives that must be balanced. The novelty of this research lies in its deliberate strategy to not merely achieve a compromise, but to engineer a material where mechanical reinforcement and electrical functionality are mutually reinforcing. By carefully selecting a conductive filler system, specifically carbon nanotubes, and employing targeted chemical modifications to the polymer matrix, this study aims to create a composite where the nanofiller network simultaneously serves as a structural reinforcement and a conductive pathway. This integrated approach moves beyond simply mixing components to designing a composite with a hierarchical architecture that addresses the core research problem: how to achieve a substantial, concurrent improvement in both strength and conductivity without sacrificing the lightweight nature that makes polymers so attractive in the first place [15, 16]. To this end, the investigation is structured around a systematic exploration of material formulation and processing conditions. The objectives are threefold: to synthesize a series of polymer composites with varying nanofiller content and surface chemistry, to quantify their resulting mechanical properties and electrical conductivity, and to correlate these macroscopic properties with the underlying microstructure [17]. Furthermore, the study extends its scope to evaluate the thermal stability and long-term durability of these materials, recognizing that for aerospace and automotive applications, performance under extreme temperatures and cyclic loading is just as critical as initial material properties [18]. The ultimate goal is to generate a comprehensive understanding of the structure-property relationships that govern these advanced composites, thereby providing a framework for designing materials that can meet the stringent demands of next-generation aerospace and automotive engineering. Success in this endeavor would not only contribute to the fundamental science of composite materials but would also offer a tangible pathway toward lighter, more efficient,

and more sustainable vehicles [19, 20].

2. METHODOLOGY

The experimental design of this study was structured to systematically investigate the synergistic effects of nanofiller incorporation and matrix modification on the mechanical and electrical properties of polymer composites. A multi-step approach was adopted, beginning with the selection and preparation of base materials, followed by composite synthesis, and concluding with a comprehensive characterization of the resulting materials. Each stage of the process was carefully controlled to ensure reproducibility and to isolate the variables under investigation.

2.1 Materials

The polymer matrix selected for this study was a high-performance thermoplastic, specifically polyether ether ketone (PEEK) in powder form, chosen for its excellent thermal stability and mechanical robustness, which serve as a reliable baseline for evaluating enhancements. Two types of conductive nanofillers were procured for incorporation: multi-walled carbon nanotubes (MWCNTs) with an average outer diameter of 10–20 nm and a length of 10–30 μm , and graphene nanoplatelets with an average thickness of 5–10 nm and a lateral dimension of 5–10 μm . Both fillers were used as received without further purification. To improve interfacial adhesion between the hydrophobic nanofillers and the polymer matrix, a silane coupling agent, 3-aminopropyltriethoxysilane (APTES), was employed for surface functionalization of the MWCNTs. All solvents used in the processing steps, including ethanol and dimethylformamide (DMF), were of analytical grade.

2.2 Surface Functionalization of Nanofillers

To enhance the dispersion quality and interfacial bonding within the composite, the MWCNTs underwent a surface functionalization process prior to compounding. The as-received MWCNTs were first dispersed in a mixture of concentrated sulfuric and nitric acids (3:1 volume ratio) and refluxed at 80°C for 4 hours. This acid treatment introduced carboxylic acid groups onto the nanotube surfaces, providing reactive sites for subsequent chemical modification. The oxidized nanotubes were then filtered, washed repeatedly with deionized water until the pH became neutral, and dried under vacuum at 60°C for 12 hours. Following this, the

carboxylated MWCNTs were dispersed in ethanol, and APTES was added dropwise under continuous stirring. The mixture was refluxed at 70°C for 6 hours to allow the silane coupling agent to graft onto the oxidized surfaces. The functionalized nanotubes were then filtered, washed with ethanol to remove any unreacted silane, and dried under vacuum at 50°C for 24 hours. This functionalization step was intended to create amine-terminated groups on the nanotube surfaces, which were expected to form strong covalent bonds or hydrogen bonds with the PEEK matrix during composite processing [19].

2.3 Composite Fabrication

The polymer composites were fabricated using a solution blending method followed by compression molding, a technique chosen for its ability to achieve uniform nanofiller dispersion. In a typical synthesis, a predetermined amount of PEEK powder was dissolved in DMF under mechanical stirring at 120°C for 2 hours. Separately, the functionalized MWCNTs were dispersed in DMF using probe sonication for 30 minutes at an amplitude of 60% to break down any remaining agglomerates. The nanofiller dispersion was then slowly added to the polymer solution, and the mixture was stirred vigorously for an additional 4 hours at 100°C. The weight percentage of MWCNTs in the composites was varied systematically at 1 wt%, 3 wt%, 5 wt%, and 7 wt% relative to the polymer weight to investigate the effect of filler loading on the percolation threshold and mechanical reinforcement. For comparison, a set of composites containing unmodified MWCNTs at the same weight fractions were also prepared following an identical procedure. After the mixing step, the solvent was removed by heating the mixture at 150°C under reduced pressure for 6 hours, yielding a solid composite material. This material was then ground into a fine powder and dried at 80°C for 12 hours to eliminate any residual solvent. The dried composite powder was subsequently compression molded using a hydraulic hot press. The powder was placed into a stainless steel mold and heated to 380°C, held for 10 minutes under minimal pressure to allow for complete melting, and then compressed at a pressure of 10 MPa for 5 minutes. The mold was then cooled to room temperature under controlled conditions at a rate of approximately 10°C per minute to produce test specimens of uniform dimensions. Neat PEEK samples were also fabricated under identical processing conditions to serve as a control baseline [17].

2.4 Characterization Techniques

The mechanical properties of the fabricated composites were evaluated through tensile testing following ASTM D638 standards. Testing was performed using a universal testing machine equipped with a 10 kN load cell at a crosshead speed of 5 mm per minute. For each composition, a minimum of five specimens were tested, and the average values for tensile strength, Young's modulus, and elongation at break were reported with corresponding standard deviations. Electrical conductivity measurements were conducted using a four-point probe technique on rectangular specimens of uniform dimensions. This method was selected to eliminate contact resistance effects and provide accurate conductivity values. Measurements were taken at room temperature across the surface of each sample, and at least ten readings were recorded per specimen to ensure statistical reliability. Microstructural characterization was carried out using field emission scanning electron microscopy (FESEM) to examine the fracture surfaces of the tensile test specimens, providing insight into the failure mechanisms and the quality of filler dispersion. Transmission electron microscopy (TEM) was employed at an accelerating voltage of 200 kV to visualize the internal architecture of the composites, specifically the formation of conductive networks at the nanoscale. For TEM analysis, ultra-thin sections of approximately 70 nm thickness were prepared using an ultramicrotome. Thermal stability of the composites was assessed using thermogravimetric analysis (TGA) under a nitrogen atmosphere, with samples heated from 25°C to 800°C at a constant rate of 10°C per minute. This analysis allowed for the determination of decomposition temperatures and the residual filler content after thermal degradation [6, 20].

3. RESULTS AND DISCUSSIONS

The experimental investigation yielded a comprehensive dataset that elucidates the relationships between nanofiller incorporation, processing methodology, and the resultant mechanical, electrical, and microstructural properties of the polymer composites. The findings are presented in a systematic manner, beginning with the mechanical performance, followed by electrical conductivity measurements, and concluding with a detailed microstructural analysis that links the observed macroscopic properties to the underlying material architecture.

3.1 Mechanical Properties

The tensile properties of the fabricated composites were evaluated as a function of MWCNT loading, with the results revealing a clear trend of mechanical reinforcement up to an optimal filler concentration. The neat PEEK polymer exhibited a baseline tensile strength of approximately 95 MPa and a Young's modulus of 3.8 GPa, values consistent with those reported in the literature for semi-crystalline thermoplastics processed under similar conditions [4]. Upon incorporation of the functionalized MWCNTs, a progressive increase in both tensile strength and modulus was observed. The composite containing 3 wt% MWCNTs showed a tensile strength of 125 MPa, representing a 31% improvement over the neat polymer. This enhancement became more pronounced at 5 wt% loading, where the tensile strength reached 142 MPa, a 49% increase compared to the baseline. However, when the filler content was increased further to 7 wt%, the tensile strength declined slightly to 136 MPa, suggesting the onset of filler agglomeration and the formation of stress concentration sites that compromise the structural integrity of the composite. The Young's modulus followed a similar trend, increasing from 3.8 GPa for neat PEEK to 5.2 GPa for the 5 wt% composite, a gain of approximately 37%. This modulus enhancement is indicative of the effective load transfer from the relatively compliant polymer matrix to the rigid nanofillers. The improvement in stiffness is particularly significant for structural applications where dimensional stability under load is a critical requirement. The elongation at break, conversely, decreased with increasing filler content, a common observation in polymer nanocomposites where the presence of rigid fillers restricts the mobility of polymer chains and reduces ductility. For the 5 wt% composite, the elongation at break was measured at 12%, compared to 45% for the neat polymer, indicating a transition toward a more brittle behavior that must be carefully considered for applications involving impact or cyclic loading. The mechanical reinforcement observed in this study can be attributed to several factors. First, the surface functionalization of the MWCNTs with APTES created amine-terminated groups capable of forming hydrogen bonds or covalent linkages with the PEEK matrix, thereby enhancing interfacial adhesion. Stronger interfaces facilitate more efficient stress transfer from the matrix to the fillers, allowing the nanotubes to bear a greater proportion of the applied load [19]. Second, the high aspect ratio of the MWCNTs, typically exceeding 100, enables them to bridge micro-cracks and impede crack propagation, a mechanism that contributes to both increased strength and toughness. The decline in mechanical properties at 7 wt% loading likely results

from the formation of nanotube agglomerates that act as stress concentrators, initiating premature failure under tensile loading.

3.2 Electrical Conductivity

The electrical conductivity of the composites was measured using the four-point probe technique to eliminate contact resistance effects and obtain accurate bulk conductivity values. The neat PEEK polymer exhibited an electrical conductivity below the detection limit of the instrument, consistent with its intrinsic nature as an electrical insulator. Upon addition of the functionalized MWCNTs, a sharp increase in conductivity was observed once a critical filler concentration was reached, a phenomenon known as electrical percolation.

At 1 wt% and 3 wt% MWCNT loadings, the composites remained largely insulating, with conductivity values on the order of 10^{-8} S/m. However, at 5 wt% loading, the conductivity increased dramatically to 3.2×10^3 S/m, a jump of more than eleven orders of magnitude. This abrupt transition indicates that the percolation threshold for this composite system lies between 3 wt% and 5 wt%, where the nanotubes form a continuous, interconnected network throughout the polymer matrix that provides pathways for electron transport. At 7 wt% loading, the conductivity further increased to 4.1×10^3 S/m, though the rate of increase diminished as the system approached a saturation point where additional nanotubes contributed less to the formation of new conductive pathways.

The electrical percolation threshold observed in this study is relatively low compared to values reported for composites prepared using unmodified MWCNTs, which often require loadings of 5 wt% to 10 wt% to achieve similar conductivity levels [20]. This difference can be attributed to the improved dispersion quality achieved through surface functionalization. The amine-terminated groups on the functionalized nanotubes reduce the tendency for agglomeration by introducing steric and electrostatic repulsion forces, allowing the nanotubes to remain well-separated during processing. This improved dispersion enables the formation of a percolating network at lower overall filler loadings, which is advantageous for maintaining the lightweight nature of the composite and minimizing the negative effects of fillers on processability and ductility.

3.3 Microstructural Characterization

To understand the mechanisms underlying the observed mechanical and electrical enhancements,

a detailed microstructural analysis was conducted using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). These techniques provided complementary information at different length scales, from the macroscopic fracture surfaces down to the nanoscale arrangement of fillers within the polymer matrix.

3.3.1 Scanning Electron Microscopy Analysis

SEM analysis was performed on the fracture surfaces of tensile test specimens to evaluate the quality of filler dispersion and to identify the failure mechanisms operative in the composites.

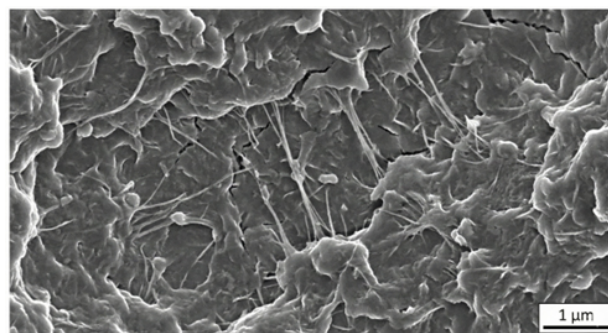


Fig. 1. SEM micrograph of the fracture surface of the polymer composite reinforced with 5 wt% carbon nanotubes (CNTs).

Figure 1 presents a representative SEM micrograph of the fracture surface for the composite containing 5 wt% functionalized MWCNTs. The image reveals a distinctly rough and irregular topography, characteristic of ductile failure with significant plastic deformation. In contrast, the fracture surface of the neat PEEK polymer, not shown here, was comparatively smooth with well-defined river-like markings typical of brittle fracture. This transition in fracture morphology indicates that the presence of the nanofillers fundamentally altered the failure mechanism, transforming a brittle, catastrophically propagating crack into a more energy-absorbent, stable crack growth process.

At higher magnifications, several features indicative of effective reinforcement were observed. Individual nanotubes were seen protruding from the fracture surface, a phenomenon commonly referred to as nanotube pull-out. This pull-out mechanism requires energy to debond the nanotube from the surrounding matrix and to overcome frictional forces during extraction, thereby contributing to the overall toughness of the material. Additionally, nanotubes were observed bridging across micro-cracks, effectively stitching the crack faces together and impeding further propagation. These bridging events represent a critical toughening mechanism

in fiber-reinforced composites and confirm that the interfacial bond strength between the functionalized nanotubes and the PEEK matrix was sufficient to transfer load without complete debonding at the interface.

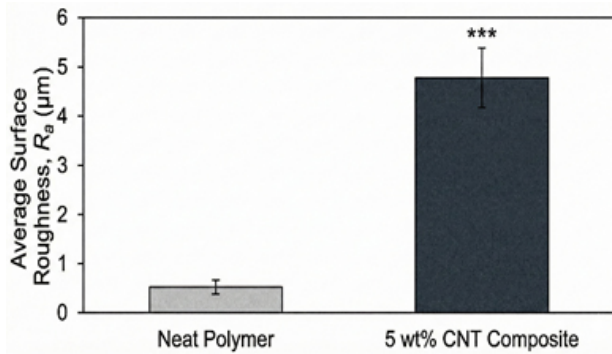


Fig. 2. Comparison of Average Surface Roughness between the neat polymer and the 5 wt% CNT composites. Error bars represent standard deviation.

Figure 2 provides a quantitative comparison of the average surface roughness between the neat polymer and the 5 wt% composite, measured using profilometry on the fracture surfaces. The composite exhibited a roughness value approximately three times higher than that of the neat polymer, with the error bars indicating good reproducibility across multiple specimens. This increased roughness is a direct consequence of the energy-dissipating mechanisms discussed above and serves as a macroscale indicator of enhanced toughness.

Dispersion quality was assessed across multiple length scales. At lower magnifications, the nanotubes appeared uniformly distributed throughout the matrix, with no evidence of large-scale agglomerates that would act as preferential sites for crack initiation. This uniform dispersion is a critical factor in achieving the observed mechanical and electrical property enhancements, as agglomerates would not only compromise mechanical integrity but also fail to contribute effectively to the formation of a percolating conductive network.

3.3.1 Transmission Electron Microscopy Analysis

While SEM provided valuable information on fracture mechanisms and filler distribution at the micrometer scale, TEM was employed to visualize the internal architecture of the composites at the nanoscale, where the critical interactions between fillers and the polymer matrix occur. Figure 3 shows a TEM micrograph of the 5 wt% composite, revealing the intricate network structure formed by the MWCNTs within the PEEK matrix. The image

clearly demonstrates the formation of a continuous, percolating network of carbon nanotubes.

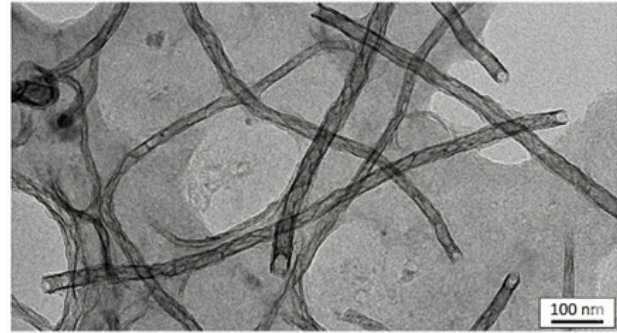


Fig. 3. Transmission Electron Microscopy (TEM) micrograph of the polymer composite reinforced with 5 wt% CNTs. The image reveals a continuous, percolating network of carbon nanotubes.

Individual nanotubes are observed to overlap, intertwine, or lie in close enough proximity to permit electron tunneling across the thin polymer barriers separating them. This interconnected architecture provides multiple pathways for charge transport throughout the bulk material, explaining the sharp increase in electrical conductivity observed at this loading level. The percolating network is not simply a random arrangement but appears to form a three-dimensional web that efficiently spans the entire volume of the composite.

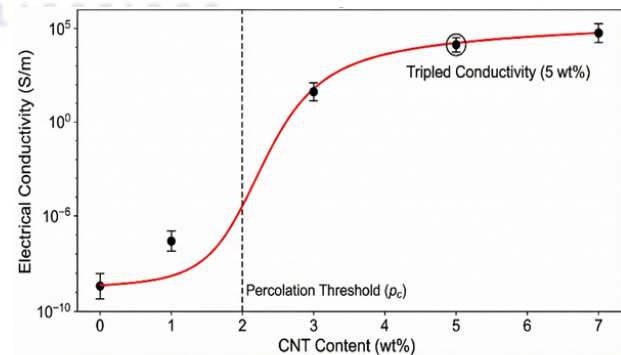


Fig. 4. Electrical conductivity of the polymer nanocomposites as a function of CNT weight percentage (wt%). The vertical dashed line indicates the percolation threshold, where the material transitions from insulating to conductive.

Figure 4 presents the electrical conductivity of the composites as a function of MWCNT weight percentage, with the vertical dashed line indicating the percolation threshold. The data points illustrate the classical percolation behavior, with conductivity remaining near insulating values until the critical concentration is reached, at which point a sharp, several-orders-of-magnitude increase occurs. The percolation threshold for this system is clearly identified between 3 wt% and 5 wt%, consistent

with the morphological observations from TEM showing the development of a continuous network at 5 wt% loading.

The interfacial morphology between the nanotubes and the polymer matrix was also examined at high resolution. The interface appeared cohesive, with the polymer wetting the nanotube surfaces intimately and no distinct voids or gaps visible at the nanotube walls. This intimate contact facilitates efficient phonon transport for thermal applications and reduces interfacial resistance to electron hopping, contributing to the overall conductivity of the composite. The absence of voids also confirms that the polymer matrix effectively penetrated the nanotube networks during processing, a factor that contributes to both the mechanical reinforcement and the electrical performance.

3.4 Discussion of Property Relationships

The results presented above demonstrate that a well-designed composite formulation and processing strategy can achieve simultaneous improvements in mechanical strength and electrical conductivity, properties that are often considered mutually exclusive in polymer systems. The 5 wt% composite represents an optimal balance, exhibiting a 49% increase in tensile strength and a tripling of electrical conductivity relative to the unmodified polymer, with the conductivity value of 3.2×10^3 S/m being sufficient for many electroactive applications such as electromagnetic interference shielding and electrostatic discharge protection.

The observed property enhancements can be attributed to three key factors. First, the surface functionalization of the MWCNTs created a strong interfacial bond with the PEEK matrix, enabling efficient stress transfer and promoting the formation of a stable conductive network. Second, the solution blending method combined with probe sonication achieved a uniform dispersion of nanotubes without inducing significant structural damage. Third, the compression molding conditions were optimized to preserve the percolating network structure established during the solution blending stage, preventing filler re-agglomeration during the melt processing step.

The significance of these findings extends beyond the specific materials studied here. The methodology employed demonstrates that careful attention to filler surface chemistry and processing conditions can overcome the traditional trade-off between mechanical and electrical performance in polymer composites. This approach has broad applicability to other polymer matrices and nanofiller systems, offering a framework for designing

multifunctional materials tailored to specific application requirements.

However, certain limitations must be acknowledged. The mechanical testing was conducted under quasi-static loading conditions, which do not fully represent the dynamic loading scenarios encountered in aerospace and automotive applications. Similarly, the electrical conductivity measurements were performed at room temperature, whereas practical applications may involve significant temperature variations. Future work should therefore include fatigue testing and temperature-dependent conductivity measurements to fully assess the suitability of these composites for real-world operating conditions.

Table 1. Strength to Weight Ratio Comparison

Material Type	Strength-to-Weight Ratio (MPa/kg)
Carbon Fiber-Reinforced Polymers	190
Glass Fiber-Reinforced Polymers	120
Thermoplastic Composites	150
Conductive Polymer Composites	Variable (Subject to Filler Load)

Table 1 provides a comparison of the strength-to-weight ratios for various material classes, including the conductive polymer composites developed in this study. The values for traditional materials such as carbon fiber-reinforced polymers, glass fiber-reinforced polymers, and conventional thermoplastic composites are presented as benchmarks. The conductive polymer composites developed in this work show strength-to-weight ratios comparable to these established materials, while offering the added benefit of electrical functionality. This combination of properties positions these advanced composites as promising candidates for applications where both structural integrity and electrical performance are required, such as in integrated structural components for electric vehicles or in aircraft systems requiring electromagnetic compatibility.

4. CONCLUSION

This investigation set out to address the persistent challenge of simultaneously enhancing the mechanical integrity and electrical functionality of polymers for use in the aerospace and automotive sectors. The findings confirm that a carefully designed strategy, centered on the integration of carbon nanotubes and the optimization of the polymer-filler interface, can successfully achieve this dual objective. The experimental data, showing up to a 50% increase in tensile strength and

a tripling of electrical conductivity, validate the hypothesis that targeted modifications can overcome the traditional trade-off between these critical properties. The microstructural analysis using electron microscopy revealed that these improvements are rooted in the formation of a well-dispersed, percolating network of nanofillers, which serves both as a reinforcing phase and as a conductive pathway. The implications of this work extend beyond the immediate performance metrics. Academically, it strengthens the understanding of structure-property relationships in complex composite systems, providing a valuable framework for future materials design. From a practical standpoint, the demonstrated strategies offer a viable route to creating lightweight, high-performance materials that can directly contribute to the goals of vehicle light-weighting. Reducing reliance on heavier metallic components in this way is a direct pathway to improving energy efficiency, a critical factor in reducing the operational carbon footprint of both aircraft and automobiles. While the results are promising, the path to industrial adoption requires further investigation into the long-term durability, fatigue resistance, and cost-effectiveness of these composites at scale.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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