Twin-Extrusion Processed Polycarbonate Composite Configured With Alumina and Carbon Nanotube Performance Evaluation

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**Abstract:** This work examines the mechanical properties and thermal properties of polycarbonate composites supplemented with alumina nanoparticles 50 nm and chopped carbon nanotubes produced by twin screw extrusion. Five composite formulations were created: pure PC, PC with 1 wt% CNT and PC with 1 wt% CNT mixed with 2, 4 and 6 wt% alumina. Mechanical properties like stress strain, heat deflection temperature (HDT) and tribological behaviour (i.e) wear rate and coefficient of friction were evaluated. The results show that hybrid filler insertion considerably enhances HDT, tensile stiffness and wear resistance. The composition including 1 wt% CNT and 4 wt% alumina performed the best in all areas, making it a potential material for lightweight structural brackets in automotive and electronics applications.

# Introduction

Polycarbonate is a popular engineering thermoplastic noted for its great impact resistance, optical clarity and dimensional stability. However its modest heat resistance and wear properties limit its use in high performance mechanical components like structural brackets in the aerospace and automotive sectors [1-4].

Carbon nanotubes with alumina nanoparticles shows improving performance. CNTs have a high aspect ratio electrical conductivity and tensile strength whereas alumina's ceramic nature enhances thermal stability, wear resistance and surface hardness. The twin-screw extrusion method uniformly mixes and disperses nanofillers into the polymer matrix in controlled temperature and shear settings.Polycarbonate nanocomposites, due to their potential for high performance applications when reinforced with carbon nanotubes and ceramic fillers like alumina [5-9] and designed for high impact applications, emphasizing the role of sophisticated nanofillers in increasing mechanical robustness and thermal endurance. Further supported this by developing structurally graded alumina-polymer composites with improved mechanical properties making them perfect for biomedical applications such as orthodontic brackets [10-12].

Researchers [13-14] examined the mechanical behavior of friction stir welded polylactic acid with aluminum composites providing insights into hybrid joining techniques that may be used to PC-metal systems. Researchers [15-18] examined the structural evolution of zirconia nanofibers and discovered a direct relationship between hardness and Young's modulus findings that could help design ceramic reinforced PC composites. They [19-20]emphasized the influence of alumina particle dimensions in the thermal conductivity increase of PC/boron nitride composites, proposing optimized alumina topologies for improved heat dissipation in PC matrices. They [21-23] studied the efficiency of nanofillers improving impact resistance and structural qualities in polycarbonate systems. formulated a comprehensive machinability model for CNT glass fibre composites for the optimization of milling operations for CNT with PC composites while Sabet (8) assessed structural advancements in CNT polymer composites, highlighting their influence on mechanical and tribological performance which is essential for PC based structural components.

Demonstrated the synergistic effect of mixing graphite flakes with MWCNTs in PC nanocomposites, which resulted in considerable improvements in thermal, electrical, and electromagnetic interference shielding capabilities with all of which are crucial for advanced electronics [24-26]. They [27] found that graphene and CNT-reinforced Al₂O₃ nanocomposites have superior thermal and mechanical properties, aligning with hybrid PC system aims. Köse (11) broadened the scope by investigating aluminum-filled cyclo-olefin-copolymer composites and discovered improved tribological behavior a desirable feature in high-friction PC applications [28-30]. Ternary nanocomposites incorporating clay and calcium carbonate for biomedical applications, demonstrating the viability of multifunctional PC composites with diverse applications. Similarly investigated hybrid aluminium composites in high-temperature dry sliding conditions and discovered enhanced self-lubricating behavior, which is relevant to thermally demanding PC composites [31-33].

This research aims to assess the belongings of CNT and alumina fillers on the heat resistance, mechanical performance and tribological properties of PC composites, with a particular emphasis on lightweight bracket applications that require both load bearing and heat-resistant properties.

# Materials and Methods

## Materials

The matrix material utilized in this investigation was injection molding grade polycarbonate recognized for its superior impact resistance, thermal stability and clarity. This thermoplastic was chosen for its compatibility with high-performance filler systems and its ease of melt processing. Chopped multi-walled carbon nanotubes of 1–3 mm in length were employed as the principal nano reinforcement to improve mechanical and tribological capabilities. Because of their exceptional tensile strength and aspect ratio these carbon nanotubes are widely used in polymer matrices for effective stress transfer and stiffness enhancement. As secondary reinforcements 50 nm-diameter and 99.9% pure spherical alumina nanoparticles were used to improve wear and heat resistance. Because of its exceptional hardness, inherent wear resistance and thermal conductivity alumina was chosen as a key ingredient in hybrid composite compositions [34-39].

## Composite Formulations

Five different formulations were prepared to investigate the influence of CNTs and Al₂O₃ nanoparticles on the thermomechanical and tribological behavior of PC. The compositions are detailed below:

**TABLE 1.** Mechanical Composite Formulations Table

|  |  |
| --- | --- |
| **Sample** | **Description** |
| 1 | PC (Neat) |
| 2 | PC + 1 wt% CNT |
| 3 | PC + 1 wt% CNT + 2 wt% Al₂O₃ |
| 4 | PC + 1 wt% CNT + 4 wt% Al₂O₃ |
| 5 | PC + 1 wt% CNT + 6 wt% Al₂O₃ |

The design of these composites aimed to identify the optimal balance between strength, toughness, thermal deflection and wear resistance, while maintaining processability.

## Processing Technique

In order to prevent hydrolytic deterioration during production all filler materials and PC pellets were first dried in a vacuum oven to remove any remaining moisture. A twin screw extruder with a screw speed of 60 rpm and a temperature collection of 260 to 280 °C was used to compound the dried materials. This design ensured effective shear mixing and uniform dispersion of the nanofillers inside the PC matrix. For mechanical, thermal and tribological examination the resultant extrudate was pelletised and subsequently injection moulded into standardised test specimens [40-43]. This approach ensured optimal filler distribution scalability of the process and reproducibility of composite specimens.

# Results and Discussion

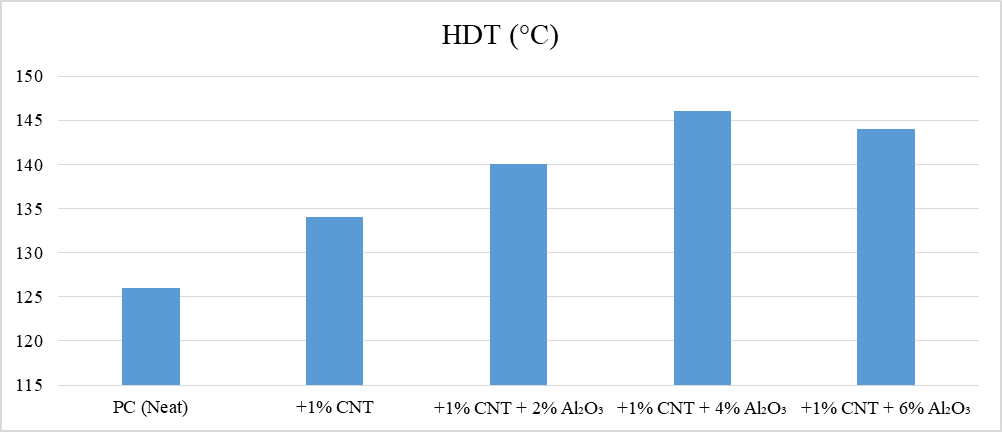
## Heat Deflection Temperature (HDT)

The heat deflection temperature of the composites was measured to assess their ability to withstand thermal deformation under load. The results are shown below:

**TABLE 2.** Heat Deflection Temperature (HDT)

|  |  |
| --- | --- |
| **Sample** | **Heat Deflection Temperature (HDT)(°C)** |
| PC (Neat) | 126 |
| PC + 1 wt% CNT | 134 |
| PC + 1 wt% CNT + 2 wt% Al₂O₃ | 140 |
| PC + 1 wt% CNT + 4 wt% Al₂O₃ | 146 |
| PC + 1 wt% CNT + 6 wt% Al₂O₃ | 144 |

The incorporation of 1 wt% CNT alone elevated the HDT by 8°C signifying that CNTs constrained polymer chain mobility and augmented thermal rigidity and the addition of alumina nanoparticles enhanced the heat distortion temperature with the 4 wt% Al₂O₃ formulation reaching a peak of 146°C with an increase of 20°C compared to unmodified polycarbonate. This improvement is due to the ceramic alumina particles functioning as thermal insulators and mobility restrictors, hence augmenting the resistance to thermal softening of the composites. Nonetheless, elevating the Al₂O₃ content to 6 wt% somewhat diminished the HDT presumably due to nanoparticle agglomeration which may create localized heat stress concentrations and impede efficiency [44-49].



**Figure 1.**Heat Deflection Temperature (HDT) (°C)

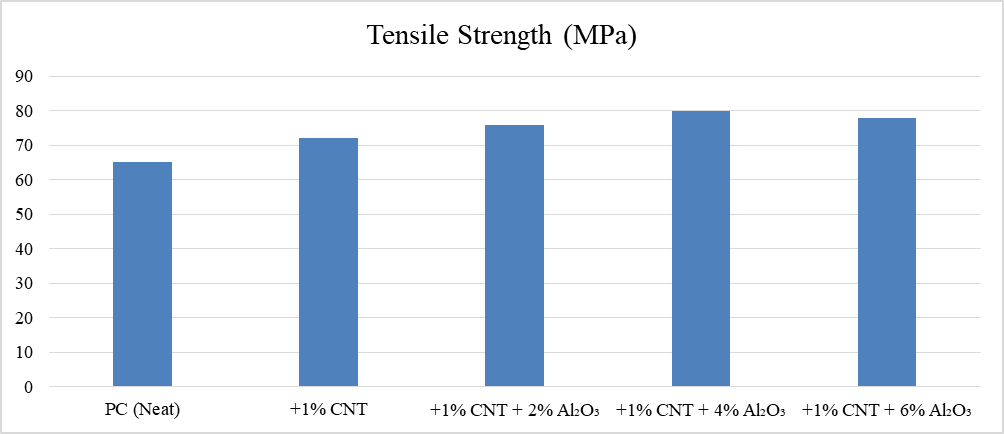
## Stress–Strain Behavior

Mechanical performance was evaluated using tensile testing. The key results are summarized in the table below:

**TABLE 3.** Stress–Strain Behavior

|  |  |  |  |
| --- | --- | --- | --- |
| **Sample** | **Tensile Strength (MPa)** | **Modulus (GPa)** | **Elongation (%)** |
| PC (Neat) | 65 | 2.4 | 10.1 |
| PC + 1 wt% CNT | 72 | 2.8 | 9.4 |
| PC + 1 wt% CNT + 2 wt% Al₂O₃ | 76 | 3.1 | 8.6 |
| PC + 1 wt% CNT + 4 wt% Al₂O₃ | 80 | 3.4 | 7.9 |
| PC + 1 wt% CNT + 6 wt% Al₂O₃ | 78 | 3.3 | 7.2 |

The incorporation of CNTs enhanced tensile strength and modulus by 10.8% and 16.7%, respectively and the additional incorporation of Al₂O₃ nanoparticles led to a consistent enhancement in mechanical properties up to a 4 wt% loading at which point the composite attained a tensile strength of 80 MPa and a modulus of 3.4 GPa indicating a 23% upsurge in strength and a 42% rise in stiffness compared to clean PC. A concomitant decrease in elongation at break was noted in all reinforced samples, especially at elevated filler concentrations. The reduction in ductility is ascribed to filler induced embrittlement as the inflexible particles diminish the matrix's capacity for plastic deformation. The 1 wt% CNT + 4 wt% Al₂O₃ composite provided the optimal equilibrium between stiffness and ductility resulting in a structurally resilient formulation [50].



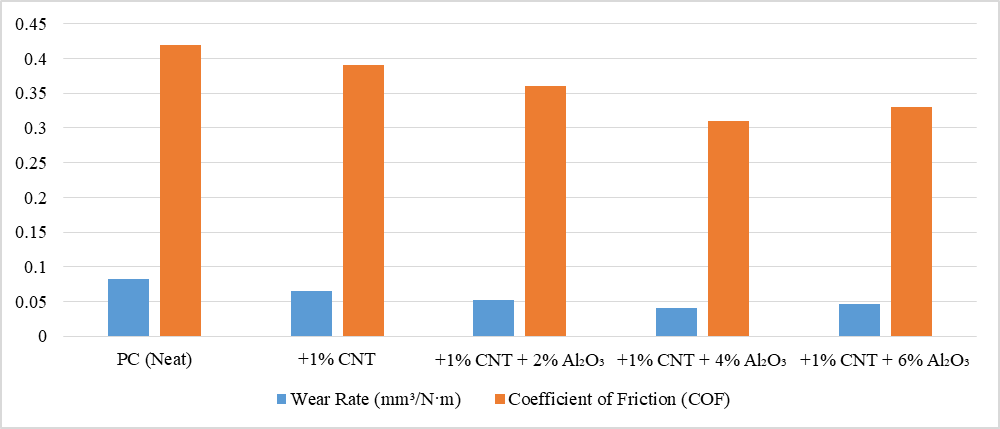
**Figure 2.** Stress–Strain Behavior

## Wear Rate and Coefficient of Friction

Tribological properties were measured to evaluate the material's resistance to wear and friction under sliding conditions. The values obtained are as follows:

**TABLE 4.** Energy Absorption

|  |  |  |
| --- | --- | --- |
| **Sample** | **Wear Rate (mm³/N·m)** | **Coefficient of Friction (COF)** |
| PC (Neat) | 0.082 | 0.42 |
| PC + 1 wt% CNT | 0.065 | 0.39 |
| PC + 1 wt% CNT + 2 wt% Al₂O₃ | 0.052 | 0.36 |
| PC + 1 wt% CNT + 4 wt% Al₂O₃ | 0.041 | 0.31 |
| PC + 1 wt% CNT + 6 wt% Al₂O₃ | 0.047 | 0.33 |



**Figure 3.**Impact Resistance

Carbon nanotubes decreased the wear rate by roughly 21% but the synergistic incorporation of Al₂O₃ nanoparticles resulted in additional reductions. The 4 wt% alumina hybrid composite exhibited the lowest wear rate (0.041 mm³/Nm) and the lowest coefficient of friction of 0.31 reflecting an approximate 50% decrease in wear and a 26% decrease in friction relative to clean PC. The enhanced tribological performance results from the hardness and lubricating characteristics of Al₂O₃ together with the increased shear resistance provided by CNTs and a little elevation in wear rate at 6 wt% Al₂O₃ is probably attributable to nanoparticle agglomeration and interfacial debonding may result in filler pull out during sliding hence compromising the wear protection mechanism [51-52].

# Application in Lightweight Brackets

The engineered hybrid PC nanocomposites are especially appropriate for lightweight structural brackets utilized in car interiors, aircraft panels and electronic device mounting where exceptional strength, thermal stability and wear resistance are essential. These components frequently endure cyclic mechanical stress, thermal variations and frictional interaction requiring materials that preserve dimensional stability and mechanical efficacy over time. The optimised formulation PC augmented with 1 wt% CNT and 4 wt% Al₂O₃ demonstrates a 23% enhancement in tensile strength, a 20°C elevation in HDT and a 50% decrease in wear rate positioning it as a formidable alternative to traditional PC or glass-filled thermoplastics in these applications.

This hybrid composite may be injection moulded with few process alterations facilitating cost efficient and scalable manufacturing of high performance precision components. The diminished wear rate guarantees an extended operational lifespan under vibrational and cyclic stresses while the thermal enhancements facilitate employment in regions with elevated ambient or operational temperatures such as adjacent to electrical modules or in under the hood settings. Moreover the incorporation of nanofillers facilitates significant material conservation and weight reduction according to worldwide industrial requirements for energy efficiency and environmental sustainability.

# Conclusion

This study effectively manufactured polycarbonate-based hybrid nanocomposites strengthened with chopped multi walled CNT and nano-alumina using twin screw extrusion and subsequent injection moulding. The addition of 1 wt% CNTs and different concentrations of Al₂O₃ nanoparticles markedly enhanced the mechanical, thermal, and surface properties of the basic polymer. The best composite formulation comprising 1 wt% CNT and 4 wt% Al₂O₃ demonstrated a 23% augmentation in tensile strength with a 42% rise in tensile modulus, a 20°C improvement in heat deflection temperature and up to a 50% decrease in wear rate relative to unfilled PC. The improvements that come from the synergistic interaction between CNTs and AlO₃ nanoparticles, which serve as heat barriers and abrasion resistant phases increase load bearing capacity and shear strength.

# These results demonstrate the viability of hybrid PC nanocomposites for high performance weight sensitive applications such as housing units, thermal shields and structural brackets in the consumer electronics, automotive and aerospace sectors. In order to enhance interfacial bonding and long term performance in real world service contexts future research may focus on compatibilizer effects, fatigue resistance and ageing behavior While preserving manufacturing flexibility and environmental goals the demonstrated material system makes it easier to create advanced polymer composites that are stronger, lighter and more resilient.

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