Ultrasonication Blending Action and Combination of Fiber–Ceramic Actions on Functional Behaviour of Epoxy Hybrid Composites

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Abstract: This study examines how the thermal, tribological and mechanical properties of epoxy composites are affected by ultrasonication assisted dispersion as well as the combined effects of carbon fibre and titanium dioxide nanoparticle reinforcement. Using a hand lay up process the composites were created with epoxy resin (100:10 mix ratio with hardener), reinforced with a 300 x 300 x 1 mm layer of carbon fibre and different concentrations of TiO₂ nanoparticles (3, 6, 9 wt%). TiO₂ was ultrasonically disseminated to guarantee homogeneity prior to blending. TiO₂ improved heat resistance and wear characteristics whereas carbon fibre increased tensile strength and load-bearing capacity. The 6 wt% TiO₂ hybrid composite offers optimal strength, thermal stability and wear resistance making it ideal for protected cell enclosures and impact-resistant structural casings.

# Introduction

Epoxy resins are extensively utilized in structural composites owing to its elevated modulus, superior adhesion and chemical resistance. Conventional epoxy demonstrates inadequate wear and temperature resistance, particularly under cyclic or dynamic loading conditions [1-5]. This limits its application in protective enclosures and ballistic protection unless well reinforced. Carbon fibre, characterized by its superior rigidity and tensile strength, offers exceptional load transmission and mechanical performance. Titanium dioxide nanoparticles (TiO₂, ~50 nm) recognized for their exceptional hardness, UV resistance, and thermal barrier capabilities, are progressively utilized to improve the surface and thermal properties of composites.

The integration of titanium dioxide nanoparticles into epoxy resin matrices has involvedsignificant interest because of its capacity to improve mechanical, thermal and tribological properties. [6-7] shown that the mechanical properties of TiO₂ epoxy nanocomposites are suggestively influenced by nanoparticle size which affects dispersion quality and interfacial adhesion. It showed the role of TiO₂ in enhancing both mechanical and thermal stability in hybrid epoxy systems [8]. It revealed that TiO₂ reinforcement enhances tensile strength and thermal deflection properties due to efficient stress transmission at the filler matrix interface [9-10]. Ultrasonication techniques was utilized to improve nanoparticle dispersion as demonstrated by works including [10-11] highlight the efficacy of ultrasonic energy in disaggregating agglomerates hence enhancing adhesion and wear resistance. While the integrated TiO₂ with silicon carbide in carbon fibre composites inside hybrid systems demonstrating enhanced tensile properties and fracture resistance [12-14]. They addressed the foundations of ultrasound-assisted nanocomposite synthesis, emphasizing the significance of cavitation energy for attaining uniform integration of nanofillers [15].

Hybrid ceramic reinforcing methodologies are increasingly gaining traction. They indicated that the incorporation of Al₂O₃ and SiC nanoparticles with carbon fibres significantly enhances stiffness and toughness [16-20]. Likewise, validated that nano-TiO₂ substantially enhances both mechanical and thermal properties in fiber reinforced epoxy systems [21-25]. Theyexamined the application of vacuum bagging and nanofillers such as Al₂O₃ and nanographene in natural fibre composites highlighting the promise of hybrid nano engineered systems. Multi walled carbon nanotubes have been examined for their capacity to enhance tensile strength and thermal stability in epoxy matrices [26-31]. They applied atomic scale modelling to clarify the adhesion and wetting of nanofillers on epoxy functionalized surfaces offering insights into interfacial optimization methods [32-34].It assessed the thermogravimetric properties and morphological changes in epoxy composites using hybrid ceramic fillers highlighting the significance of optimization in enhancing functional performance [35]. Finally [36-37] provided evidence of augmented multifunctionality in carbon fiber epoxy composites with the incorporation of TiO₂ nanoparticles yielding advantages such as enhanced UV resistance, wear durability, and interfacial strength.

Ultrasonication blending guarantees homogeneous nanoparticle dispersion and inhibits agglomeration, thus improving interface compatibility. This study investigates the enhancement of functional properties of epoxy composites, fabricated via the hand lay up process, by integrating a continuous carbon fibre layer with ultrasonically dispersed TiO₂ fillers.

# Materials and Methods

## Materials

This study utilized a matrix system of a two part epoxy resin made from Diglycidyl Ether of Bisphenol A combined with an aliphatic amine-based hardener in a 100:10 weight ratio. This amalgamation offers superior mechanical strength, chemical resistance, and processing convenience. Carbon fibre fabric of size 300 mm × 300 mm × 1 mm was chosen as the principal reinforcement due to its superior strength to weight ratio and anisotropic stiffness and the unidirectional carbon fabric provided the structural foundation of the composite. Titanium dioxide nanoparticles in the anatase phase with an average particle size of 50 nm and 99.8% purity were utilized as the ceramic nanofiller to enhance mechanical, thermal and wear properties. Acetone used as a solvent for dispersing TiO₂ nanoparticles to achieve optimal mixing and uniform distribution inside the epoxy matrix.

## Composite Formulations

**TABLE 1**Composite Composition

| **Configuration ID** | **Composite Composition** |
| --- | --- |
| **C1** | Epoxy + Carbon fiber (no TiO₂) |
| **C2** | Epoxy + Carbon fiber + 3 wt% TiO₂ |
| **C3** | Epoxy + Carbon fiber + 6 wt% TiO₂ |
| **C4** | Epoxy + Carbon fiber + 9 wt% TiO₂ |

4 unique composite configurations were created to study the impact of titanium dioxide nanoparticle on the performance of epoxy carbon fibre composites. All formulations utilized Diglycidyl Ether of Bisphenol A epoxy resin augmented with woven unidirectional carbon fibre fabric and differing weight percentages of nano TiO₂. The TiO₂ utilized was in the anatase phase exhibiting the particle size of 50 nm and a purity of 99.8%.

These formulations were designed to understand the effect of increasing TiO₂ concentration on mechanical strength, thermal stability, and wear resistance, with C1 serving as the control.

## Fabrication Process

The fabrication technique for epoxy carbon fibre composites enhanced with TiO₂ nanoparticles was carefully designed to provide consistent nanoparticle dispersion and effective fibre impregnation. Initially TiO₂ nanoparticles were ultrasonically dispersed in acetone for 30 minutes to disaggregate agglomerates and achieve a homogeneous suspension [38-40]. Then the dispersion was physically combined with epoxy glue to guarantee that the nanoparticles were consistently distributed throughout the matrix and to start the curing process an aliphatic amine hardener was added to the resin system at a weight ratio of 100:10 epoxy to hardener after everything had been thoroughly mixed. After placing a 300 mm × 300 mm × 1 mm unidirectional carbon fibre cloth in a flat mould the prepared TiO₂ epoxy mixture was mixed using a hand lay up approach and complete fibre saturation and effective interfacial adhesion were guaranteed by this technique. To improve the final laminate mechanical and thermal resistance the composite panels were post cured for two hours at 60°C after being cured for twenty four hours at ambient temperature to promote matrix crosslinking [41-45]. High performance composites can be manufactured in laboratory and pilot-scale settings using this scalable and reasonably priced hand lay up approach which provides exact control over filler integration and reinforcing placement.

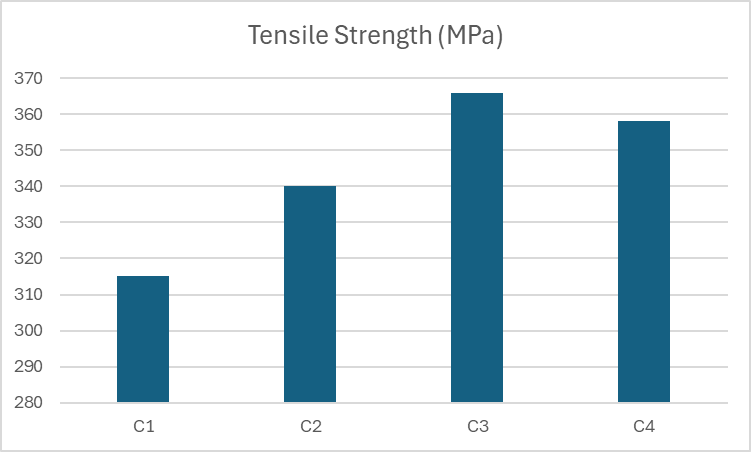
# Results and Discussion

## Tensile Strength

Tensile tests shown a gradual improvement in strength with an increase in TiO₂ content up to 6 wt%. The control specimen C1 exhibited a tensile strength of 315 MPa. The incorporation of 3 wt% TiO₂ in C2 enhanced the strength to 340 MPa, whilst the addition of 6 wt% TiO₂ in C3 further boosted it to a maximum of 366 MPa indicating a 16% enhancement relative to the baselineand with this enhancement results from the effective load transfer facilitated by the uniformly distributed TiO₂ nanoparticles which augment interfacial bonding and diminish voids within the matrix. With 9 wt% TiO₂ in C4, a minor reduction in strength to 358 MPa was observed and this decrease is likely due to nanoparticle agglomeration which can serve as stress concentrators and compromise the composite structure.

**TABLE 2.** Tensile Strength of Epoxy–Carbon Fiber–TiO₂ Composites

| **Configuration** | **TiO₂ Content (wt%)** | **Tensile Strength (MPa)** | **% Increase from C1** |
| --- | --- | --- | --- |
| C1 | 0 | 315 | — |
| C2 | 3 | 340 | +7.9% |
| C3 | 6 | 366 | +16.2% |
| C4 | 9 | 358 | +13.6% |



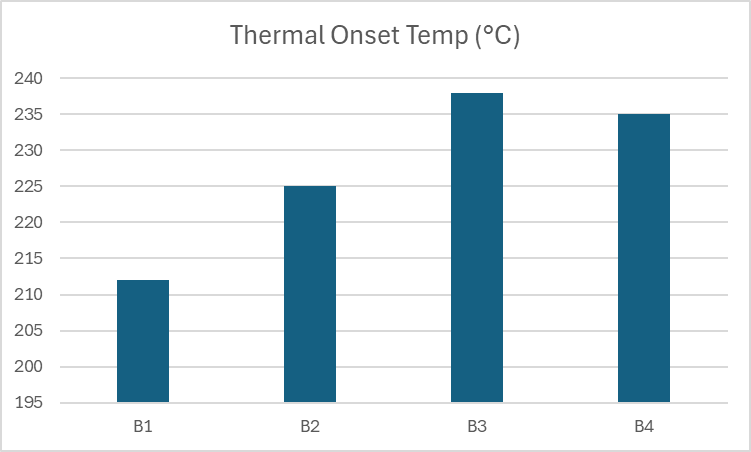
**FIGURE 1.**Tensile Strength of Epoxy–Carbon Fiber–TiO₂ Composites

## Heat Resistance

The thermal stability of the composites was assessed by degradation onset temperature. The pristine epoxy carbon fibre composite (C1) commenced degradation at 212°C. The onset temperature with 3 wt% TiO₂ (C2) was 225°C, whilst 6 wt% TiO₂ (C3) exhibited the greatest thermal stability at 238°C reflecting a 26°C enhancement compared to the control. This phenomenon is ascribed to the thermal shielding properties of TiO₂ nanoparticles, which serve as impediments to thermal conductivity and limit heat transfer inside the matrix. At 9 wt% TiO₂ (C4) the starting temperature slightly fell to 235°C suggesting filler saturation and potential particle agglomeration which diminished the thermal efficiency of the nanoparticles [46-48].

**TABLE 3.** Thermal Degradation Onset Temperature

| **Blend ID** | **TiO₂ Content (wt%)** | **Thermal Onset Temp (°C)** | **ΔT from Control (°C)** |
| --- | --- | --- | --- |
| C1 | 0 | 212 | — |
| C2 | 3 | 225 | +13 |
| C3 | 6 | 238 | **+26** |
| C4 | 9 | 235 | +23 |



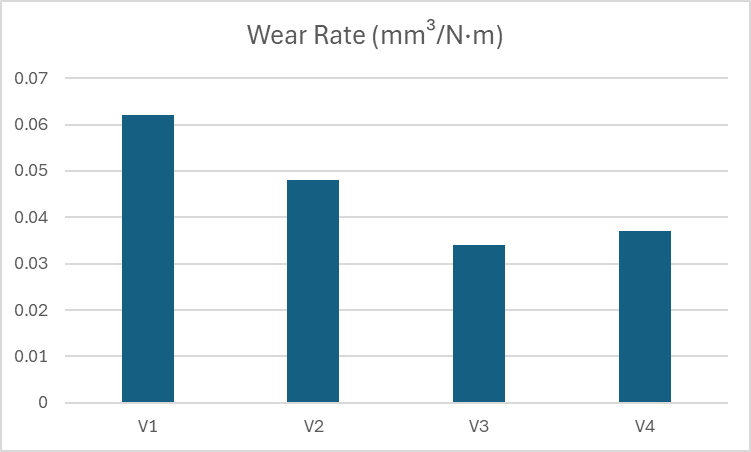
**FIGURE 2.**Thermal Degradation Onset Temperature

## Wear Rate

Pin-on-disc wear tests demonstrated that the incorporation of TiO₂ nanoparticles markedly improved wear resistance. The control variation V1 had a wear rate of 0.062 mm³/N•m and a coefficient of friction of 0.45. The incorporation of 3 wt% TiO₂ (C2) decreased the wear rate to 0.048 mm³/N•m while the optimal outcome was attained with 6 wt% TiO₂ (C3) exhibiting a wear rate of 0.034 mm³/N•m a 45% reduction compared to the control and the CoF significantly improved down to 0.33. At 9 wt% TiO₂ (C4), the wear rate increased marginally to 0.037 mm³/N•m, perhaps attributable to surface cracking or micro-defects caused by excessive nanoparticle aggregation. These observations indicate that 6 wt% TiO₂ is the ideal concentration for wear performance. [49-50].

**TABLE 4.** Wear Rate and Coefficient of Friction

| **Variant** | **TiO₂ Content (wt%)** | **Wear Rate (mm³/N·m)** | **% Reduction in Wear** | **Coefficient of Friction** |
| --- | --- | --- | --- | --- |
| C1 | 0 | 0.062 | — | 0.45 |
| C2 | 3 | 0.048 | 22.6% | 0.39 |
| C3 | 6 | 0.034 | **45.2%** | 0.33 |
| C4 | 9 | 0.037 | 40.3% | 0.35 |



**FIGURE 3.** Wear Rate and Coefficient of Friction

# Application in Protective Cells

The engineered hybrid composites exhibit significant potential for application in protective cellular structures including smart armour panels energy storage enclosure and defense grade casings where mechanical and thermal performance under stress is paramount. These applications require materials that demonstrate strong impact and tensile strength, efficient thermal insulation, and minimal wear under dynamic situations. The C3 design consisting of epoxy reinforced with carbon fibre and 6 wt% TiO₂, exhibited the most superior performance.

* A 16% augmentation in tensile strength (366 MPa),
* A 26°C elevation in thermal onset temperature (238°C),
* A 45% reduction in wear rate (0.034 mm³/N•m).

This combination of lightweight structure, mechanical resilience and thermal resistance renders the composite ideal for modular high performance systems where cost effective processing methods such as hand lay up are preferred without sacrificing quality.

# Conclusion

This study confirms the efficacy of integrating carbon fibre fabric with TiO₂ nanoparticles in an epoxy matrix for performance improvement. With a tensile strength of 366 MPa thermal stability of 238°C and a wear rate of 0.034 mm³/N•m the optimized formulation containing 6 weight percent TiO₂ demonstrated outstanding performance across all critical parameters. The homogeneous dispersion of nanoparticles, reduced agglomeration and enhanced property improvements were made possible by ultrasonication and mechanical stirring. The amalgamation of superior strength, little wear and improved thermal performance renders these hybrid composites optimal for protective applications in the defence, aerospace and energy industries. The study endorses the viability of economical fabrication techniques as hand lay up, facilitating the scalable manufacturing of new multifunctional composites.

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