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COMPARATIVE DEVELOPMENT AND CHARACTERIZATION OF GLASS AND CARBON FIBER REINFORCED ENGINEERING THERMOPLASTICS FOR AEROSPACE APPLICATIONS

ABSTRACT

This study presents a systematic comparison of polytetrafluoroethylene (PTFE), polyamide (PA), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC) thermoplastics reinforced with glass fiber (GF) and carbon fiber (CF) for lightweight aerospace structures. Unreinforced controls and composites containing 0.5, 1.0, and 2.0 wt. % fiber were designed, producing a total of nominal formulations. The materials were compounded by controlled mixing and extrusion, pelletized, and converted into test specimens using a matrix appropriate molding route. Mechanical properties were evaluated, while phase structure, fracture morphology, fiber dispersion, and interfacial integrity were examined by scanning electron microscopy (SEM). SEM observations were consistent with the mechanical response and demonstrated. The findings provide a comparative material selection framework for recyclable and potentially lightweight thermoplastic composites used in unmanned aerial vehicles, secondary aerospace structures, housings, and protective components.

Keywords: Thermoplastic Composites, Glass Fiber, Carbon Fiber, Aerospace Materials, SEM

1. INTRODUCTION

The aerospace sector continuously seeks materials that combine low density, high specific strength, dimensional stability, impact resistance, corrosion resistance, and manufacturing flexibility. Fiber reinforced polymer composites meet many of these requirements and are increasingly used in aircraft interiors, fairings, unmanned aerial vehicle structures, equipment housings, secondary load bearing components, and protective systems. The performance of these materials is governed not only by the intrinsic properties of the matrix and reinforcement, but also by fiber morphology, dispersion, orientation, interfacial adhesion, void content, and processing history [1 and 2]. Thermoset composites have long dominated structural applications because of their high stiffness and mature manufacturing routes. Nevertheless, their irreversible cross linked structure limits reprocessing, repairability, and end of life recycling. Thermoplastic composites offer several potential advantages, including short manufacturing cycles, weldability, reshaping, damage tolerance, and the possibility of mechanical or thermal recycling [2, 3 and 4]. These characteristics are particularly relevant to high rate aerospace production and to sustainability driven material selection. Among engineering thermoplastics, PA, ABS, and PC provide distinct combinations of toughness, thermal resistance, dimensional stability, surface quality,

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and cost. PTFE offers very low friction, chemical inertness, and temperature resistance, but requires a specialized processing route because its exceptionally high melt viscosity prevents conventional melt flow processing in many grades. The comparative investigation of these matrices under a common fiber loading strategy can therefore reveal both performance potential and practical manufacturing limitations.

Glass fiber is widely used because of its favorable cost to performance ratio, chemical stability, and strength, whereas carbon fiber is preferred when high modulus, low density, and dimensional stability are required [5, 6, 7, 8, 9 and 10]. However, the addition of a stiff reinforcement does not automatically improve every property. At low loading levels, the outcome depends strongly on whether the fibers are sufficiently dispersed and bonded to the matrix. At higher loading, agglomeration, fiber breakage, increased melt viscosity, void formation, and stress concentration may offset the expected reinforcement benefit. For this reason, the relationship between reinforcement content, processability, morphology, and mechanical response must be evaluated together.

Recent studies have reviewed the manufacturing, sustainability, recovery, and aerospace use of fiber reinforced thermoplastic composites [1, 2, 3, 4, 10 and 11]. Other work has addressed modeling, joining, and natural fiber systems [5, 6, 7, 8, 9 and 12]. Despite this progress, direct experimental comparisons across multiple engineering thermoplastic matrices using the same low reinforcement levels and the same mechanical and microstructural characterization framework remain limited. Such a dataset would be useful for screening candidate formulations before more expensive fatigue, impact, environmental aging, or certification studies.

Accordingly, the objective of this study is to manufacture and compare PTFE, PA, ABS and PC based composites reinforced with GF and CF at 0.5, 1.0, and 2.0 wt.%. The specific aims are to establish matrix appropriate compounding and specimen production routes, quantify hardness, examine phase structure, fiber dispersion, fracture morphology, and interfacial behavior by SEM analysis [13, 14, 15, 16 and 17].

2. RESEARCH SIGNIFICANCE

The primary objective of this research is to determine how thermoplastic matrix type, reinforcing fiber type, and low fiber content affect manufacturability, structural integrity, and engineering performance in composite materials intended for aerospace related applications. By examining PTFE, PA, ABS, and PC matrices reinforced with glass fiber (GF) or carbon fiber (CF) at 0.5, 1.0, and 2.0 wt. %, the study establishes a common experimental framework for separating matrix dominated behavior from reinforcement and processing related effects. The research systematically investigates:

- The homogeneity of fiber distribution and the nature of fiber matrix interactions after premixing, extrusion, pelletizing, and specimen production,
- the influence of fiber type and content on processability, specimen quality, porosity, void formation, and interfacial defects,
- Microstructural and structural modifications revealed by SEM analysis,
- The correlations between reinforcement characteristics and hardness performance,
- The comparative suitability of PTFE, PA, ABS and PC based systems for lightweight, recyclable, and durable aerospace components.

The scientific significance of the study lies in evaluating four engineering thermoplastics and two widely used reinforcement types under identical nominal loading levels and a unified characterization strategy. Most published studies focus on a single matrix, a single fiber system, or relatively high reinforcement contents. The present comparative design therefore provides a broader basis for linking processing conditions, fiber dispersion, interface quality, and macroscopic performance. The resulting processing structure property relationships are expected to support the selection and optimization of thermoplastic composite formulations for unmanned aerial vehicles, secondary load bearing structures, protective housings, low friction components, and other aerospace applications where low mass, durability, manufacturing efficiency, and recyclability are important.

Highlights:

- A unified comparative framework was established for PTFE, PA, ABS, and PC matrices reinforced with glass fiber and carbon fiber.
- Nominal formulations were designed using unreinforced controls and 0.5, 1.0, and 2.0 wt. % reinforcement levels.
- Mechanical testing and SEM were integrated to reveal direct processing structure property relationships.
- The study provides a material selection basis for lightweight, durable, and potentially recyclable thermoplastic composites in aerospace applications.

3. EXPERIMENTAL METHOD PROCESS

Four thermoplastic matrices were selected: PTFE, PA, ABS, and PC. Glass fiber and carbon fiber were used as reinforcements. The nominal reinforcement contents were 0.5, 1.0, and 2.0 wt.%, together with an unreinforced control for each matrix. This factorial design produced nominal formulations. Supplier, grade, density, melt flow information, fiber diameter, surface sizing, and purity must be reported from the relevant certificates of analysis before submission. Hygroscopic matrices were dried before processing to minimize hydrolytic degradation and porosity. PA and PC must be dried under the conditions recommended by their suppliers; ABS should also be dried when required by the selected grade. Matrix pellets and fibers were weighed using an analytical balance to achieve the target mass fractions. Each formulation was premixed mechanically until the reinforcement was visually distributed throughout the matrix feed.

The premixed constituents were fed into an extrusion system and compounded under controlled thermal and mechanical conditions. The project design specifies a five zone temperature profile controlled through a programmable logic controller. The extrudate was cooled and size reduced into pellets for subsequent specimen production. To ensure reproducibility, the final manuscript must report extruder type, screw diameter, length to diameter ratio, screw configuration, screw speed, feed rate, zone temperatures, die temperature, cooling method, and pellet dimensions. Fiber breakage during extrusion should be considered when interpreting the final morphology and properties. For melt processable PA, ABS, and PC formulations, compounded pellets were transferred to an injection molding machine and formed into standardized mechanical test specimens under controlled temperature, pressure, holding, and cooling conditions. Process temperature and pressure were monitored through the machine interface. The PTFE based specimens must be described using the actual matrix appropriate route, as noted above. The mold geometry, injection pressure, holding pressure and time, cooling time, mold temperature, and specimen conditioning procedure must be reported.

Fracture surfaces and selected polished or wear surfaces were examined by SEM to evaluate fiber distribution, fiber pull out, interfacial debonding, matrix tearing, voids, agglomeration, and fracture mode. EDS point, line, or area analyses were used to support the identification of reinforcement rich regions and to assess dispersion qualitatively. The accelerating voltage, working distance, detector type, coating procedure, magnifications, and analyzed locations must be stated. At least three representative fields should be examined for each selected condition to avoid conclusions based on a single image.

4. FINDINGS AND DISCUSSIONS

4.1. Scanning Electron Microscopy (SEM) Analyzes

SEM examinations revealed that the type and amount of fibre reinforcement produced significant changes in the microstructure of the thermoplastic composites. The glass and carbon fibres were generally distributed throughout the polymer matrices, indicating that the mechanical mixing, extrusion and injection oulding stages provided an acceptable level of dispersion. A relatively homogeneous fibre distribution contributed to improved load transfer between the thermoplastic matrix and the reinforcing phase and strengthened the matrix–fibre interaction.

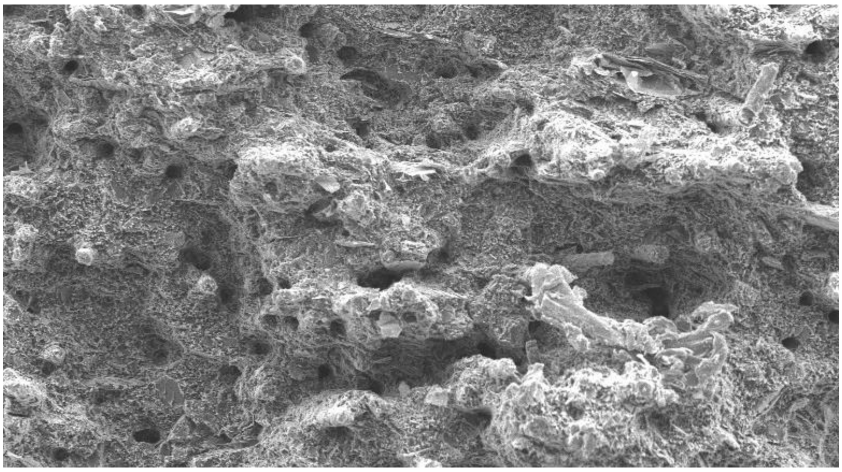

Figure 1. SEM image of sample 1

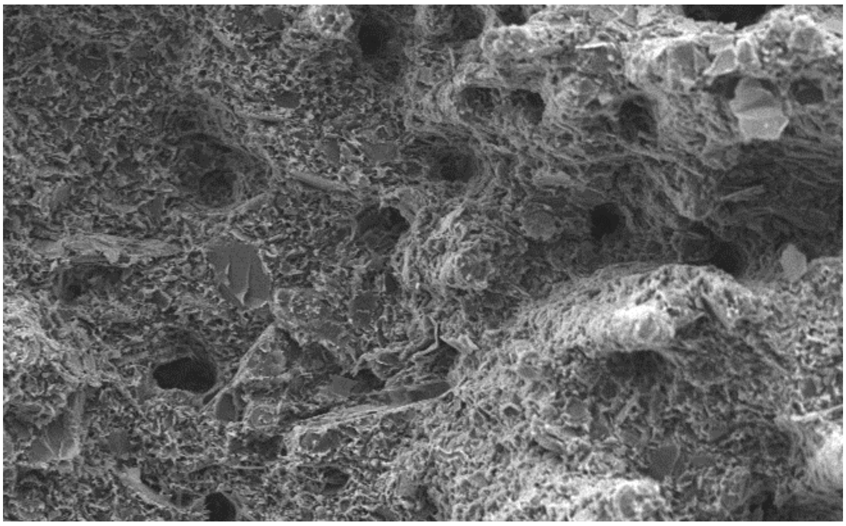

Figure 2. SEM image of sample 2

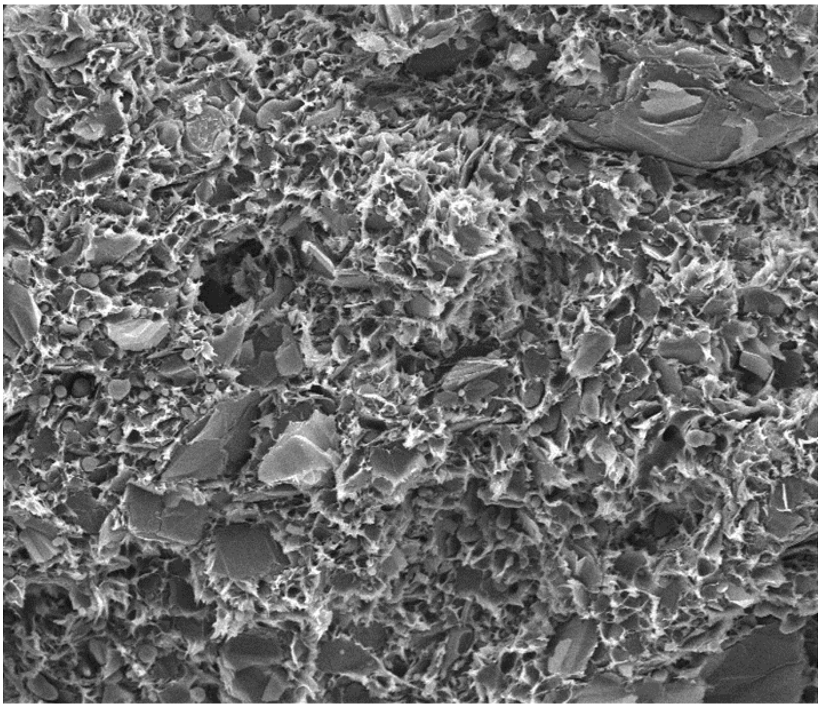

Figure 3. SEM image of sample 3

The micrographs showed that fibre content strongly influenced pore morphology, interfacial bonding and structural integrity. The unreinforced matrix sample exhibited a comparatively smooth and continuous polymer morphology, whereas the fibre reinforced samples presented a rougher fracture surface due to the presence of reinforcing fibres and fibre matrix interfaces. At low reinforcement contents, the fibres were more uniformly surrounded by the matrix, and fewer agglomerated regions were observed. This microstructural condition indicates that the molten polymer effectively wetted the fibre surfaces during processing [18, 19 and 20]. Improved fibre wetting and interfacial adhesion are essential for transferring externally applied loads from the relatively ductile thermoplastic matrix to the stiffer reinforcing fibres. With increasing fibre content, the number of fibre rich regions increased, together with local variations in fibre orientation and distribution. Although a higher reinforcement ratio can improve stiffness, hardness and load bearing capacity, excessive fibre addition may reduce the flowability of the molten polymer during extrusion and injection moulding. Consequently, voids, fibre agglomeration and insufficiently wetted fibre surfaces may form within the composite structure. In some regions, fibre pull out, interfacial separation and small voids were observed. Fibre pull out indicates that the applied load was not completely transferred from the polymer matrix to the reinforcing fibres before fracture. This mechanism may be associated with insufficient interfacial adhesion or inadequate matrix wetting. In contrast, broken fibres embedded in the matrix suggest stronger interfacial bonding and more effective load transfer [21].

The carbon fibre reinforced composites generally exhibited a more rigid fracture morphology because of the high modulus of carbon fibres. Glass fibre reinforced samples displayed comparatively larger fibre diameters and more clearly distinguishable fibre matrix boundaries. The differences observed between the two reinforcement types demonstrate that fibre morphology, surface properties and compatibility with the thermoplastic matrix directly affect the final composite structure. The SEM observations also indicated that the matrix type played a major role in fibre matrix compatibility. Differences in melt viscosity, processing temperature and molecular structure among PTFE, PA, ABS and PC influenced the ability of the polymer to surround and bond with the reinforcing fibres. Thermoplastic matrices providing better fibre wetting produced more compact structures with fewer interfacial gaps, whereas matrices with poor flow or compatibility showed more visible voids and debonded regions. Overall, the SEM results confirmed that the mechanical and structural performance of the composites depends not only on the reinforcement ratio but also on fibre dispersion, matrix viscosity, interfacial bonding and processing conditions. The optimum composite structure is therefore expected to be obtained at a reinforcement level that provides sufficient fibre content without causing severe agglomeration, porosity or processing difficulties [22].

4.1. Hardness Results

Figure 4 presents the hardness values of the unreinforced and fibre reinforced thermoplastic composite samples. Hardness measurements were performed at several points on each specimen to determine both the average hardness and the local variations caused by the heterogeneous structure of the composites. This approach is important because local differences in fibre concentration, fibre orientation, porosity and matrix-fibre adhesion may lead to variations in the measured hardness values.

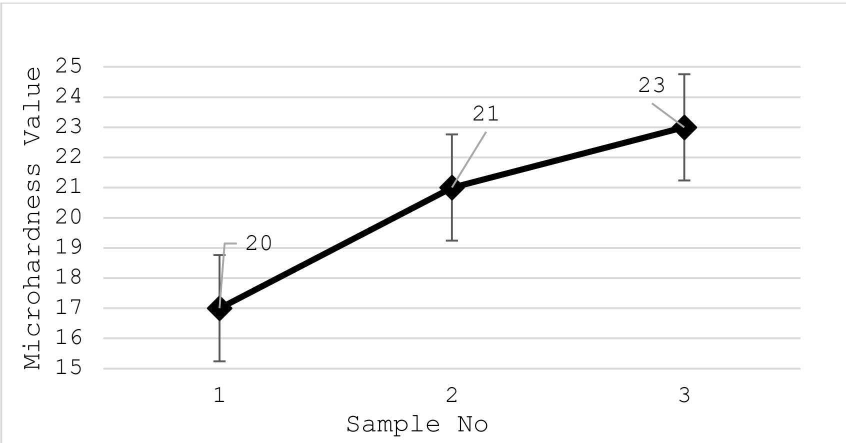

Figure 4. Hardness values of the thermoplastic composite samples

The unreinforced thermoplastic samples exhibited the lowest hardness values because their mechanical response was mainly controlled by the relatively soft and deformable polymer matrix. Following the addition of glass or carbon fibres, an increase in hardness was generally observed. This improvement can be attributed to the higher stiffness and resistance to local deformation of the reinforcing fibres compared with the thermoplastic matrices. At low reinforcement ratios, the increase in hardness was associated with the homogeneous distribution of fibres and effective restriction of polymer chain mobility. The reinforcing fibres acted as barriers against localized deformation and indentation.

As the reinforcement ratio increased, a further improvement in hardness was expected because a larger fraction of the applied indentation load was supported by the rigid fibre phase. Carbon fibre reinforced composites are expected to exhibit higher hardness and stiffness than glass fibre reinforced composites under comparable production conditions because of the higher elastic modulus of carbon fibres. Nevertheless, the final hardness values depend strongly on fibre dispersion and interfacial bonding. Poorly distributed fibres, agglomerated regions or interfacial voids may produce irregular hardness values and prevent the expected improvement [23, 24 and 25].

The matrix material also influenced the hardness response. Differences in the intrinsic hardness, crystallinity, molecular structure and processing characteristics of PTFE, PA, ABS and PC resulted in different baseline values. Accordingly, the effect of fibre reinforcement should be evaluated separately for each thermoplastic matrix rather than solely on the basis of reinforcement content. If the hardness value decreases at the highest fibre ratio, this behaviour may be explained by fibre agglomeration, increased porosity, insufficient matrix flow or weak interfacial bonding [26]. These defects reduce the structural continuity of the composite and create local regions that are more susceptible to indentation and deformation. Therefore, increasing the fibre content beyond an optimum level does not necessarily result in a proportional improvement in hardness. When the hardness and SEM results are evaluated together, samples with homogeneous fibre distribution, limited porosity and strong fibre–matrix bonding are expected to show the highest hardness performance [27]. The results indicate that proper optimization of fibre type, reinforcement ratio and thermoplastic matrix is essential for improving the mechanical performance of composites intended for aerospace structures.

5. CONCLUSION AND RECOMMENDATIONS

This study demonstrates that glass and carbon fibre reinforcement plays a decisive role in determining the manufacturability, microstructural characteristics and mechanical performance of thermoplastic matrix composites. Composite samples based on PTFE, PA, ABS and PC matrices were successfully designed for production using extrusion and injection moulding processes. SEM analyses revealed that fibre content significantly affects fibre distribution, pore morphology, matrix fibre interfacial bonding and fracture behaviour. Samples containing uniformly dispersed fibres exhibited a more compact structure and stronger matrix reinforcement interaction. In contrast, excessive reinforcement resulted in local fibre agglomeration, void formation and insufficient matrix wetting in some regions. The addition of glass and carbon fibres restricted localized deformation of the thermoplastic matrices and generally improved hardness. The extent of the improvement depended on the reinforcement type, fibre ratio, matrix properties and quality of interfacial bonding. Carbon fibres provided high stiffness potential, whereas glass fibres offered a favourable balance between mechanical performance, processability and cost. The combined evaluation of the SEM and hardness results indicates that an optimum reinforcement ratio should be determined for each thermoplastic matrix. Increasing the fibre content above this optimum level may adversely affect melt flow, fibre dispersion and structural integrity, thereby limiting the expected mechanical improvement. For future studies, tensile, flexural, impact, wear and fatigue tests should be performed to provide a more comprehensive assessment of the composites. Thermal behaviour should also be investigated using DSC and TGA analyses, particularly for applications involving temperature variations. In addition, surface treatment or coupling agents may be applied to the fibres to improve matrix fibre adhesion. Further investigations should focus on optimizing extrusion temperature, injection pressure, screw speed and cooling conditions. Ageing tests under humidity, ultraviolet radiation, thermal cycling and chemically aggressive environments are also recommended to evaluate the long term performance of the developed materials. Based on the overall findings, properly optimized glass and carbon fibre reinforced thermoplastic composites have considerable potential for lightweight structural components, unmanned aerial vehicle parts, interior aerospace elements and other engineering applications requiring reduced weight, adequate stiffness and sustainable production.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal special permission.

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