Chapter 17
Multifunctional Hybrid Hierarchical Composites

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Abstract

The pursuit of lightweight, multifunctional materials is accelerating across the automotive, aerospace, defence, and high-performance transportation sectors as industries aim to achieve net-zero emissions by 2050. Conventional micro-reinforcement composites often lack impact resistance and multifunctionality, while modern nano-reinforcement strategies face dispersion and scalability challenges. Inspired by nature's hierarchical architectures, we introduce a new class of hybrid composites that strategically integrate 0D quantum dots, 1D nanotubes, and 2D platelets with polymer matrices to form self-assembled fibrous assemblies. These reinforcements enable efficient stress transfer, toughness, and multifunctional integration, while scalable manufacturing methods such as injection moulding, extrusion, and additive manufacturing ensure industrial feasibility. Our first commercial material, AX Gratek PP40, demonstrated simultaneous improvements of 22% in tensile strength, 86% in impact strength, and 81% in EMI-shielding, alongside an 18% weight reduction compared to industry benchmarks. Building upon this, AX Foatek PP40, a foamed variant inspired by butterfly wings, achieved up to 116% higher impact strength and 62% enhanced thermal management while reducing weight by 38%. Most recently, AX Clatek PP40, inspired by compact bone, delivered exceptional gains in processability, strength, and toughness, positioning it for next-generation electric vehicle and electronics applications. Together, these advances establish hierarchical hybrid composites as a paradigm shift in material design. At NanoMorphix, our proprietary AegisX™ technology extends these principles to transparent, self-healing, and impact-resistant coatings, exemplifying the future of resilient, sustainable, and multifunctional material innovation.

Keywords: *Multifunctional Bio-inspired Materials, Synergistic Effect, Hierarchical Hybrid Composites, Nano-/ Micro-Architecture, Lightweighting*

Introduction

Driven by stringent environmental policies and ambitious sustainability goals, the automotive, aerospace, defence, and high-performance transportation sectors are increasingly adopting lightweight structural materials to enhance energy efficiency and ensure long-term sustainability. With a collective target of achieving net-zero emissions by 2050, the demand for lightweight, multifunctional materials has intensified, offering a pivotal solution to meet these ambitious objectives[1,2]. Unfortunately,

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[1]Lei Zhu et al., "Light-Weighting in Aerospace Component and System Design," *Propulsion and Power Research* 7, no. 2 (2018): 103–19, https://doi.org/10.1016/J.JPPR.2018.04.001.

[2]Alan I. Taub and Alan A. Luo, "Advanced Lightweight Materials and Manufacturing Processes for Automotive Applications," *MRS Bulletin* 40, no. 12 (2015): 1045–54, https://doi.org/10.1557/MRS.2015.268.

traditional micro-reinforcement approaches lack the impact and fatigue resistance, as well as the inherent multifunctionality, required for a sustainable future. Meanwhile, modern nano-reinforcement strategies often face challenges with dispersion and distribution, resulting in complex manufacturing processes that limit scalability. This has catalysed the emergence of avant-garde hybrid reinforcement approaches, which synergistically combine multi-scale reinforcements to overcome these limitations and unlock new performance thresholds.

Nature offers materials with unparalleled engineering that seamlessly integrate strength, toughness, and multifunctionality through hierarchical architectures (or nano-/micro-structuring). Biological systems like nacre, compact bone (Figure **1**A), and butterflies achieve exceptional performance by coordinating interactions across multiple length scales. A critical aspect of this synergy is the geometric compatibility (or length-scale) and dimensionality of their hierarchical constituents, which promote efficient stress transfer, toughening, and functional integration. Inspired by these principles, our hybrid composite technologies to date combine polymer matrices with organic, ceramic, and metallic reinforcements to form self-assembled hierarchical fibrous assemblies (e.g., covalent, electrostatic, etc.). These reinforcements have been systematically tested across dimensionalities and length scales, spanning 0D quantum dots, 1D nanotubes, and 2D platelets, to validate their self-assembly behaviour and performance. These advanced materials are produced using scalable, high-throughput manufacturing methods, including injection moulding, extrusion, hybrid layup, and additive manufacturing. As a result, this avant-garde bio-inspired approach has enabled the successful development of multiple multifunctional hybrid composite materials, circumventing the limitations of current standards.

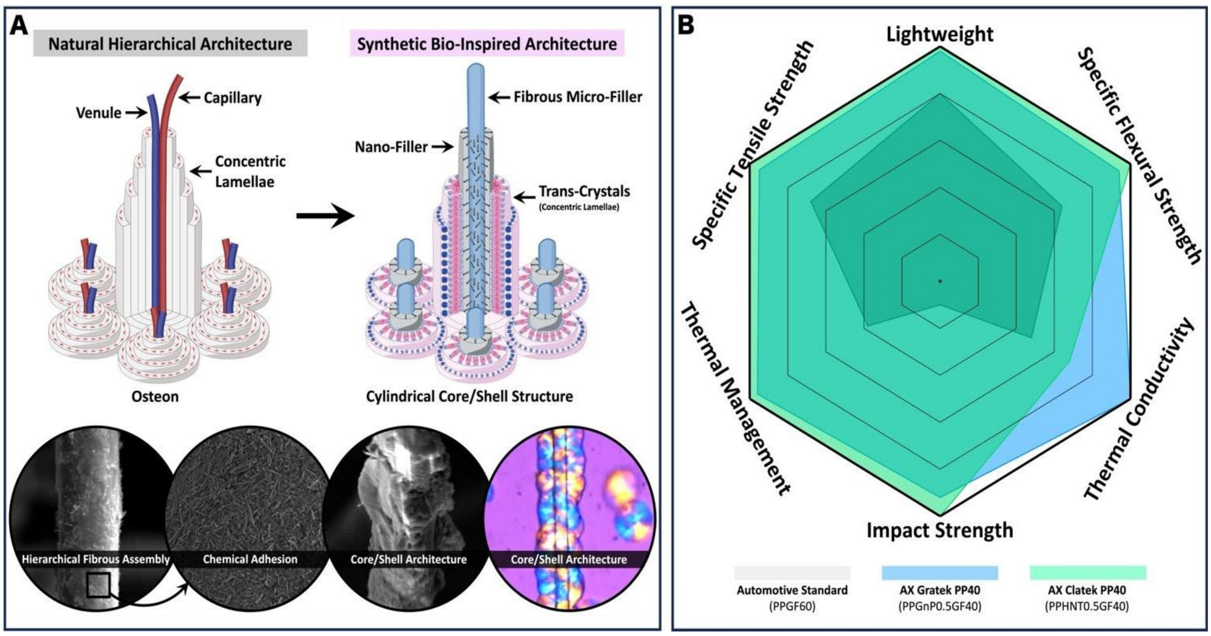

Figure 1: (A) Bio-Mimetic Design Principles for Compact Bone, and (B) Primary Material Candidates.

Results and Discussion

Our initial state-of-the-art hybrid composite material, now commercially known as *AX Gratek PP40,*[3,4], was developed through our long-term partnership with Axiom Group Inc., a leading Tier 1 automotive parts manufacturer based in Ontario, Canada, that supplies components to major OEMs, including Tesla, Volkswagen, and Stellantis. AX Gratek PP40 (PPGnP0.5GF40) is a polypropylene (PP)-based *1D/2D* hybrid composite fabricated via industry-scale injection moulding, featuring self-assembled hierarchical fibrous assemblies, which consist of nano-sized graphene nanoplatelets (GnPs; 0.5 wt.% GnP) covalently bonded to chemically modified micro-sized glass fibres (GFs; 40 wt.% GF), mimicking the multiscale architecture found in butterfly legs. This material demonstrates improvements (Figure **1**B) of up to 22% in specific tensile strength, 21% in specific flexural strength, 86% in impact strength, 52% in thermal conductivity, and 81% in electromagnetic interference (EMI)-shielding alongside an 18% weight reduction compared to automotive industrial standards (PPGF60; 60 wt.% GF)[3,4,5,6,7].

In essence, maximising the density of covalently bonded GnPs onto the GFs yields optimised hierarchical fibrous assemblies that refine the crystalline microstructure of the matrix through trans-crystallisation, forming a gradient interphase at the filler–matrix interface and promoting the development of soft and tough β-crystals that suppress filler agglomeration. Additionally, the volume exclusion effect induced by the GFs facilitates the formation of GnP-based thermally and electrically conductive networks, thereby enhancing phonon and photon transport, respectively. Strategically controlling the reinforcement surface chemistries, through amino-functionalization, and concentrations has been shown to directly influence the magnitude of these mechanisms, effectively amplifying their synergistic effect[8]. This control enables the material properties of the resulting avant-garde hybrid composites to be precisely tailored for high-performance applications.

Building upon this foundation, for the first time, we developed a foamed hybrid composites technology, commercially known as *AX Foatek PP40*, that resembles the natural porous architectures found in butterfly wings to harness and emulate their inherent robust structural and thermal management

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[3]Nello D. Sansone et al., Polymer Composite, US Patent US20240064947A1, filed September 15,2023, and issued February 22,2024, https://patents.google.com/patent/US20240064947A1/en.

[4]Nello D. Sansone et al., Hybrid Graphene Nanoplatelets and Glass Fibers Polymer Composites, World Intellectual Property Organization WO2024038416A1, filed August 18,2023, and issued February 22, 2024, https://patents.google.com/patent/WO2024038416A1/en.

[5]Nello D. Sansone et al., Tailoring Multifunctional and Lightweight Hierarchical Hybrid Graphene Nanoplatelet and Glass Fiber Composites, *ACS Applied Materials and Interfaces* 14, 35 (2022): 40232-40246, https://doi.org/10.1021/acsami.2c11231.

[6]Nello D. Sansone et al., Synergy in Bio-Inspired Hybrid Composites with Hierarchically Structured Fibrous Reinforcements, *Chemical Engineering Journal* 487, (2024): 1385–8947, https://doi.org/10.1016/j.cej.2024.150357.

[7]Meysam Salari et al., Insights into Synergy-Induced Multifunctional Property Enhancement Mechanisms in Hybrid Graphene Nanoplatelet Reinforced Polymer Composites, *Chemical Engineering Journal* 463**,** (2023): 142406, https://doi.org/10.1016/j.cej.2023.142406.

[8]Rafaela Aguiar et al., Designing the Microstructural Architecture of Bioinspired Hierarchical Hybrid Nanocomposites, *Advanced Composites and Hybrid Materials* 7, no. 2 (2024), https://doi.org/10.1007/s42114-024-00854-1.

performance. AX Foatek PP40 (PPGnP0.5GF40-VF20) is the foamed variant of AX Gratek PP40 (PPGnP0.5GF40), engineered with a 20% void fraction (VF) using supercritical carbon dioxide through MuCell Technology. This process is integrated with industry-scale injection moulding, enabling a streamlined and scalable manufacturing approach. In essence, the mechanical, thermal insulation, and thermal management performances were found to be governed by synergistic enhancements resulting from the intricate interrelationship between the overall morphological architecture and the crystalline microstructure, influenced by the reinforcement concentration, orientation, distribution, and porosity. Specifically, the hierarchical fibrous assembly in the hybrid composites exhibited a higher degree of orientation compared to the GFs in biphasic composites, resulting in preferential anisotropic stress and heat transfer, while simultaneously refining the foam structure by reducing cell size and increasing cell density, thereby enhancing both mechanical and thermal insulation properties. Thus, the synergy-induced thermal management performance is governed by the joint action of the preferential heat dissipation of the skins and the outstanding insulation of the refined cellular core.

Additionally, the nano-scale stiffness variations among the crystalline polymorphs within the enhanced microstructure, where β-crystals enhance toughness and ductility, γ-crystals increase strength and stiffness, and trans-crystals create a gradient interphase that facilitates load transfer at the interface, collectively lead to superior mechanical performance. As a result, compared to the leading biphasic composite adopted in the automotive industry for structurally demanding components, this hybrid composite technology was tailorable to achieve improvements up to 32%, 36%, and 116% in specific tensile strength, specific flexural strength, and impact strength, respectively, as well as 66% in thermal insulation and 62% in thermal management performance, with a 38% weight reduction[9]. Ultimately, a combination of mechanical robustness and lightweighting makes it an ideal candidate for next-generation structural battery casings, lightweight automotive body panels, and underbody shielding in electric vehicles.

Similarly, our newest state-of-the-art *1D/1D* hybrid composite material (PPHNT0.5GF40), now commercially known as *AX Clatek PP40* (Patent-Pending), is composed of nano-sized halloysite nanotubes (HNTs; 0.5 wt.% HNT) electrostatically self-assembled onto micro-sized GFs (40 wt.% GF), emulating the hierarchical organisation of osteons in compact bone (Figure 1A). This candidate delivers improvements (Figure 1B) of up to 27% in specific tensile strength, 30% in specific flexural strength, 88% in impact strength, 46% in thermal management, and a remarkable 255% increase in processability (melt-flow index), along with a 20% weight reduction relative to standard composites (PPGF60)[10]. Its enhanced processability enables complex part geometries through high-throughput manufacturing, while its compatibility with pigments and coatings supports use in both structural and aesthetic components, including interior panels and housings for consumer electronics.

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[9]Nello D. Sansone et al., Butterfly-Inspired Hierarchical Hybrid Composites for Lightweight Structural Thermal Management Applications, *Advanced Functional Materials*, (2025): 2420744, https://doi.org/10.1002/ADFM.202420744.

[10]Rafaela Aguiar et al., Tailoring Synergistic Multifunctionality in Lightweight Bio-Inspired Cylindrical Core-Shell Hybrid Composites, *Advanced Functional Materials*, (2024), https://doi.org/10.1002/ADFM.202403728.

Conclusion

Ultimately, hierarchical hybrid composites represent a paradigm shift in the design and scalable manufacturing of multifunctional composite materials. By uniting biomimetic design, AI-driven predictive modelling with micromechanics-based homogenization theory[11], and scalable processing with strategic multi-phase reinforcement architectures, this technology overcomes the intrinsic limitations of both traditional and modern composite materials. The result is a versatile, application-tunable materials ecosystem that not only meets but also exceeds the performance demands of next-generation transportation, defence, and high-performance systems. With proven industrial validation, commercial traction, and a robust scientific foundation, this technology establishes a blueprint for the future of sustainable material innovation, where nature-inspired engineering and digital design converge to deliver lightweight, high-performance, and multifunctional solutions for a net-zero future.

At NanoMorphix, our proprietary AegisX™ coating technology is built upon these very design principles, merging hierarchical architecture with scalable processing to create self-healing, transparent, and impact-resistant composites. AegisX™ typifies how biomimetic inspiration, advanced modelling, and hybrid reinforcements can be translated into real-world applications, from next-generation armoured vehicles to aerospace systems. This technology not only demonstrates the transformative potential of hierarchical composites today but also charts the course for the future of material design, where resilience, sustainability, and multifunctionality redefine the boundaries of engineering innovation.

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