Journal of Composites and Compounds 6(2024) 1-6

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Journal of Composites and Compounds

Review of fabrication, characteristics, and applications of multi-scale polymer composites

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A B S T R A C T

This review focuses on the multi-scale polymer composites, their applications, structural characteristics, and manufacturing processes. Using micro or nano-sized particles as fibers, multi-scale composite reinforcements improve the thermal, mechanical, and functional characteristics of polymers in ways that single-scale composites cannot. Several manufacturing procedures are evaluated to attain enough dispersion and significant interfacial adhesion between the reinforcements and the polymer matrix. These are essential for the electronics, automotive, and aerospace sectors to have devices with improved functionality and adaptability. Along with the sustainable design issues that multi-scale polymer composites encounter in order to become high-performance materials, the examination examines interface engineering, scalable production, and property optimization control.

A R T I C L E   I N F O R M A T I O N

Article History:
Received 01 April 2024
Received in revised form 10 June 2024
Accepted 15 June 2024

Keywords:
Multi-scale
Polymer composites
Thermal conductivity
Electrical properties
Applications

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1. Introduction

Multi-scale polymer composites are new and unique classes of materials that increase mechanical, thermal, and functional performance due to utilizing matrices and reinforcing particles/re-enforcements on all size scales from nano (or molecular) to macro [1-3], and combining the advantages of polymers with other fillers in a variety of applications such as: fibers, graphene, and nanoparticles [1, 4]. The application of polymer composites has expanded into high-performance industries, primarily due to recent advancements in the ability to quantify and characterize multi-scale composites, which has resulted in a better ability to control the structural, processing, and property relationships in polymer composites [3, 5].

Multi-scale polymer composites are produced using various manufacturing processes, including electrospinning, resin infusion, hand lay-up, and hybrid manufacturing [6, 7]. In addition, advanced methods include vacuum bagging, compression molding, and 3 and 4D printings [7]. By manipulating the composite design, the methods can improve interfacial adhesion between polymer matrix and fillers, understand reinforcement, and improve filler placement [8]. Significant advances in manufacturing process can also contribute to maximizing mechanical strength and durability, as well as substantively address other issues with production such as voids, residual stress and other parameters affecting the repeatability and reliability of the end product [1, 7]. The hierarchical arrangements have a considerable impact on the features of multi-length scale polymer

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https://doi.org/10.61882/jcc.6.2.3

composites [9]. While fibers provide additional structural support at the micro-scale, fillers enhance the matrix at the nano-scale by increasing conductive and load transfer ability [4, 10], providing a synergistic reinforcement system that enables composites to exhibit properties such as durability in environmental conditions, impact resistance and unmatched structural strength, which are pertinent features for advanced technology use when deployed as composites [4, 11].

As noted in existing research [12], multi-scale polymer composites have emerged as an influential part within many sectors including biomedicine, electronics, automotive, and aerospace. Their unique strength, flexibility, and corrosion resistance have allowed us to leverage prefabricated sensors, energy harvesting, light-weight frame work, and self-healing materials [5, 13].

The incorporation of nanomaterials (i.e., graphene) expands electrical and mechanical properties into smarter and flexible structures [14, 15]. Sustainability issues, at a variety of scales, are becoming ever more prominent in the production of polymer composite materials [16].

More organizations are looking into reclaimed polymers, bio-based resins, and natural fibers, which enhance functionality while minimizing environmental impact. Modern, sustainable composite materials are becoming even more widespread thanks to new production methods, like additive manufacturing, which offers increased material efficiency and design freedom [3, 17].

The aim of this study is to thoroughly explore the current situation of polymer blends at different sizes, along with their diverse applications, properties, and manufacture. Then it identifies advances in the development of the material, new functions, and ways of producing it while recognizing challenges and potential research futures. Its purpose is to promote the production of new polymer blends that meet the changing needs of contemporary engineering and the never-ending sustainability demands needed by combining information from different disciplines.

2. Fabrication techniques

The performance, structure, and electrical properties of multi-scale polymer composites can be improved and enhanced by using fillers of various dimensions, from very small to large [1, 18]. The basic processes that are limited to the prepreg lay-up process, resin infusion, and manual lay-up process, such as stacking and curing fibers and resin together, are very feasible for improving composite performance and reducing voids.

Other methods typically used are vacuum bagging, and curing in an autoclave. The proper dispersion of nanomaterials, such as carbon nanotubes, is essential to avoid excessive resin viscosity, and filter effects when performed in a process such as resin transfer moulding (RTM) or vacuum assisted resin transfer moulding (VARTM) [19, 20].

Modified infusion methods have been developed to achieve greater impregnation and dispersion of nanofillers, including film infusion [20].

Advanced technologies like additive manufacturing and surface coating are also emerging to optimize composite quality and functionality across scales [21]. These fabrication approaches balance processability, scalability, and material performance for applications in automotive, aerospace, and other high-performance fields [20, 21].

Depending on the intended reinforcement scale and ultimate usage, fabrication techniques are frequently employed for multi-scale polymer composites. Each has unique benefits and difficulties. Fig. 1 and Table 1 list many of these techniques.

3. Characteristics of multi-scale polymer composites

Because of their hierarchical structure, which incorporates reinforcements at several length scales, such as nano, micro, and macro, multi-scale polymer composites have unique properties (Fig. 2). Table 2 shows these traits.

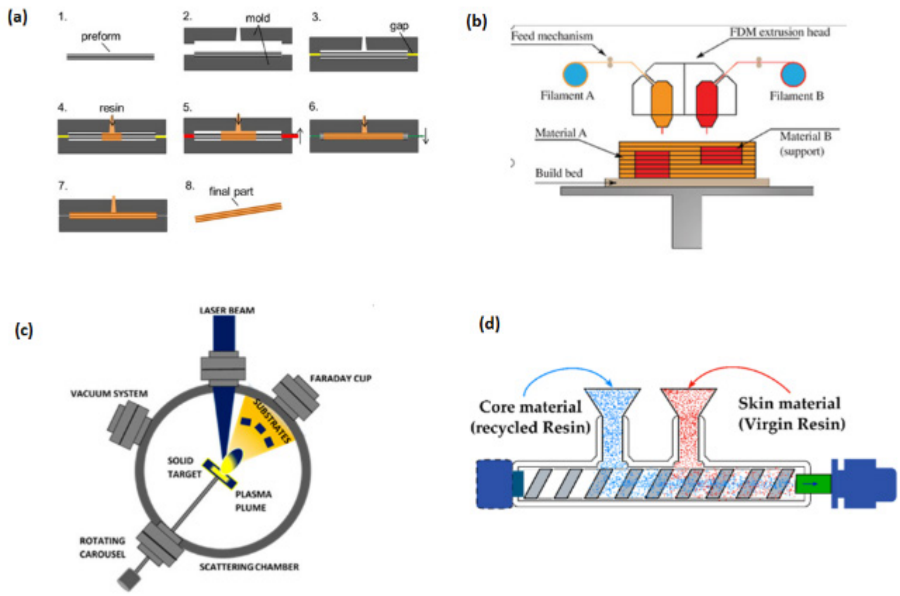

Fig 1. Schematic of some fabrication techniques of multi-scale polymer composites, a) Resin transfer molding (RTM) [22], b) Fused deposition modeling (FDM) [23], c) Pulsed laser deposition (PLD) [24], d) Injection molding process [25].

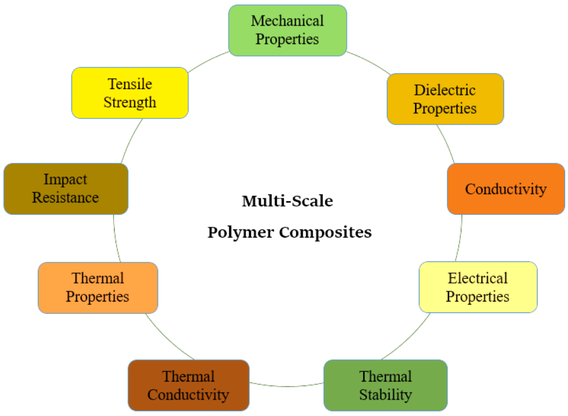

Fig 2. Properties of multi-scale polymer composites.

Table 1
Fabrication techniques of multi-scale polymer composites.

Fabrication technique	Description	Advantages	Limitations	Refs.
Traditional methods	Injection molding Extrusion Calendaring hot pressing	High repeatability process control suitable for complex shapes	Limited to specific geometries less control at the nanoscale	[22]
Additive manufacturing (3D printing)	Layer-by-layer Fused Deposition Modeling (FDM) Powder Bed Fusion (PBF)	Precise control over complex geometries ability to incorporate nanomaterials and fibers	Feedstock preparation difficulties printing defects limited scalability	[21, 26-29]
Electrohydrodynamic (EHD) processing	Utilizes electric fields to evenly deposit fluids containing nanomaterials	High precision and uniformity low temperature processing	Slow process sensitive to the environment nozzle clogging	[30]
Advanced laser-assisted deposition	Pulsed Laser Deposition (PLD) Laser-Induced Forward Transfer (LIFT)	Precise control of film thickness Uniformity Adhesion suitable for materials with several components	Requires laser equipment process complexity	[31]
Resin transfer molding	Resin Transfer Molding (RTM) Vacuum-Assisted Resin Transfer Molding (VARTM)	suitable for large parts incorporate nano-reinforcements increase viscosity improving mechanical propertie	Restricted to low-viscosity resins High tooling costs	[1, 20]
Surface coating technologies	Techniques to apply functional coatings on polymer composites	Enhances surface properties corrosion resistance flame retardancy	May require multiple steps or specialized equipment	[21]
Magnetic pulse powder compaction	Dynamic compaction method for powder-based polymer composites	Improves molding quality reduces failure behavior	Specialized equipment needed	[21]
Automatic fiber dispersion	An advanced method to uniformly distribute fibers within the polymer matrix	Achieves desired mechanical properties by uniform reinforcement distribution	Process complexity	[32]

Table 2
Characteristics of Multi-Scale Polymer Composites

Property	Description	Refs
Mechanical properties	Multi-scale polymer composites improve mechanical strength and stiffness by combining macroscale fibers (carbon, glass) with nanoscale fillers (such as carbon nanotubes, graphene). When filler content and dispersion are optimized, tensile strength and modulus increase. Micro and interfacial bonding significantly impact mechanical performance.	[11, 33-38]
Tensile strength	Hybrid fillers significantly enhance tensile strength. For instance, carbon fiber-reinforced PA 6,6 composites can achieve tensile strengths of up to 252 MPa. Multi-scale reinforcements, such as MWCNT and B4C, improve tensile strength depending on their concentration and the duration of mixing.	[33-35]
Impact resistance	Hybrid fillers enhance impact resistance, with carbon fiber reinforced composites achieving values up to 8.84 kJ/m². The type of filler and the fiber-matrix interface play crucial roles in determining impact resistance.	[34, 35]
Thermal properties	Many studies have shown that nanoparticle-reinforced fiber/polymer composites exhibit remarkable thermal properties. This is due to the fibers' thermal stability and increased interactions between the nanofillers and the matrix, which restrict the movement of polymer chains during thermal treatments and contribute to improved performance stability.	[39, 40]
Thermal conductivity	Due to matrix dominance, through-thickness conductivity remains modest (~1 W/mK), while in-plane thermal conductivity is significantly enhanced by carbon fibers and carbon nanotubes (up to ~10 W/mK). Compared to as-synthesized CNTs, heat-treated CNTs exhibit superior thermal conductivity. In PA composites, SiC fillers can increase conductivity from 0.25 to 3.83 W/mK.	[34]
Thermal stability	Fillers significantly improve polymer composites' thermal stability, enabling greater operating temperatures and resistance to deterioration. Epoxy-Kevlar composites, for instance, perform well thermally at high temperatures (~693 K contact temperature).	[35, 41, 42]
Electrical properties	Due to their enhanced interfacial strength, the fillers form excellent continuous networks in multiscale composites, achieving superior electrical characteristics. For example, Cortes et al. added silver nanowires to the carbon fiber/PEEK composites matrix, increasing their transverse electrical conductivity by at least three times.	[36, 43]
Conductivity	Network formation, filler type, loading, and dispersion significantly impact electrical and thermal conductivities. CNTs and CNFs create conductive networks that enhance these conductivities.	[33, 44]
Dielectric properties	Type and loading of the nanofiller affect dielectric characteristics; metal oxide fillers in biodegradable polymer matrices impact dielectric behavior and the efficiency of electromagnetic interference shielding. Dielectric constant and loss are dependent on filler dispersion and filler-matrix interactions.	[45, 46]

4. Applications of multi-scale polymer composites

Multi-scale polymer composites have distinctive qualities that make them extremely adaptable materials with excellent structural and functional qualities appropriate for cutting-edge engineering applications, particularly in the high-performance industries of electronics, automotive, aerospace, and others.

4.1. Automotive industry

Excellent stiffness, strength, and stability are provided by carbon fiber-reinforced components. Nanofillers can be utilized to customize the strength of these composites. [47, 48] In the automobile industry, injection-molded and heavy steel components are replaced with sophisticated multiscale composites. Multi-scale composite automotive components are safer, lighter, and more economical with gasoline. Carbon fiber cars are popular because of their properties and aesthetics [49]. Imoisili et al. [50] produced a natural fiber reinforced hybrid nanocomposite for the automotive industry by combining multiwalled carbon nanotubes (MWCNT) with treated plantain (Musa paradisiaca) fiber in a single epoxy resin matrix. The hybrid composites' mechanical qualities, such as their increased mechanical strength by around 50%. The outcome suggests mechanical and thermal characteristics for possible industrial uses. AL-Oqla et al. [51] conducted another study to determine whether date palm fibers can be incorporated into natural fiber reinforced polymer composites (NFC) for the automotive industry.

4.2. Electronics and electrical applications

Composite materials are increasingly being employed in electrical applications such as coupling capacitors, circuit breakers, bushings, and so on, thanks to the rapid expansion of the electrical industry. Due to the vastly different property requirements, electrical and structural composites have very different design characteristics [52]. Many electronic sensors have been prototyped recently. Nanomaterials, polymers (including conducting polymers and biopolymers), and their composites are also widely employed in biosensor interfaces, further broadening the functional scope of polymer-based materials [53]. Simon et al. [54] used the FDM method to fabricate a variety of sensors utilizing carbon black/PCL composite, such as capacitive and piezoresistive sensors. When the electrical resistance changed, the piezoresistive sensors could identify the change in mechanical flex.

4.3. Medical devices

Among other applications, multi-scale polymer composites have been utilized in medical implants, tissue engineering, orthopedics, cosmetic orthodontics, drug delivery, and wound dressing [55, 56]. The intended applications determine whether NFRPCs are produced for medical use [56]. In one work, Mangat et al. [57] employed a low-cost destock printer to create three-dimensional structural composites with natural fiber insertion and fused filament deposition for scaffold-based biomedical applications. Rahman et al. [58] gave another example of a biological use. To achieve a high extraction yield, several reaction parameters were optimized in this study to extract nano- and microcrystalline cellulose (CC) from jute fiber. Polylactic acid was combined with CC (3–15%) to create the composite films. Furthermore, the samples demonstrated non-toxic characteristics and may be used as bone implant parent material.

4.4. Aerospace

A lightweight body and exceptional strength are necessary for aircraft to use less fuel. Composites, weighing up to 20–50% less than the original materials, make up around 50% of airplane components. Carbon fiber is the main component of sophisticated composite technologies because of its exceptional strength-to-weight ratio. The high cost of carbon fiber remains an issue. Furthermore, aramid fiber-reinforced composites are employed to build wing components that safeguard the fuel-carrying engine pylons, offering superior impact resistance and rigidity [49, 59]. Approximately 50% of the components in airplanes manufactured by Boeing and Airbus consist of multi-scale composites. Boeing has successfully replaced about 11,000 metal parts with 1,500 composite alternatives. These hybrid composites provide benefits such as corrosion resistance, thermal stability, mechanical strength, and damage tolerance [49, 60].

5. Conclusion

The overview of multi-scale polymer composites' features, applications, and manufacturing processes highlights the significant progress made in incorporating reinforcements of various sizes, from nano to macro, to provide enhanced multifunctional qualities. To address drawbacks such as poor out-of-plane properties in conventional composites, these composites combine standard fiber reinforcements with the unique electrical, mechanical, and thermal capabilities of nanoscale fillers, like carbon nanotubes. The resulting multi-scale composites are suitable for high-performance electronics, aerospace, and automotive sectors due to their improved electrical conductivity, multifunctionality, and greater mechanical strength. Despite these advancements, challenges remain in achieving cost-effective production, scalable manufacturing, and uniform nanofiller dispersion while maintaining multifunctional integration and consistent quality.

Future studies on multi-scale polymer composites are expected to enhance fabrication techniques to increase repeatability and scalability, including cutting-edge 3D and 4D printing technologies that provide precise control over composite design and characteristics. Developing intelligent, self-healing, and stimuli-responsive composites that can adapt to damage or environmental changes is also becoming increasingly important, boosting their application in advanced industries like energy harvesting and wearable electronics. Furthermore, an essential area for innovation is modifying interfacial chemistry to optimize stress transmission and multifunctionality at the nano-micro interface. Employing biocompatible and sustainable materials will also be vital to meet legal and environmental standards. Considering all factors, the next generation of polymer composites is expected to be driven by the convergence of multi-scale design, multifunctionality, and advanced production techniques, paving the way for new industrial applications and enhancing performance attributes

Author contributions

Farnaz Sadeghi: Investigation, Writing—Original Draft Preparation and Writing—Review and Editing. **Jalaladdin Hosseinzadeh:** Visualization, Writing—Original Draft Preparation and Writing—Review and Editing. **Masoumeh Tabebordbar:** Investigation, Writing—Original Draft Preparation and Writing—Original Draft Preparation.

Funding

No funding was received for this study.

Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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