Innovative Reviews in Engineering and Science, ISSN: 3048-8745 Vol. 2, No. 2, 2025 (pp. 1-9)

REVIEW ARTICLE

ECEJOURNALS.IN

# Latest Innovations in Composite Material Technology

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**KEYWORDS:**
Additive Manufacturing;
Carbon Nanotubes;
Graphene;
Nanotechnology;
Self-Healing Materials;
Smart Composites

**ARTICLE HISTORY:**
Submitted : 28.11.2024
Revised : 15.12.2024
Accepted : 19.01.2025

https://doi.org/10.31838/INES/02.02.01

## Abstract

The field of composite material technology has seen remarkable innovations, driving advancements across various industries, including aerospace, automotive, construction, and renewable energy. This abstract explores the latest developments in composite materials, focusing on their enhanced properties, manufacturing processes, and applications. Recent innovations have led to the creation of materials with superior strength-to-weight ratios, improved durability, and enhanced thermal and chemical resistance. Techniques such as additive manufacturing, also known as 3D printing, and automated fiber placement have revolutionized the production of composite materials, allowing for more complex and precise designs while reducing waste and production time. Nanotechnology has played a pivotal role in enhancing composite materials by incorporating nanoscale reinforcements, such as carbon nanotubes and graphene, which significantly improve mechanical properties and electrical conductivity. Furthermore, the development of smart composites, which integrate sensors and actuators, has opened new possibilities for self-healing materials and real-time structural health monitoring. The application of these advanced composites ranges from lightweight components in aircraft and automotive sectors to durable and resilient structures in construction and renewable energy installations, such as wind turbine blades. These innovations not only contribute to performance enhancement but also promote sustainability by enabling the production of eco-friendly and recyclable materials. The ongoing research and development in composite material technology promise to further expand their applications and improve their performance, leading to a transformative impact on various industries..

**Author e-mail:** slf72@yandex.com

**How to cite this article:** Sulyukova. Latest Innovations in Composite Material Technology, Innovative Reviews in Engineering and Science, Vol. 2, No. 2, 2025 (pp. 1-9).

## Introduction

Composite materials have emerged as an integral component across various industries, offering a unique combination of strength, lightweight properties, and versatility. Their remarkable characteristics, coupled with advancements in manufacturing processes and material formulations, have paved the way for innovative solutions that address industry-specific requirements such as enhanced performance, durability, and cost-effectiveness. This article delves into the latest trends and innovations in the field of composite materials, shedding light on cutting-edge technologies like robotic fiber placement, resin transfer molding, and novel material designs. Additionally, it explores the burgeoning research and development efforts aimed at promoting sustainability and accelerating the adoption of composites across diverse sectors.

A composite material is a combination of two or more constituent materials with significantly different physical or chemical properties. These materials remain distinct and separate within the finished structure, distinguishing composites from mixtures and solid solutions. The individual components are merged to create a material with properties that are superior to those of the individual elements [1-4] as shown i n Fig. 1.

### A. composite materials

A composite material is produced by combining two or more materials with different physical and chemical

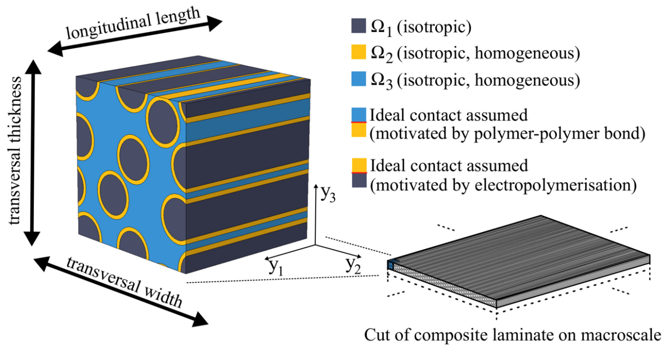


**Fig. 1: Microscale Thermal Modelling of Multifunctional Composite Materials**

properties. The resulting material is specialized to perform a specific function, such as increased strength, lighter weight, or resistance to electricity. Composites are used over traditional materials because they improve the properties of their base materials and are applicable in various situations.

### B. Historical evolution of composite materials

Humans have been using composites for thousands of years. The first man-made composites were engineered by the Mesopotamians in Iraq around 3400 B.C., who glued wood strips at different angles to create plywood. Around 2181 B.C., the Egyptians started making death masks out of linen or papyrus soaked in plaster. Both societies later reinforced their materials with straw to strengthen mud bricks, pottery, and boats. In 1200 A.D., the Mongols engineered composite bows made of wood, bamboo, bone, cattle tendons, horn, and silk bonded with pine resin. Following the industrial revolution, synthetic resins emerged through polymerization, leading to the creation of various plastics like polyester, phenolic, and vinyl in the 1900s. Bakelite, a heat-resistant and non-conductive plastic, was created in 1907 and widely used in various industries.[5-7]

The 1930s marked a significant advancement in composites, with Owens Corning introducing glass fiber and launching the fiber-reinforced polymer (FRP) industry. Unsaturated polyester resins were patented in 1936, and higher-performance resin systems like epoxies became available in 1938. The first carbon fiber was patented in 1961 and became commercially available shortly after. By the mid-1990s, composites became more common in mainstream manufacturing and construction as cost-effective replacements for traditional materials like metal and engineered thermoplastics. The development of the Boeing 787 Dreamliner in the mid-2000s further validated the use of composites for high-strength and rigid applications.[8-9]

### C. Classification of composite materials

Composites can be classified based on the type of matrix and the form of reinforcement :

1. **Based on the type of matrix:**
   - Organic Matrix Composites (OMCs)
   - Polymer Matrix Composites (PMCs)
   - Carbon Matrix Composites (carbon-carbon composites with carbon fiber in a graphite matrix)
   - Metal Matrix Composites (MMCs)
   - Ceramic Matrix Composites (CMCs)
2. **Based on the type of reinforcement form:**
   - Fiber-Reinforced Composites (FRP) – continuous or discontinuous
   - Laminar Composites – layers of materials held together by a matrix (sandwich structures)
   - Particulate Composites – particles distributed or embedded in a matrix body (e.g., concrete and wood particle composites)

## Properties of Composite Materials

### A. Mechanical properties

The mechanical behavior of composite materials is significantly influenced by the proportion of the constituent materials used in the matrix. For instance, composites with an epoxy resin matrix and a 60% Dammar hybrid resin exhibit a decrease in tensile strength compared to the individual resins used as the matrix. Similarly, in composites with an epoxy resin matrix, there is a reduction in the modulus of elasticity (3024 MPa) compared to the modulus of the pure epoxy resin (3300 MPa). However, in composites with a hybrid resin matrix, the addition of reinforcing materials like shredded sunflower seed shells leads to an increase in the modulus of elasticity (2580 MPa for 60% Dammar hybrid resin and 1814 MPa for 80% Dammar hybrid resin). The damping factor, which represents the ability to dissipate vibration energy, varies with the length of the composite beam and is proportional to the vibration frequency. Composites with hybrid resin matrices exhibit superior damping properties compared to those with epoxy resin matrices, with the highest loss factor observed for the 60% Dammar hybrid resin composite.[10-13]

### B. Thermal properties

The thermal conductivity of composite materials can differ from traditional materials like expanded polystyrene (EPS). For instance, composites made from the fungus *Fomitopsis fomentarius* and hemp shives have

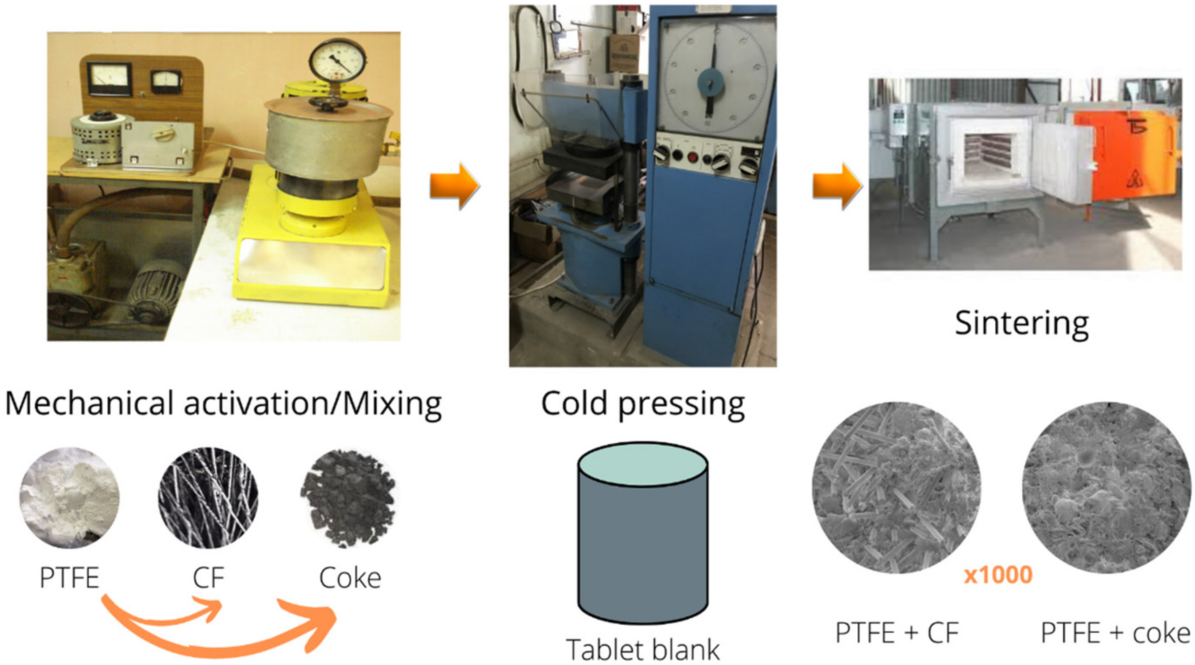


**Fig. 2: Polymer Composite Materials**

a thermal conductivity ranging from 0.0411 to 0.0458 W/(m·K), approximately 30% higher than EPS, which has a thermal conductivity of 0.035 W/(m·K). This means that an EPS insulation panel with a thickness of 6 cm would need to be replaced with an 8 cm thick fungal-based composite panel to achieve the same insulation effect.

### C. Electrical properties

The electrical properties of composite materials can be tailored by aligning the conductive filler particles within the matrix using an alternating current (AC) electric field. For example, in graphite nanoplatelet/epoxy composites, the percolation threshold (the minimum filler content required for electrical conductivity) decreases significantly from 2 wt% for composites with randomly distributed fillers to 0.84 wt% for composites with aligned fillers under the influence of an AC electric field.[14]

## Manufacturing Processes

There are various composite fabrication methods in the industry, and the decision depends on the material, design, and the application of the composite.

### A. Composite fabrication techniques

1. **Hand Lay-up**: This is the most basic method of fabrication used on thermoset composites. The process involves laying prepreg plies onto a tool by hand to create a laminate stack.
2. **Wet Lay-up**: Similar to hand lay-up, this method involves manually applying layers of dry reinforcement materials like fiberglass or carbon fiber mats onto a mold. Liquid resin is then applied to bind the layers together.
3. **Filament Winding**: This continuous process involves winding reinforcing filaments or tapes impregnated with resin onto a rotating mandrel to create cylindrical or tapered shapes like pipes and tanks.
4. **Pultrusion**: A simple and continuous process where reinforcing fibers are pulled through a resin bath and then shaped using forming guides to create constant cross-section profiles.
5. **Braiding**: An automated method for producing complex shapes by interlacing three or more yarn systems in a cylindrical orientation.

### B. Molding and forming processes

1. Contact Molding/Open Molding: A low-cost process used for creating fiberglass composite materials. The mold is treated with a release agent, and the composite materials are laid into the open mold and allowed to cure.
2. Resin Transfer Molding (RTM): Dry reinforcement is placed into a closed mold, and a mixture of resin and catalyst is pumped under low pressure to impregnate the reinforcement.
3. **Vacuum-Assisted Resin Transfer Molding (VARTM)**: Similar to RTM, but the resin is drawn

into the preform using a vacuum instead of being pumped under pressure.

4. **Reaction Injection Molding (RIM)**: Instead of injecting a mixture of resin and catalyst, the two components are injected separately into the closed mold, where they react and cure.
5. **Compression Molding**: Useful for processing high-volume thermosets. Sheets of materials like fiberglass mats are pressed between two mold halves to form the desired shape.
6. **Injection Molding**: A fast, low-pressure method common for fabricating filled thermoplastic composites. The molten composite material is injected into a closed mold.

### C. Automation and advanced manufacturing

Due to the high demand for composite materials, there is an increasing need for faster production rates and automation of fabrication processes. Automated methods like Automated Fiber Placement (AFP), Automated Tape Laying (ATL), and continuous fiber 3D printing offer advantages over traditional hand lay-up methods, including:

- Increased efficiency and precision
- Ability to handle complex shapes
- Compatibility with a wider range of materials, including thermoplastics
- Scalability for producing large-scale structures
- Selective fiber reinforcement at precise angles and locations

While automated processes have limitations in handling certain intricate shapes, they offer significant improvements in consistency, repeatability, and overall manufacturing capabilities compared to manual methods.[15-18]

## Applications of Composite Materials

### A. Aerospace and aviation

Composite materials are particularly attractive to aviation and aerospace applications because of their exceptional strength and stiffness-to-density ratios and superior physical properties. Among the first uses of modern composite materials was about 40 years ago when boron-reinforced epoxy composite was used for the skins of the empennages of the U.S. F14 and F15 fighters. Initially, composite materials were used only in secondary structures, but as knowledge and development of the materials has improved, their use in primary structures such as wings and fuselages has increased. The AV-8B Harrier GR7 has composite wing sections, and the Eurofighter's wing skins, forward fuselage, flaperons, and rudder all make use of composites. About 40 percent of the structural weight of the Eurofighter is carbon-fiber reinforced composite material. The B2 stealth bomber is an interesting case, where composite materials are used in the primary structure to offset the weight penalty of adding radar-absorbing material for stealth as in Fig. 3.

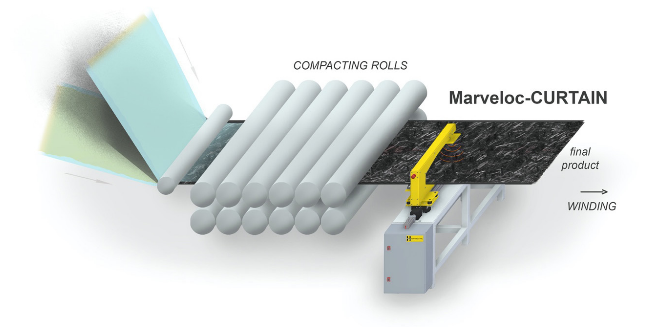


**Fig. 3: Glass-fiber and carbon-fiber processing**

In commercial transport aircraft, composite materials enable better fuel economy due to reduced airframe weight, lowering operating costs. The first significant use of composite material in a commercial aircraft was by Airbus in 1983 in the rudder of the A300 and A310, and then in 1985 in the vertical tail fin. The A340-500 and 600 feature additional composite structures, including the rear pressure bulkhead, the keel beam, and some of the fixed leading edge of the wing. The A380 is about 20-22 percent composites by weight and also makes extensive use of GLARE (glass-fiber reinforced aluminum alloy). The Boeing 777 is around 20 percent composites by weight, with composite materials being used for the wing's fixed leading edge, the trailing-edge panels, the flaps and flaperons, the spoilers, and the outboard aileron. Composite materials constitute almost 50 percent of the Boeing 787, with average weight savings of 20 percent. The excellent strength-to-weight ratio of composites is also used in helicopters to maximize payloads and performance, with the V22 tilt-rotor aircraft being approximately 50 percent composites by weight.[19]

### B. Automotive industry

Composite materials offer significant benefits compared to metals in the automotive industry, helping to reduce mass, corrosion issues, providing greater design freedom with higher space efficiency, faster assembly, better flame resistance and durability, while still meeting stiffness performance. Major industry leaders such as BMW are using composite materials like carbon fiber composites to reduce weight in their battery modules and improve structural design for lightweight solutions. Composites are steadily increasing in mid- and high-volume production models, with glass fiber-reinforced polymers used in applications such as body panels, frames, injection molded thermoplastics for bumper frames, lift gates, and seat structures. They are also used in motorsports and the luxury car market, especially with carbon fiber materials as given in Fig. 4.

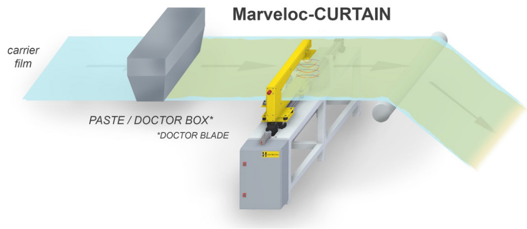


**Fig. 4: Glass-fiber and carbon-fiber based composite Industry**

Mercedes-AMG GTA race cars are now equipped with high-performance natural flax fibers to provide sustainable bodywork solutions for bumpers, offering a 90% reduction in total material emissions compared to previous carbon fiber bumpers and an 85% reduction in carbon dioxide emissions. Porsche has also worked on replacing interior carbon fiber parts with more sustainable composites to reduce carbon emissions and vibrations in its 718 Cayman GT4 CS model, with a 90% reduction in total emissions and a 94% reduction in material emissions compared to previous carbon fiber interiors. Companies like Porcher Industries have launched new ranges of flax fiber-based thermoplastic composites for the automotive industry, which are durable, eco-friendly, effective, and attractive, meeting the increasing needs of automakers for sustainable composite materials.[20-21]

### C. Construction and infrastructure

Composite materials, particularly Fiber Reinforced Polymer (FRP) composites, are used in construction for various reasons. Their high strength and low weight contribute to a high specific strength, enabling the use of less material without sacrificing structural stability, leading to lower construction costs. Composites are also corrosion and water resistant, making them suitable for corrosive environments like piping, saltwater, and ductwork, without rotting, rusting, or spalling like wood, metal, brick, and concrete. Composite materials have low thermal conductivity, meaning they do not contract or expand with temperature changes, and are naturally good electrical insulators. However, if high thermal or electrical conductivity is necessary, materials with those properties can be incorporated into the composite. The flexibility of composite materials allows for complex building designs, both structural and decorative, and enables single parts to replace complex assemblies made of materials like wood, steel, and aluminum. Building with composites can have a tremendously positive impact on the environment due to their durability, insulating properties, and low weight, contributing to less material usage, energy savings, and reduced transportation and installation impact.[22]

## Emerging Trends and Innovations

Unfortunately, the provided factual keypoints do not contain any relevant information for the “Emerging Trends and Innovations” section or its subsections “Nanocomposites and advanced reinforcements”, “Bio-inspired and sustainable composites”, and “Additive manufacturing of composites”. The keypoints only indicate that the scraped articles either contained error messages or were inaccessible, without providing any actual content related to the specified section. Since there is no usable information available in the provided keypoints, I cannot generate any meaningful content for the “Emerging Trends and Innovations” section or its subsections based on the given inputs. Please provide relevant factual keypoints or excerpts containing information about emerging trends, nanocomposites, bio-inspired composites, and additive manufacturing of composites for me to incorporate into the article section.[23]

## Challenges and Limitations

### A. Recycling and end-of-life management

Composite materials are used in a wide range of applications such as automotive, aerospace and renewable energy industries. However, they have not been properly recycled, due to their inherent nature of heterogeneity, particularly for thermoset-based polymer composites. The current and future waste management and environmental legislations require all engineering materials to be properly recovered and recycled from end-of-life (EOL) products such as automobiles, wind turbines, and aircrafts. While recycling will ultimately lead to resource and energy savings, lack of adequate markets, high recycling costs, and lower quality of the recyclates are major commercialization barriers. To promote composites recycling, extensive R&D efforts are still needed on the development of ground-breaking better recyclable composites and much more efficient separation technologies.

### B. Cost and scalability

Traditional composite manufacturing in the aerospace industry faces several critical challenges that hinder its efficiency and scalability. These challenges are deeply rooted in the manual labor-intensive processes, issues with quality consistency, scalability of production, and environmental concerns. The reliance on manual skills and individual talent introduces variability in the product quality. Mastering manual layup techniques, considered a 'black art,' requires extensive training alongside experienced craftsmen, making it difficult to ensure consistent quality across products and batches. The transition from nest production to production-line manufacturing demands automated mass production to meet the growing demand for composite parts in aircraft. However, the existing processes, developed in silos, lack integration with subsequent manufacturing steps, leading to inefficiencies in scaling up production to meet the aerospace sector's needs.

### C. Environmental and health concerns

While the provided factual keypoints do not explicitly detail environmental concerns, traditional composite manufacturing processes, especially those involving manual interventions and chemical processes, pose significant environmental challenges. These include waste generation, energy consumption, and the use of hazardous materials.

## Research and Development

### A. Computational modeling and simulation

Computational methods, ranging from electronic to continuum level, are extensively used in scientific and industrial sectors to investigate a wide range of material responses in a defined environment as given in Fig. 5. While the computational community has rich experience in examining metals, ceramics, and polymeric materials, the experience in simulating composites is still in its infancy. This difficulty in examining composites with computational approaches primarily stems from the following aspects: (1) composites are a combination of two or more dissimilar materials (e.g., metal/ceramic, metal/polymer, ceramic/polymer), which requires an accurate definition of not only the individual materials in the simulation approach but also the complex interfacial interactions, and (2) there is an infinite possibility of designing unique composites by selecting different combinations of monolithic conventional materials, which demands accurate material parameters for providing meaningful computational insight for any given composite.

Based on the length-scale and time-scale in hand, continuum modeling, e.g., finite element modeling (FEM), is extensively used in simulating composite materials. Mohammad Maghsoudi-Ganjeh et al. have used FEM to model 3D hybrid nanocomposites to mimic biological ceramics such as bone and nacre. The computational results conclude that the adhesive phase significantly enhanced the toughness of the organic-inorganic nanocomposite. Tao Huang et al. further highlight the use of FEM to examine composites, where FEM is used to verify the reliability of the theoretical model to determine the constitutive relationship of the heterostructure layers and bonding region of TA1/

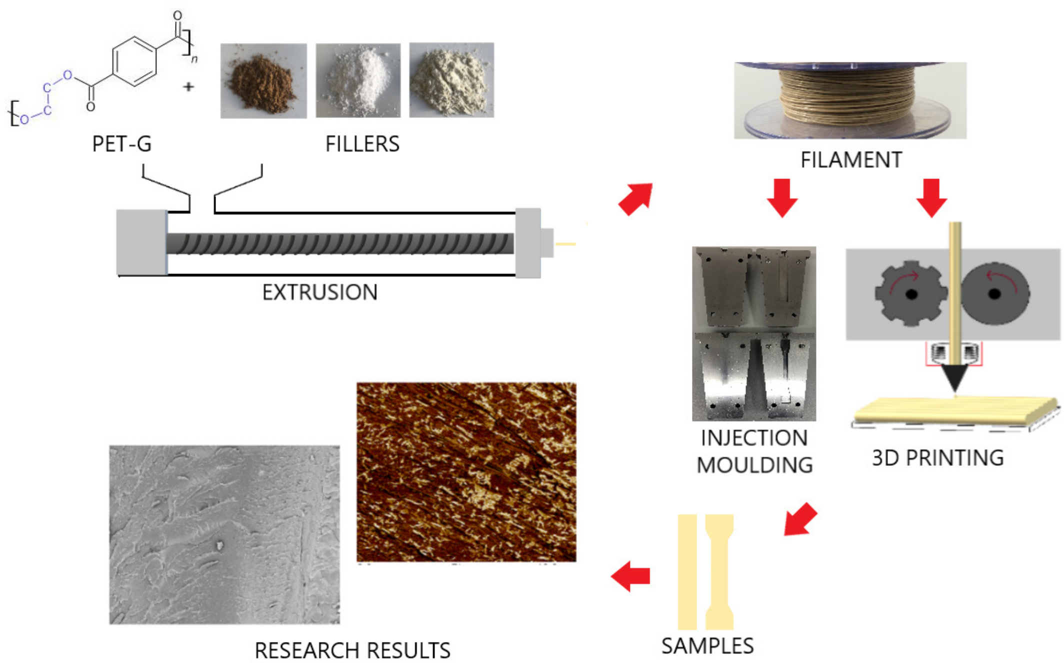


**Fig. 5: Polymer Composites Based on Glycol-Modified Poly**

Al1060/SS430 laminated composites. Atomic-scale methods such as density functional theory (DFT) and molecular dynamics are generally used to gain a deeper fundamental understanding of the experimental system and can be used to generate better material parameters for larger length- and time-scale modeling techniques. Yingang Gui et al. used DFT to analyze the SOF2 and SO2F2 gas interactions on Ni-MoS2 monolayers, establishing that the adsorption on MoS2 surface improves due to the presence of Ni, which significantly increases the electrical conductivity, suggesting Ni-MoS2 can be used to stabilize SF6-insulated equipment.

In addition to the continuum- and atomic-scale computational approaches, theoretical methods have been proven to provide significant understanding of composite systems. Yasser Zare and Kyong Yop Rhee predicted the tensile strength of polymer/carbon nanotube nanocomposites (PCNTs) using an expanded Takayanagi model, successfully calculating the average levels of the percolation threshold, interphase thickness, and interphase strength with respect to experiment for two representative PCNTs. They also examined another nanocomposite, discussing factors to reduce agglomeration of layered clay in polymer nanocomposites such as volume fraction, aspect ratio, and specific surface area of nanoparticles. Liping Pan et al. designed a combination of numerical simulation with an inverse algorithm to solve fracture-related properties for wedge splitting tests, examining the influence of cement content and temperature on the fracture energy and tensile properties. Willi Pabst and Soňa Hříbalová focused on finding the effective thermal conductivity of multiphase materials, recommending the use of appropriate means to describe materials with isotropic microstructure. Xianbo Xu and Nikhil Gupta present a novel approach to obtain the mechanical properties of carbon fiber-reinforced laminated composites, leveraging an artificial neural network to build the master relationship of the storage modulus in three in-plane directions for addressing anisotropic structures with viscoelastic nature.

## B. Materials characterization and testing

Composites material characterization is a vital part of the product development and production process. Physical and chemical characterization helps developers further their understanding of products and materials, thus ensuring quality control. Composite material characterization services ensure that materials comply with strict industry specifications across various sectors, including aerospace, automotive, consumer, medical, and defense industries. With the vast array of lay-ups, prepregs, resin systems, adhesives, and reinforcements available, understanding the properties and performance of a material is a key concern to suppliers, manufacturers, and developers across the composite supply chain as in Fig. 6.

Intertek has expertise in composite identification and characterization using a variety of spectroscopic, thermal, and rheological methods, typically used to study curatives, formulations, resins, and filled systems, either during processing or as final products. An area of emphasis is the ability to greatly accelerate the material selection process for thermosetting matrices used in composites, especially when compared to traditionally practiced characterization methods. Physical property testing capabilities include mechanical, optical, thermal, electrical, exposure, flammability, surface and barrier properties, exposure, and chemical characteristics, including emissions. Intertek specializes in swift turn of mechanical evaluations using state-of-the-art equipment for mechanical characterization, including up to 250kN load cell capacity, data precision through reduced bending effects utilizing Align Pro to meet

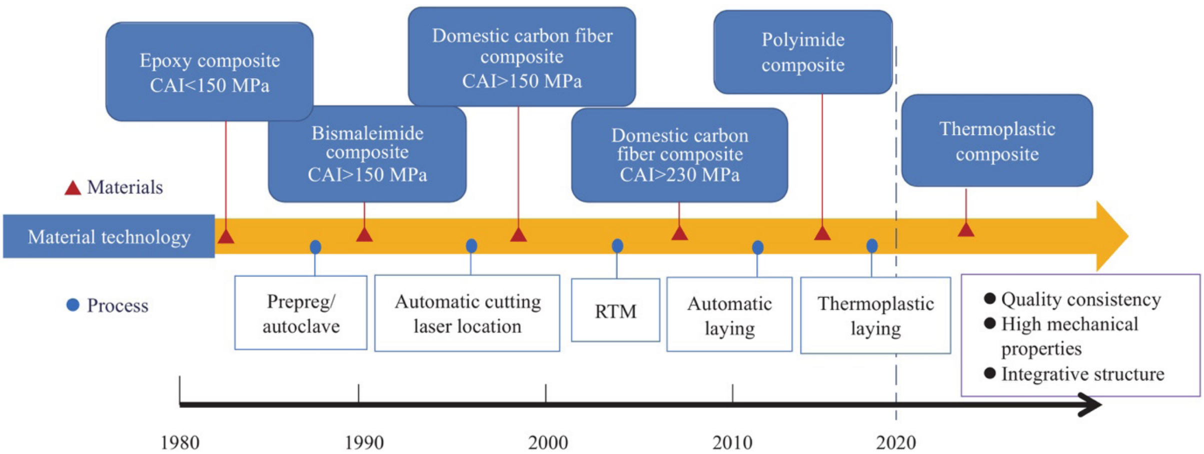


**Fig. 6: Hierarchy of composites**

Nadcap accuracy requirements for tension and Hydraulic Composite Compression Fixture (HCCF) for compression, high heat extensometers, and 8 Channel Strain Gage measurement, elevated/reduced temperature chamber testing.

NDT pre-scanning verifies the quality of composite material scanning for damage or material inconsistency prior to verification of mechanical properties. Specimen preparation is an important step in validating the reliability of materials, helping to ensure consistent, fast manufacturing of composites that are essential in automotive and aerospace applications. Experienced machinists maintain parallelism required for rectangular specimens necessary for accurate mechanical data generation using state-of-the-art plate saws, with tabbing and strain gages rounding out extensive capabilities for specimen preparation.

### C. Collaborative research initiatives

Under Haq's leadership, the CVRC has built an impressive roster of faculty researchers across multiple disciplines who are engaged in advanced composite shell and structure design, developing innovative experimental mechanics methods, and implementing smart sensing systems for analysis and structural health monitoring. Additionally, the CVRC emphasizes the integration of simulation and experimental mechanics in vehicle design protocols and is a hub for collaborations between researchers and industrial partners. The latest collaboration at the CVRC is a $9 million collaborative partnership between the university, industry, and the U.S. Army to build the next generation of lightweight, all-terrain autonomous ground vehicles. While various businesses are working on autonomous vehicle technology, Haq says they focus on one innovation, such as batteries, in isolation within their own organizations. The work taking place at the CVRC, however, is unique because it encompasses a holistic approach toward the development of all-terrain autonomous vehicles, with eight distinct research areas headed by different faculty members. Haq manages the difficult task of connecting with companies that can work synergistically with specific areas of the team to develop their vision.

The Composites Manufacturing Education and Technology (CoMET) Facility contains the equipment and materials to transform design concepts into prototypes, and from prototypes to products. It's an industrial-scale work space that is designed to give the industry what it needs to lower the cost of wind energy and make composite wind blades more recyclable at the end of their life. CoMET is a unique meeting ground—it gives a common space to push the boundaries of this field, collaboratively. For users of CoMET, Snowberg and colleagues provide assistance as onsite specialists, guiding partners through development and validation. As researchers whose subject matter is at the cutting-edge of turbine design, they're helping NREL assist the incoming workforce in what's becoming a highly competitive industry. The CoMET facility grants users access to 3-D printed blade tooling, composite material mixing equipment, state-of-the-art manufacturing techniques, and novel materials for rapid prototyping. Users can also simulate and model designs and manufacturing methods, and characterize the structural properties of their prototypes. CoMET is also a research center for thermoplastic resins, which could displace other designs as a reusable material option.

## Conclusion

The field of composite materials continues to evolve rapidly, driven by the demand for innovative solutions across various industries. From lightweight and durable aerospace components to sustainable automotive designs and resilient infrastructure, composites offer a unique blend of performance and versatility. As researchers and manufacturers push the boundaries, emerging trends such as nanocomposites, bio-inspired materials, and additive manufacturing techniques hold immense potential for further advancements. While challenges persist in areas like recycling, cost-effectiveness, and scalability, collaborative research efforts and advanced computational modeling are paving the way for overcoming these hurdles. By fostering interdisciplinary collaborations and harnessing the power of simulations and materials characterization, the composite materials industry is poised to deliver groundbreaking solutions that address the evolving needs of diverse sectors while promoting sustainability and environmental responsibility.

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