Nanomaterials for Fabrication of Thermomechanical Robust Composite

Priyambada Mallick, Santosh Ku. Satpathy, and Srikanta Moharana

Abstract Nanomaterials have received a lot of interest as an emerging material because of their small size, surface effect, and tunneling effect, along with their potential utilization in traditional materials, electronic devices, energy storage devices, and other industries. Nanoparticles are nanomaterials with dimensions ranging from 1 to 100 nm. Nanomaterials with remarkable structural, mechanical, catalytic, optical, electrical, and magnetic characteristics that differ significantly from the bulk materials can be created. They can be categorized differently based on their qualities, forms, and sizes. There are different nanomaterials, including metals and ceramics are reinforced in the polymeric matrix to obtain composites with improved physical and chemical characteristics. A lot of research has been extensively reported on the impact of introducing nanomaterials into the polymeric matrix. The effect of nanomaterial selection, synthesis technique, grain size, and boundary structures on the mechanical characteristics of nanomaterials is presented in this chapter. Hybrid polymeric composites have undergone significant development and utilization for energy applications in recent times. However, future applications in the fields of engineering, industry, and medicine can be made possible by progressing further research on the molding technique of nanomaterials. Therefore, scientists and researchers put efforts into investigating the molding and fabrication technique as well as strengthening the process of an advanced, robust nanocomposite to fulfill the essential needs in future application. This chapter provides an overview of nanostructured materials along with composite preparation processes and discusses the effect that these approaches have on the thermomechanical performance of nanomaterial-based robust composites. However, future applications in the fields of engineering, industry, and medicine can be made possible by progressing further research on the molding technique of nanomaterials. As a result, scientists and researchers are investigating the molding and fabrication technique, as well as strengthening the process of an advanced robust nanocomposite to meet the critical needs in a future application.

Keywords Nanomaterial · Polymers · Mechanical properties · Composites

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1 Introduction

Nanotechnology has piqued the interest of many over the last two decades due to its potential for the development of novel nanomaterials and device structures with exceptional physical and chemical characteristics. Recently, nanomaterials having a size of one dimension with a scale of 1–100 nm in 3D space are gaining much more attention as emerging materials. Due to its small size, surface morphology, different phases, and quantum tunneling effect, it has a lot of remarkable potential applications in the fields of electronics, automotive, electrochemical, biomedical, photochemical, electrical, medical, and industrial. Nanomaterials have extraordinary physiochemical performances, including melting point, thermoelectric activities, photo-absorbing properties, reactivity, scattering, and optical activities, with enhanced catalytic properties in comparison with their polycrystalline equivalents. Efforts to investigate nanostructured materials and their derivatives are critical for developing innovative materials with exceptional qualities. It has been proven that by employing various manufacturing procedures, it is possible to generate new sophisticated nanomaterials with amazing properties for a diverse set of applications. These structural, electrical, and magnetic properties of the material are greatly affected by the content of nanomaterials, the process of fabrication, grain size, and grain boundary structures. A lot of research has been extensively reported on the impact of introducing nanomaterials into the polymeric matrix. The effect of nanomaterial selection, synthesis technique, grain size, and boundary structures on the mechanical characteristics of nanomaterials is presented in this chapter. Researchers and scientists have recently investigated the thermomechanical nature of nanomaterials based on these characteristics [1]. But the problem and issues related to the improvement of the thermomechanical properties of advanced robust nanocomposites have not been completely solved till now [2]. The most important thermomechanical parameters in nanocomposites include stiffness, glass transition, storage and loss modulus, coefficient of damping (tan), distortion heat, temperature, and coefficient of thermal expansion, among others [3]. To improve their function, the thermomechanical and mechanical properties must be thoroughly investigated. Herein, we have only focused on the thermomechanical properties of a robust composite. Also introduced is the current progress in research and application range of nanomaterials, which is remarkable for the development of thermomechanically robust composites [4]. To improve mechanical and thermophysical properties, nanoparticles are dispersed in a matrix material such as metals, ceramics, or polymers. Polymer nanocomposite materials have found use in critical domains such as the automobile and aerospace industries. A material's mechanical properties define how it behaves under a variety of circumstances and stresses. Mechanical characteristics such as brittleness, strength, plasticity, toughness, hardness, ductility, yield stress, rigidity, and elasticity are the ten standard components of conventional materials' mechanical properties in metals. Most inorganic and non-metallic materials are brittle and lack desirable mechanical qualities, including plasticity, toughness, elasticity, ductility, etc. In addition, unlike inorganic materials, organic ones can be pliable without exhibiting traits like brittleness or rigidity. Because of the size, shape, and quantum nature of nanoparticles, nanomaterials exhibit remarkable mechanical capabilities. When nanoparticles are incorporated into a polymeric material, the grain boundary is strengthened, and the material's mechanical characteristics are enhanced due to the formation of an intra- and intergranular structure [4–7]. For example, adding 3 wt/% nano-SiO_2 to concrete can improve its compressive strength, bending strength, and splitting tensile strength [8].

It is feasible, for example, to increase the compressive strength, bending strength, and splitting tensile strength of concrete by adding 3 wt/% nano-SiO_2 [9]. The tensile strength, elongation at break, and impact strength of kenaf epoxy composites are significantly enhanced by the addition of 3% nano-sized oil palm empty fruit string filler. Because of their outstanding mechanical properties and unique traits not seen in macroscopic materials, nanomaterials have a wide range of potential uses. To identify possible technical applications and industrial productions, we must first determine the mechanical properties of various nanomaterials and composite materials. In this book chapter, an overview of nanomaterials, synthesis methodologies, and the mechanical properties of nanomaterials and their composites is presented.

2 Overview of Nanostructured Materials

In recent years, researchers and industrialists have shown a lot of interest in the preparation and development of advanced nanostructured materials [10] with excellent performance. The high surface areas and enlarged chemical reactivity, combined with the improved mechanical strength of the nanostructured materials, have gained them worldwide attention. In general, nanomaterials are categorized as natural (obtained from nature and obey all the laws of nature), incidental (by-products obtained from industry like coal dust), and engineering nanomaterials (obtained from advanced synthesis techniques with complex shapes) [11]. In general, nanostructured materials are materials that look mostly like crystallites and have at least one nanoscale dimension in terms of grain size and thickness (layer) that is less than 100 nm. Based on the dimensions of the features, these nanomaterials can be categorized into four types: [12]:

(i) Zero-dimensional (0D) nanomaterials having nanoscale dimensions in all directions, e.g., nanospheres, nanoparticles, quantum dots, etc.
(ii) One-dimensional (1D) nanomaterials have comparatively large-scale dimensions in one direction than others, e.g., nanorods, nanotubes, nanowires, nanobelts, nanoribbons, nanostars, etc.
(iii) Two-dimensional (2D) nanomaterials having comparatively large-scale dimensions in any two directions than others, e.g., graphene nanosheets, nanoplates, nanodisks, etc. [13]

(iv) Three-dimensional (3D) nanomaterials have comparatively large-scale dimensions in three directions than others, e.g., nanotetrapods, nanoflowers, nanocombs, etc.

Nanostructured materials have become a fascinating domain in the diverse fields of biotechnology, bioengineering, the medical field, condensed matter physics, material chemistry, and ionics engineering, as well as the academic, industrial, and commercial sectors [14]. Nanostructured (NS) materials usually exhibit various excellent characteristics such as high strength and hardness, increased diffusivity, and useful sintering properties [15, 16]. On the basis of composition, nanomaterials may be classified into four different types [11].

(i) Carbon-based nanomaterials: Carbon nanotubes, graphene, porous carbon, etc., with high conductivity and stability play a crucial role in the practical applicability and advancement of multifunctional interdisciplinary areas.
(ii) Metal-based nanomaterials: These materials are made up of various metals such as gold (Au), silver (Ag), platinum (Pt), and copper (Cu) and have excellent physical, chemical, and catalytic properties. They can be applied for sensors, paints, cosmetics (sunscreen), and dental care. [17] Also, metal oxide nanomaterials such as zinc oxide (ZnO), tin oxide (SnO_2), and copper oxide (CuO) have a wide range of applications in the fields of electronics and photonics, optoelectronics, solar cells, energy, etc.
(iii) Polymer-based nanomaterials: These are composed of a matrix and a filler, such as polyaniline, polypyrrole, poly(dopamine), and others, and have a high sensitivity for direct application in sensors and bioengineering [18].
(iv) Composite nanomaterials: These are mixtures of simple nanoparticles or compounds such as nanoclays and nanoflowers. There are several nanostructured materials found in the form of composites [19–21], capsules, porous materials [22], and fibers on a nanometric scale.

The other types of nanostructured materials (ceramics, optical materials, polymers, and metal nanocoats) and various nanodevices related to sensing switches, etc., have been reported [23]. Various applications of nanostructured materials include a wide range in pharmaceutical, industrial chemistry, electronics, space applications, energy storage applications [24–26], materials and metallurgy, biological fields, and the food and medical industries [27].

Recently, nanostructured materials used in the field of nanomedicine may lead to an important contribution to the fields of drug delivery, nanomedicine, and medical imaging [28]. Siwick and his team [29] have developed a nanostructured material with a special emphasis on the structure of a photonic crystal for application in 3D optical data storage with high density. Vaqueiro et al. [30] have reported on thermoelectric materials for the better utility of earlier resources of energy like building power manufacturing systems, which extract valuable electrical power from the wasted heat. It has paved the way for improvements in thermoelectric performance achieved through nanostructured materials. Ozturk and his group have synthesized a carbonaceous material [sandwiched graphene-fullerene composites (SGFC)], which is formed via a covalent bond (junction) among layers of graphene and non-homogeneously distributed fullerene. The outcome of this study opened a new path for potential candidates for application in hydrogen storage applications (ultra-lightweight) due to their superior surface ratio and adaptable porous microstructure [31]. It has been reported that nanostructured materials have a great influence on tissue engineering, with distinctive performances demanding significant applicability in rigid and flexible tissue engineering [32]. The polymeric nanofibers from the domain of organic nanomaterials might be utilized as an aid in the cultivation of cells [33] and also have more opportunities for various inorganic nanomaterials [34–36]. Recently, polymeric nanostructured materials (PNMs) have played a considerable role in the diagnosis and treatment of diseases. These nanostructured materials have a broad range of applications in the food sector, such as nanofood, probiotics, nanocoating in edible form, and modern packaging [34]. Kumar and his colleagues discovered that silver epoxy nanocomposite [37] had the highest thermal conductivity, Young's modulus, and tensile strength values when compared to sole epoxy nanocomposite.

3 Nanomaterial Fabrication Techniques

The enhancement of thermomechanical properties such as thermal energy transport, melting point, thermoelectric activities, photo-absorbing property, reactivity, scattering, and optical activities in nanomaterials does not depend only on the nature of individual components but also on the various fabrication techniques, the morphology, and the nature of the interface. One of the major critical issues with nanomaterials is the loss of their original properties during fabrication, which limits their applications. Various fabrication techniques, including physical and chemical methods, use surfactants to prevent the agglomeration [38] of nanomaterials, which is crucial for developing the mechanical and thermomechanical properties. A lot of nanomaterials have been prepared over the last century by the old technique, which comprises grinding and mixing ingredient powders and then calcining them in a furnace at a high temperature. But chemical methods are more considerable because of the strong covalent bonds under different conditions [39]. Some of the most suitable chemical techniques for the fabrication of nanomaterials are chemical vapor deposition (CVD), molecular beam epitaxy (MBE), the sol–gel technique, hydrothermal synthesis, molecular self-assembly, lithography, etc., which are discussed in detail below.

(i) **Chemical Vapor Deposition (CVD)**

Chemical vapor deposition (CVD) is a very promising technique that is mostly used in the semiconductor industry for the synthesis of nanometric layers of inorganic materials on the surface of 3D substrates and for depositing thin films of various materials [38]. Chemical vapor condensation or chemical vapor synthesis occurs when solid films are deposited on surfaces. There are four successive steps involved in this process: (a) introduction of the volatile or vaporized precursors (which may be solid, liquid, or gas under ambient conditions) by carrier gas to the reactor chamber; (b) adsorption of the substrate to one or more volatiles at a high temperature, which favors homogeneous nucleation to form by-products; (c) breakdown of these products on a heated substrate, followed by heterogeneous nucleation and solid layer or grain development; and (d) the creation and extraction of volatile products under certain conditions (temperature, pressure, substrate, etc.) from the chamber by the carrier gas [39].

The quality of the by-products produced through CVD techniques is influenced by various factors, such as type and quality of precursors, desired volatility, thermal ability, temperature and pressure in the chamber, chemical properties of the substrate and gas carrier, and time and rate of deposition. Based on the type of chamber and precursors, the CVD techniques are categorized into various types, which are given in Fig. 1.

One of the most widely used precursors for the fabrication of nanoparticles in CVD techniques is silver nitrate ($AgNO_3$). In 2018, Piotr Piszczek synthesized silver nanoparticles using CVD techniques, which reduce the cytotoxicity of silver-based nanoparticles [40]. Wang and his colleagues recently used this technique to create pure, structurally uniform, single-crystalline semiconducting oxides free of defects and dislocations, such as ZnO, In_2O_3, Ga_2O_3, CdO, PbO_2, and SnO_2. Zhao discovered in 2019 that the CVD technique is the most advantageous synthesis technique for surface modification of nanomaterials [38]. The CVD process enables control over the structure, shape, and development of the robust nanocomposite that is formed. However, the CVD method has some disadvantages, such as long reaction times (1 min to hours) and low-temperature processes (in the range of 700–1473 K) [41], which can be overcome by using modern technology.

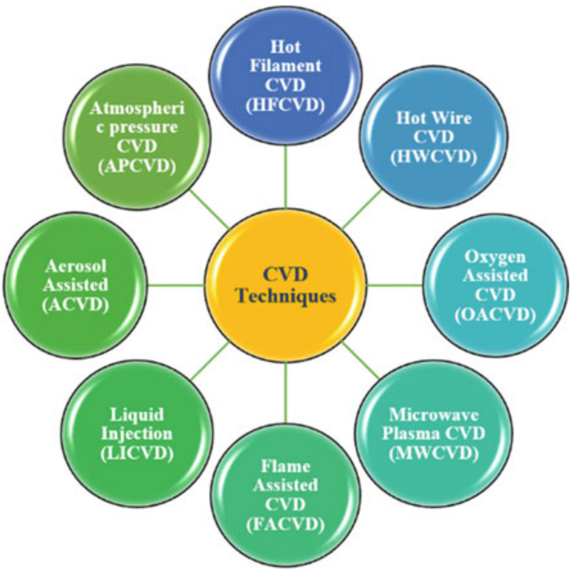


Fig. 1 Different types of chemical vapor deposition techniques

(ii) **Molecular Beam Epitaxy**

One of the most time-consuming, technically demanding, and challenging physical evaporation experimental techniques is molecular beam epitaxy (MBE) [42], which allows for the layer-by-layer expansion of thin films of various novel nanomaterials without the innovation of any chemical reactions. It can also be used to deposit a wide range of materials, including metals, semiconductors, magnetic materials, oxides, organic molecules, chalcogenide layers, etc. For the development of chemical sensors, the nanomaterials should be synthesized using a novel technique that can control the structure, composition, and morphology of the surface. Molecular beam epitaxy (MBE) is the most favorable process for the preparation of nanomaterials.

This method works on the principle of vacuum evaporation, where thermal molecular and atomic beams directly impinge on a heated substrate under ultra-high vacuum (UHV) conditions [43]. The UHV condition helps with minimal impurities and surface modification to extract high-purity nanomaterials. MBE, as a low-temperature process, reduces autodoping, allows for precise control of the doping process, and keeps the growth rate between 0.01 and 0.3 m per minute. A typical MBE experimental setup consists of two or more Knudsen effusion cells (K-Cells) containing pure solid elements like selenium, silicon, bismuth, gelinium, etc., a UHV chamber (where the growth of materials takes place), and a sample holder with a substrate. The first step in the MBE growth process is to heat the K-cells to the appropriate temperatures until the elements in each cell sublimate. The shutters are then opened, allowing physical vapor from each K-cell to permeate into the chamber until it reaches the substrate, where it is deposited, and the thin film gets formed. The final composition and stoichiometry of the film will be determined by the temperature and surface atomic structure of the substrate, as well as the flux ratios of individual components reaching the substrate. The substrate can be continually turned at modest rotation speeds (1–2 revolutions per minute) using a stepper motor coupled to the magnetic manipulator for more uniform development. In 2013, Lorenzo Morresi concluded that the evaporation and growth of materials can be influenced by temperature controllers, shutters, beam flux monitors, mass analyzers, and reflection high-energy electron diffraction (RHEED) systems [43]. Ishikawa reported that the MBE technique is a novel process for the preparation of robust composites [44]. Asghar and his team successfully prepared zinc oxide (ZnO) nanoparticles by using this technique [45]. Growth of porous nanostructures in GaN with low dimension can be obtained by synthesizing the nanomaterials using molecular beam epitaxy (MBE) techniques [46]. Later, E. Fadaly and his team synthesized InAs nanowires on silicon (Si) by using this technique and observed catalyst-free growth of the nanowires [47].

(iii) **Sol–gel Synthesis**

Although the sol–gel process is one of the outdated chemical synthesis techniques that was developed in 1940 [47], the importance of this process in material fabrication has been growing rapidly. Sol–gel processes have a remarkable advantage for preparing superfine nanopowders of metal oxides (MO) as well as non-oxide materials. The mechanical and chemical stability of the materials can be improved by fabricating with this technique, which is very useful for the development of the sensor. Inorganic and organic/inorganic hybrid material creation and processing are both generically referred to as "sol–gel" in the literature. Sol–gel processing generally involves the creation of colloidal suspensions (referred to as "sol"), which are then transformed into gels and finally into solid material. The formation of a sol, a colloidal suspension, is the first step in the sol–gel process. Colloid precursors feature a metal atom surrounded by ligands, which can be either inorganic anions or organic alkoxides. Sol denotes dispersed solid colloidal particles in a solution solvent, whereas gel denotes a 3D porous, interconnected network structure in the liquid phase [48]. In this process, sol is transformed into a gel by following several steps. Dispersed solid nanoparticles (sols with a diameter of 1–100 nm) are mixed in a homogeneous liquid medium and agglomerated to form a continuous three-dimensional network (gel) with pore diameters in the sub-micrometer domain in the liquid phase (Fig. 2).

The properties of sol-gels depend on important parameters such as pH, type of solvent, temperature, time, catalysts, and agitation mechanisms [38, 41]. Rahman used the sol–gel technique to create silica nanoparticles with improved mechanical, thermal, physical, and chemical properties [49]. In a recent study [29], a sol–gel processing technology was developed to generate a wide range of ceramic materials, including Al2O3, Fe2O3, SiO2, TiO2, and others. In 2021, Kumar and his team prepared TiO2 nanoparticles using this technique and observed excellent interfacial bonds of the nanoparticles with epoxy materials and glass fibers [50].

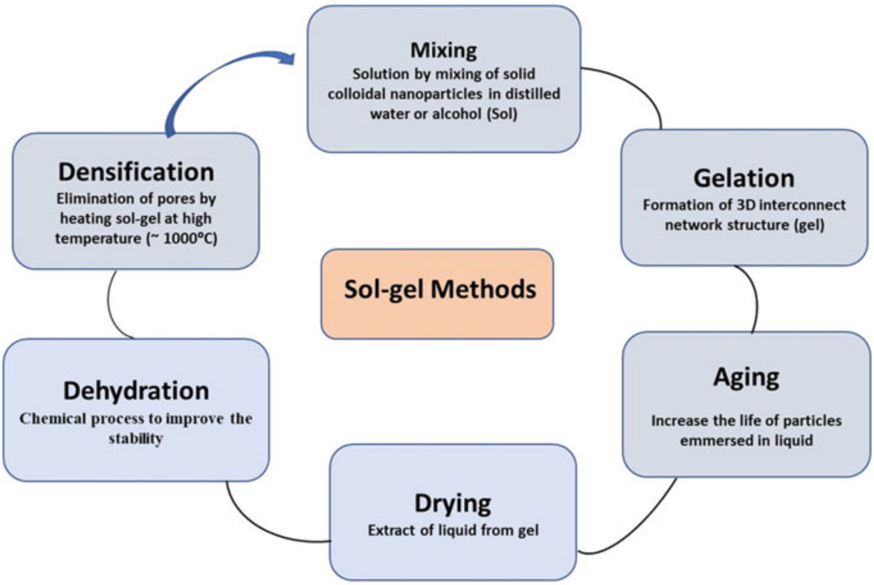


Fig. 2 Flow diagram for the different steps of the sol–gel technique

(iv) **Hydrothermal Synthesis**

Hydrothermal synthesis (also known as solvothermal synthesis) is a single-step process to prepare the ultrafine nanomaterials in a hydrothermal environment (i.e., neither the solution is non-aqueous nor aqueous) at a low temperature in the range of 100–3740 °C without the use of a calcination process. The basic principle of the technique is a reaction in an aqueous solution or suspension of the precursors at high temperature and pressure [51, 52]. Recently, the hydrothermal process has gained much more attention for the synthesis of nanomaterials as grain size, shape, crystalline state, and surface morphology of materials can be changed by controlling various factors such as the property of the solvent, concentration of reactants, temperature, aging, pH time, and additives in this technique [36]. Under fixed pressure and temperature, the hydrothermal technique is carried out in specific equipment known as an autoclave. The autoclave is loaded with reagents and then placed in the oven for some time, allowing the reaction to take place without direct supervision. This procedure is performed at high temperatures. This process produces chemically synthesized nanostructured powders with excellent consistency and particle uniformity and an appropriate particle size that has higher mechanical or electrical properties. The nanomaterials that are synthesized by using this process have worldwide applications in the fields of solar cells, batteries, MLCCs, etc. [18]. Benega and his colleagues reported in 2021 that carbon-based nanocomposites prepared by hydrothermal synthesis had superior physiochemical properties than others [53]. Kigozi observed that the metal oxide-based nanocomposite that is prepared using this technique can be used in energy storage applications with enhanced stability [54].

(v) **Molecular self-assembly**

One of the most successful chemical synthesis routes for designing complex nanostructures in the range of 1–100 nm is molecular self-assembly (MSA), in which atoms or molecules assemble in equilibrium conditions to form a stable and well-defined nanophase via non-covalent bonds [55]. It is the most attractive bottom-up process because it is technologically feasible and cost-effective and provides well-defined and functional geometries with structural freedom under specific, controllable thermodynamic conditions. All natural organic and inorganic nanomaterials that are prepared using this technique are thermodynamically stable, relatively defect-free, and self-healing [56]. But the important challenge of the MSA process is the lack of knowledge on the development of molecular shape, the nature of non-covalent forces, the interplay between enthalpy and entropy, etc. Besides these, the most promising avenues for self-assembly are presently based on organic compounds, and organic compounds, as a group (although with exceptions), are electrical insulators. As a result, the methods used in the self-assembled system must be redesigned or developed to produce advanced types of organic molecules with appropriate properties for information processing and electrical or mechanical transduction. Ozin reported that the molecular self-assembly process is scientifically popular for the fabrication of nanocomposite by providing enhanced properties such as electrical, magnetic, and optical, which can develop the future of nanotechnologies as well as the daily lives of human beings and our surrounding environment [56]. Recently, Arul and his team prepared different types of nanostructures successfully to provide structural freedom for application in intracellular drug delivery [57].

(vi) **Lithography**

Lithography is the process where a substrate (like glass, silicon, gallium arsenide, etc.) coated with a photosensitive or radiation-sensitive polymer called resist is illuminated. When this resist is radiated, its physical properties change to form structures [58]. The size of formed structures is affected by the choice and thickness of the resist. Lithography is used for prototyping in electronics, microfluidics, optics, lab-on-a-chip, etc. The performance of a lithography can be determined from three parameters: (i) resolution (the minimum feature dimension that can be transferred with high fidelity to a resist film on a semiconductor wafer), (ii) registration (a measure of how accurately patterns on successive masks can be aligned or overlaid with respect to previously defined patterns on the same wafer), and (iii) throughput (the number of wafers that can be exposed per hour for a given mask level and is thus a measure of the efficiency of the lithographic process) [53]. We can produce nano and microstructures with different resolutions by using different lithography techniques, which are given below [59] (Fig. 3).

4 Robust Composite Fabrication Techniques

Robust composites can provide a variety of benefits, making them desirable in many high-performance applications. As a result, composites are increasingly being used

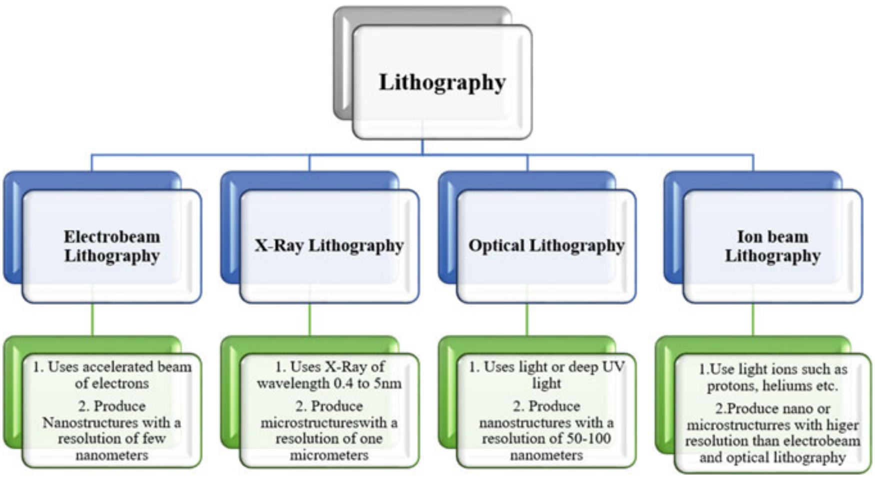


Fig. 3 Different types of lithography and their applications

not only in high-performance applications like racing cars, airplane components, and sporting goods, but also in lower-cost, higher-volume industries like automotive. With increased use comes an increased demand on manufacturing processes to maintain high quality while combining higher volumes and lower costs. Robust composite materials have many desirable properties that make them suitable for various applications [60]. To fabricate the robust composite, the researchers should handle the material in a safe and healthy environment by using protective gear and following policies. There are various fabrication techniques to shape resins and reinforcements, which are classified into two categories: (i) open molding and (ii) closed molding techniques (Fig. 4).

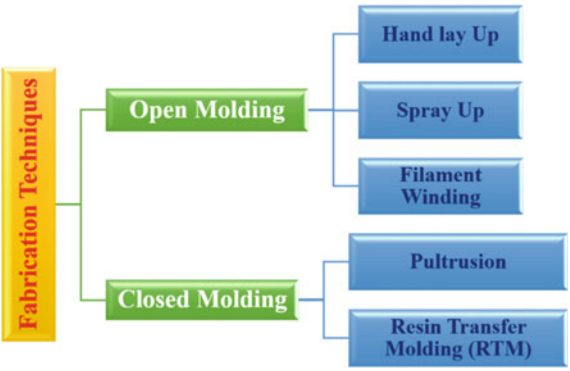
(i) **Open Molding technique**

Contact molding, or "open molding," is a low-cost process used for the production of large, robust composites where the raw materials are exposed to air before the fabrication. First, a one-sided mold is applied with a release agent and gel coat. Then, the molding materials or reinforcements are placed on top of the mold using either the spray-up process or the hand layup process. Additional layers of laminate are added to build thickness and strength as desired. The air is then rolled out of the laminate by hand, and the part is left to cure. In addition to reinforcements, low-density core materials such as balsa wood, foam, or honeycomb can be added to stiffen the laminate without adding significant weight. Open molding utilizes different processes where hand layup, spray-up, and filament winding techniques are mostly used, which are discussed below in detail.

(a) **Hand layup**

Hand layup is the most basic, simplest, and oldest technique of robust composite fabrication. The process involves laying the molding materials or reinforcements on top of the mold by hand and then acquiring the desired thickness of the laminated materials by stacking them up layer by layer. If the resin is applied to the layer of laminated material by using a brush or roller, then the process is known as wet layup, which is a different version of hand layup. A resin having high molecular weight and

Fig. 4 Various fabrication techniques for robust composite



low viscosity can be used in this process to enhance its thermal and mechanical properties. Also, these properties are greatly influenced by factors such as resin mixing and the quality and content of the laminate resin. The hand layup fabrication process is mainly used in marine and aerospace structures. Although this method is successful for fabricating the robust composite, it has various disadvantages. It requires a large amount of time and a lot of skilled employees. Recently, Abas et al. have demonstrated the effect of silicon carbide (SiC) concentration in polyester nanocomposite on the thermomechanical properties like hardness, distortion of bending, thermal conductivity, coefficient of thermal expansion, etc., that are prepared by using the hand layup technique [61].

(b) **Spray Layup**

Spray-up, also known as "chopping," is another open-mold automated technique that is faster to produce chopped laminate using multiple molds. This process depends more on the operator than the hand layup process to control the thickness and consistency of the process. Although the production volume per mold is low, it is feasible to produce substantial production quantities using multiple molds. This process uses simple, low-cost tooling, and simple processing. Portable equipment permits on-site fabrication with virtually no part-size limitations. The process involves three important stages such as (i) application of gel coat to the double-sided mold; (ii) deposition of resin on the mold through a chopper gun; (iii) addition of chopped laminate layers to acquire the desired thickness. Roll stock reinforcements, such as woven roving or knitted fabrics, can be used in conjunction with chopped laminates. The same core materials and molds as in hand layup techniques are used in this process.

(c) **Filament winding**

Another open molding technique is filament winding, which is a continuous, low-cost, highly automated, and computer-controlled fabrication method. This technique is controlled by a computer, which reduces the number of employees. Filament winding uses a rotating mandrel (made up of steel or aluminum) as the mold, which helps in the production of a laminate surface with a high strength-to-weight ratio on the outside of the product. The uniformity of by-products and fiber orientation is highly controlled by this technique. The process of filament winding follows three steps to produce highly engineered structures with maximum tolerances.—(i) provide strand roving in a resin bath and keep it on a rotating mandrel; (ii) add filament on the mandrel to achieve the desired strength; and (iii) cure the laminate on the mandrel after the addition of appropriate layers. If the chopping or spray-up process is involved in filament winding, then that process is called the "hoop chop process."

(ii) **Closed Molding Technique**

According to Composites World, closed molding is also the low-cost process used for faster and more consistent production of large, robust composites where the raw materials are exposed to air before the fabrication. But a two-sided mold is applied with a release agent and gel coat. This technique has various advantages, such as

(i) less waste production, (ii) better surface cosmetics, and (iii) suppressing post-work. Besides these, it meets the needs of local and state manufacturers by emitting less radiation. These processes are automated, reducing the number of dependent workers. This technique utilizes different processes such as vacuum bag molding, vacuum infusion process, and compression molding, where resin transfer molding (RTM) and pultrusion techniques are mostly used, which are discussed below in detail.

(a) **Resin Transfer Molding (RTM)**

One of the widely used intermediate-volume closed molding processes is resin transfer molding (RTM) for the fabrication of nanocomposite materials. This process is significantly more reliable because it provides a faster rate of production, high consistency even at room temperature, and is also cheaper than the open molding processes. The steps involved in these techniques are (i) injection of resin inside a mold that is coated with a gel under low pressure, (ii) laying up the raw materials and orientation (like 3D reinforcements) inside the mold cavity, and (iii) control of thickness and temperature by different tooling. Vacuum assist can be used to increase the flow of resin inside the mold cavity. RTM can utilize either hard (such as aluminum, electroformed nickel shells, or machined steel molds) or soft tooling (such as polyester or epoxy molds) depending upon the expected duration of the run. Tooling can range from very low-cost to high-cost, life-long molds.

(b) **Pultrusion**

The pultrusion method is a smooth, continuous, cheap, and automated technique without any post-processing methods for the fabrication of nanocomposites with both simple and complex shapes having high structural, mechanical, and thermal properties. The portmanteau term “pultrusion” is the combination of “pull” and “extrusion,” which means pulling of the material. A die pulls inserted fiber reinforcement in a hot bath of resin with specific shapes in this process. Then, that die (which may be hot oil or electric) is continuously heated to cure the resin and control the ratio of resin. The resin is inserted directly inside the die in the most recent technology, eliminating the need for an external resin bath.

5 Different Factors Influencing Mechanical Performance of Nanomaterials

The mechanical, thermal, as well as structural properties of nanomaterials are greatly affected by different factors such as their size, the quality of their raw materials, different fabrication techniques, and temperature. Nanomaterials exhibit various mechanical properties, including brittleness, strength, plasticity, hardness, toughness, fatigue strength, elasticity, ductility, rigidity, yield stress, etc.

(i) **Selection of Nanoparticle**

Different nanoparticles exhibit excellent mechanical properties. Thus, for the enhancement of the mechanical properties of nanomaterials, the selection of nanoparticles plays a vital role. Xu investigated whether the mechanical properties of robust composites improved first and then decreased as the amount of titanium diboride increased. Further, he increases the mechanical properties by adding aluminum trioxide (Al_2O_3) [62]. Thus, the addition of a large number of nanoparticles reduces the mechanical nature of nanomaterials. So, for the modification of nanomaterials with improved mechanical properties, we should focus on the amount, ratio, nanoparticle size, etc.

(ii) **Production process**

Besides the selection of nanoparticles, the production process also influences the mechanical nature of nanomaterials. Processing parameters such as sintering and calcination temperatures, synthesis techniques, processing time, choice, and concentration of nanoparticles can control the mechanical properties like hardness, rigidity, elasticity, ductility, etc., of nanomaterials. Karimzadehet al. reported in 2014 that the value of Young's modulus and hardness initially increases with increasing sintering temperature and then decreases after 1200 °C [63]. Different sintering temperatures have different influences on the mechanical properties of materials.

(iii) **Grain size**

Because nanomaterials are made up of grains and grain boundaries, we should concentrate on the various shapes and sizes of grain sizes in order to improve the mechanical properties of nanomaterials. Recently, a large number of scientists and researchers [64] investigated the effect of grain size on the mechanical properties of nanomaterials and concluded that grain size enhances the mechanical strength [65] and toughness [66] and also influences the fracture resistance [67] of nanomaterials.

(iv) **Grain boundary structure**

In robust composites, besides grain size, the structure of the grain boundary is a vital factor for the enhancement of mechanical properties. However, the density, chemical bond, and structure of the grain boundary influence the mechanical properties of nanomaterials. It has been discovered that the parameters influencing the structure of grain boundaries can have an effect on the mechanical properties of robust composites [68].

6 Effect of Thermomechanical Performance Nanomaterial-Based Robust Composites

The robust composite is a combination of matrix and nanomaterials with an improved thermomechanical nature. A large number of articles about the thermomechanical properties of nanocomposites containing nanoplatelets, nanospheres, and nanocylinders are available in the literature [69]. Surface modification of nanoparticles and adjusting the properties of the interfacial polymer layer by using proper chemistry and physics are crucial issues to enhance the thermomechanical properties of nanocomposites [70]. Recently, scientists and researchers have mainly focused on the thermomechanical factors such as coefficient of damping, modulus loss, storage, and coefficient of thermal expansion to enhance these properties by modifying the surface morphology of nanoparticles [71]. There has been a lot of research on 3D hybrid nanostructures with the goal of incorporating their exceptional qualities into polymeric matrices to create high-performance nanocomposites. It has been reported that the material's mechanical characteristics, including hardness, tensile, and flexural strength, have improved [72–75]. Usually, thermomechanical properties can be enhanced if the nanoclay is intercalated or exfoliated. In 2016, Yasmin et al. observed that the intercalation of nanoclay in epoxy composites enhanced the elastic and storage modulus and also reduced the coefficient of thermal expansion [76]. Rafieian et al. observed that the addition of cellulose nanofibrils (CNF) in the robust composite can greatly affect the mechanical properties rather than the thermal properties [77]. The addition of a carbon tube in reinforced nanocomposite can influence and obtain the values of thermal conductivity and other thermomechanical property parameters as needed [78]. Similarly, Araby et al. [79] have demonstrated the construction of conductive three-dimensional networks. They suggest that 1D nanostructures act as nanowires that transmit electrons and stress to 2D nanostructures (graphene nanoplatelets, GNPT). Therefore, 1D–2D interconnected nanostructures function as conductive channels. In addition, the hybrid reinforcement dispersion in the elastomeric matrix has also improved.

7 Mechanical Properties of Nanomaterial-Based Robust Composites

Different nanomaterials exhibit excellent mechanical properties such as elasticity, plasticity, tensile strength, stress, strain, Young's modulus, rigidity, hardness, and toughness under different external forces and environments due to the volume, surface, and quantum effects of nanoparticles [80]. Hence, by the addition of nanomaterials such as SiO2 and nanooil, the grain boundary as well as the mechanical properties of the robust composite can be improved [81]. Ajeesh et al. investigated in 2016 that the content of carbon nanofiber helps to increase the storage modulus as well as thermal conductivity in polyetherketone [82], which can be applied for high-temperature applications. Zhang et al. have demonstrated that the value of thermal conductivities increases with the addition of silica to epoxy nanocomposite, but the value of shear and elastic modulus reduces, which helps in the improvement of the thermomechanical nature of nanocomposite [83]. Due to the unique mechanical properties of nanomaterials, they will have a wide range of applications in future. With progress in further research on nanomaterials, future applications in the fields of engineering, industry, and medicine can be possible. Methods for modifying the surface of graphene using both covalent and non-covalent functionalization were reported by Kulkarni and his co-workers [84]. They explored how the electrical, mechanical, and thermal properties of graphene-epoxy composites change depending on manufacturing techniques, filler dispersion, and filler surface modification. In their analysis of graphene, carbon nanotubes (CNTs), and hybrid graphene-CNT-reinforced epoxy composites, Singh et al. [85] have fabricated epoxy-based composites with mechanical, thermal, electrical, and flame-retardant properties that were examined along with their sensitivity to the filler type and functioning. These composites are used in the application of airplane bodies, electromagnetic shielding, corrosion-resistant coatings, etc. Szeluga et al. [86] investigated the influence of graphene fillers on the mechanical, thermal, electrical, and flame-retardant properties of epoxy composites. Epoxy composite qualities were summarized in relation to filler size, exfoliation level, and functioning. Epoxy composites enhanced with graphene were examined by Atif et al. [87]. The mechanical, thermal, and electrical properties of the resulting epoxy composites were linked to the filler size, morphology, and level of functionalization. In order to enhance the damping qualities, Jin and his co-workers [84] have fabricated an IPN based on epoxy resin and polyurethane pre-polymers. However, this material has a lower tensile modulus and strength than pure epoxy. Epoxy matrix toughening is also demonstrated. By providing a wide surface area, nanoparticles facilitate the establishment of primary valence bonds at the filler/resin contact and efficient stress transfer across the interface [84].

8 Conclusions

Nanostructured materials are widely investigated for their utmost potential as the material of electrodes, especially owing to their thermomechanical performance in the domain of energy storage applications in recent times. In this chapter, an overview of nanostructured materials with their various fabrication techniques and thermomechanical properties is discussed in detail for a better understanding and future perspective. Also, this chapter focuses on important factors such as the selection of nanomaterials, processing parameters, grain size, and grain boundary structure that influence the thermomechanical behavior of nanomaterials. A robust composite having advanced thermal and mechanical properties can be obtained by using advanced fabrication techniques such as CVD, molecular beam epitaxy (MBE), the sol–gel technique, hydrothermal synthesis, molecular self-assembly, and lithography. The various open and closed molding processes are also described minutely for understanding the structural stability of robust composites for intended future applications. It has been proven that by employing various manufacturing procedures, it is possible to generate new sophisticated nanomaterials with amazing properties for a diverse set of applications. These structural, electrical, and magnetic properties of the material are greatly affected by the content of nanomaterials, the process of fabrication, grain size, and grain boundary structures. The thermomechanical properties of nanomaterials endow them with broad application prospects and huge potential value in future. But the problem and issues related to the improvement of the thermomechanical properties of advanced robust nanocomposites have not yet been completely solved. The most important thermomechanical parameters in nanocomposites include stiffness, glass transition, storage, and loss modulus, coefficient of damping (tan), distortion heat, temperature, and coefficient of thermal expansion, among others. A lot of research has been extensively reported on the impact of introducing nanomaterials into the polymeric matrix. The effect of nanomaterial selection, synthesis technique, grain size, and boundary structures on the mechanical characteristics of nanomaterials is presented in this chapter. This chapter provides an overview of nanostructured materials along with composite preparation processes and discusses the effect that these approaches have on the thermomechanical performance of nanomaterial-based robust composites. Hybrid polymeric composites have undergone significant development and utilization for energy applications in recent times. However, future applications in the fields of engineering, industry, and medicine can be made possible by progressing further research on the molding technique of nanomaterials. As a result, scientists and researchers are investigating the molding and fabrication technique, as well as strengthening the process of an advanced robust nanocomposite to meet the critical needs in a future application.

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References

1. Nikzad M, Masood SH, Sbarski I (2011) Mater Des 32:3448
2. Wang F, Zhou S, Yang M, Chen Z, Ran S (2018) Polymers 10:401
3. Huang X, Zhi C (2016) Springer 10:978
4. Wu Q, Miao WS, Gao HJ, Hui D (2020) Nanotechnol Rev 9:259–273
5. Zou B, Huang CZ, Wang J, Liu BQ (2006) Trans Tech Publications Ltd 315:154
6. Wang XH, Xu CH, Yi MD, Zhang HF (2011) Adv Mater Res 154:1319
7. Wang JL, Meng LJ (2014) Appl Mech Mater 535:785
8. Ghabban A, Zubaidi A B, Jafar M, Fakhri Z (2018) IOP ConfSer: Mater Sci Eng 454:012016
9. Saba N, Paridah MT, Abdan K, Ibrahim NA (2016) Constr Build Mater 123:15
10. Bavykin DV, Friedrich JM, Walsh FC (2006) Adv Mater 18:2807
11. Abdel Karim R, Reda Y, Abdel-Fattah A (2020) J Electrochem Soc 167:037554
12. Maglia F, Tredici IG, Anselmi-Tamburini U (2013) J Eur Ceram Soc 33:1045

13. Bag A, Lee NE (2019) J Mater Chem C 7:13367
14. Kanatzidis MG, Poeppelmeier KR, Bobev S, Guloy AM, Hwu SJ, Lachgar A, Seshadri R (2008) Prog Solid State Ch 36:133
15. Pal K, Asthana N, Aljabali AA, Bhardwaj SK, Kralj S, Penkova A, Gomes de Souza F (2021) Crit Rev Solid State Mater Sci 17
16. Bhoi NK, Singh H, Pratap S (2020) J Compos Mater 54:813
17. Iqbal M, Usanase G, Oulmi K, Aberkane F, Bendaikha T, Fessi H, Elaissari A (2016) Mater Res Bul 79:97
18. Sahay R, Reddy VJ, Ramakrishna S (2014) Int J Mech Eng 9:13
19. Patra R, Mohanty D, Nayak PK (2022) Polym Sci Ser B 7
20. Sahu AK, Satpathy SK, Rout SK (2020) Trans Electr Electron Mater 21:217
21. Mallick P, Satpathy SK, Behera B (2022) Braz J Phys 52:187
22. Wei Q, Fu Y, Zhang G, Yang D, Meng G, Sun S (2019) Nano Energy 55:234–259
23. Jeevanandam J, Barhoum A, Chan YS, Dufresne A, Danquah MK (2018) Beilstein J Nanotechnol 9:1050
24. Mallick P, Satpathy SK, Behera B (2022) Bull Mater Sci 45:198
25. Satpathy SK, Sen S, Behera B (2017) J Mater Sci Mater Electron 28:9102
26. Mallick P, Patra R, Mohanty D, Satpathy SK (2022) Sadhana 47:134
27. Nasiri N, Clarke C (2019) Biosensors 9:43
28. Mudedla SK, Singam EA, Vijay Sundar J, Pedersen MN, Murugan NA, Kongsted J, Subramanian V (2015) J PhysChem C 119:653
29. Siwick BJ, Kalinina O, Kumacheva E, Miller RD, Noolandi J (2001) J Appl Phys 90:5328
30. Vaqueiro P, Powell AV (2010) J Mater Chem 20:9577
31. Ozturk Z, Baykasoglu C, Kirca M (2016) Int J Hydrog Energy 41:6403
32. Pryjmakova J, Kaimlova M, Hubacek T, Svorcik V, Siegel J (2020) Int J MolSci 21:2521
33. Jean-Gilles R, Soscia D, Sequeira S, Melfi M, Gadre A, Castracane J, Larse M (2010) J Nanotechnol Eng Med 1
34. Sharma S, Jaiswal S, Duffy B, Jaiswal AK (2019) Bioeng 6:26
35. Mohanty NK, Pradhan RN, Satpathy SK (2014) J Mater Sci Mater Electron 25:117
36. Mohanty D, Satpathy SK, Behera B, Mohapatra RK (2020) Mater Today Proc 33:5226
37. Siva Kumar M, Kumar S, Gouda K, Bhowmik S (2021) Polym Polym Compos 29:1551
38. Ganachari SV, Banapurmath NR, Salimath B, Yaradoddi JS, Shettar AS, Hunashyal AM, Hiremath GB (2017) Handbook of ecomaterials, p 83
39. Zhao X, Wei C, Gai Z, Yu S, Ren X (2020) Chem Pap 74:767
40. Piszczek P, Radtke A (2018) Noble Precious Metals 187
41. Manawi YM, Samara A, Al-Ansari T, Atieh MA (2018) Mater 11:822
42. Henini M (Ed.) (2012) Elsevier, Newnes
43. Morresi L (2013) Bussum: Bentham Science Publishers, p 81
44. Ishikawa Y, Shibata N, Fukatsu S (1996) Appl Phys Lett 68:2249
45. Asghar M, Mahmood K, Raja MY, Hasan MA (2013) Adv Mater Res 622:919
46. Soopy AKK, Li Z, Tang T, Sun J, Xu B, Zhao C, Najar A (2021) Nanomater 11:126
47. Fadaly E(2015) Master's thesis, Molecular beam epitaxy of catalyst-free InAs nanowires on Si
48. Rao BG, Mukherjee D, Reddy BM (2017) Nanostructures for novel therapy. Elsevier
49. Sumida K, Liang K, Reboul J, Ibarra IA, Furukawa S, Falcaro P (2017) Chem Mater 29:2626
50. Ab Rahman Ismail, Padavettan Vejayakumaran (2012) J Nanomater 2012
51. Tan WK, Muto H, Kawamura G, Lockman Z, Matsuda A (2021) Nanomater 11:181
52. Holliday S, Stanishevsky A (2004) Surf Coat Technol 188:741
53. Özbay N, Şahin RY (2017) AIP Conf Proc 1809:020040
54. Benega MAG, Silva WM, Schnitzler MC, Andrade RJE, Ribeiro H (2021) Polym Test 98:107180
55. Kigozi M, Ezealigo BN, Onwualu AP, Dzade NY (2021) Chemically Deposited nanocrystalline metal oxide thin films. Springer, Cham
56. Ozin GA, Hou K, Lotsch BV, Cademartiri L, Puzzo DP, Scotognella F, Ghadimi A, Thomson J (2009) Mater Today 12:12

57. Arul A, Rana P, Das K, Pan I, Mandal D, Stewart A, Maity B, Ghosh S, Das P (2021) Nanoscale Adv 3:6176
58. Lombardo D, Calandra P, Pasqua L, Magazù S (2020) Mater 13:1048
59. Kajbafvala A, Bahmanpour H, Maneshian MH, Li M (2013)J Nanomater
60. Venugopal G, Kim SJ (2013)Advances in micro/nano electromechanical systems and fabrication technologies. IntechOpen
61. De Teresa JM (2020) Nanofabrication: nanolithography techniques and their applications. IOP Publishing
62. Li J, Zhang C, Liang R, Wang B (2008) Int J Prod Res 46:2087
63. Abas FO, Abass RU (2018) MATEC Web of Conf 225:01021
64. Xu C, Yi M, Zhang J, Fang B, Wei G (2012) Ceramic materials-progress in modern ceramics, IntechOpen
65. Karimzadeh A, Ayatollahi MR, Bushroa AR, Herliansyah MK (2014) Ceram Int 40:9159
66. Acchar W, Cairo CAA, Chiberio P (2019) Compos Struct 225:111109
67. Trombini V, Tonello KPS, Santos T, Bressiani JC, Bressiani AHDA (2012) Mater Sci Forum 727:597
68. Wang D, Zhao J, Zhou Y, Chen X, Li A, Gong Z (2013) Comput Mater Sci 77:236
69. Zhou T, Huang C (2015) Comput Mater Sci 104:177
70. Khorshidi B, Biswas I, Ghosh T, Thundat T, Sadrzadeh M (2018) Sci Rep 8:10
71. Zeng H, Wu J, Pei H, Zhang Y, Ye Y, Liao Y, Xie X (2021) Chem Eng J 405:126865
72. Subhani T, Latif M, Ahmad I, Rakha SA, Ali N, Khurram AA (2015) Mater Des 87:436
73. Chang HP, Liu HC, Tan CS (2015) Polymer 75:125
74. Li W, Dichiara A, Bai J (2013) Compos Sci Technol 74:221
75. Zhang S, Yin S, Rong C, Huo P, Jiang Z, Wang G (2013) Eur Polym J 49:3125
76. Yasmin A, Luo JJ, Abot JL, Daniel IM (2006) Compos Sci Technol 66:2415
77. Rafieian F, Shahedi M, Keramat J, Simonsen J (2014) J Food Sci 79:N100
78. Dittrich B, Wartig KA, Mülhaupt R, Schartel B (2014) Polymers 6:2875
79. Araby S, Saber N, Ma X, Kawashima N, Kang H, Shen H, Ma J (2015) Mater Des 65:690
80. Güler Ö, Bağcı N (2020) J Mater Res Technol 9:6808
81. Ajeesh G, Bhowmik S, Sivakumar V, Varshney L, Kumar V, Abraham M (2017) J Compos Mater 51:1057–1072
82. Zhang X, Wen H, Wu Y (2017) Polymers 9:430
83. Kulkarni HB, Tambe P, M Joshi G (2018) Compos Interfaces 25:381
84. Singh NP, Gupta VK, Singh AP (2019) Polymer 180:121724
85. Szeluga U, Pusz S, Kumanek B, Olszowska K, Kobyliukh A, Trzebicka B (2021) Crit Rev Solid State Mater Sci 46:152
86. Atif R, Shyha I, Inam F (2016) Polymers 8:281
87. Jin H, Zhang Y, Wang C, Sun Y, Yuan Z, Pan Y, Cheng R (2014) J Therm Anal Calorim 117:773