

Introduction to Multifunctional Epoxy Composites



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Abstract This chapter delves into the importance of understanding epoxy resins and the task of preparing epoxy nanocomposites. The most recent up-to-date multifunctional epoxy nanocomposites with electrically conductive, magnetic, thermally conductive, shape-memory, self-healing, and flame-retardant features are reviewed. Epoxy nanocomposites are used in aeronautic, automotive, anti-corrosive coatings, high voltage, and structural applications. The information offered will aid understanding and promote the use of epoxy resins and encourage the development of new applications.

Keywords Self-healing · Shape memory · Magnetic · Thermal and Electrical Conductivities · Flame Retardancy

In lightweight and high-strength applications, it is clear that a predominant tendency has led to a growth in the substitution of conventional materials with polymer composites during the previous couple of decades. Its excellent strength-to-weight ratio, toughness, and thermal stability account for this. Filler qualities, filler shape, filler-matrix interactions, matrix properties, filler orientation in the matrix, and the volume fraction of the filler are all directly related to composite performance. The thermoplastic, thermoset, or rubber matrix component of composites can be used because of their versatility and exceptional performance; thermosetting polymers are commonly employed in engineering goods. Since its introduction in the late 1940s, epoxy resin has been widely used in a variety of industrial and commercial applications. Its improved stiffness, low shrinkage, high corrosion and chemical resistance, outstanding adhesive capabilities, creditable thermomechanical properties, creditable dielectric strength, and other characteristics brand it ideal for engineering uses. Epoxy, dissimilar to polyester resins, is able to maintain mechanical and physical qualities while being exposed to strong solvents. Epoxy resin can also be used to connect practically any material, including glass, wood, stone, ceramics, plastics, and metals.

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1 Introduction

Due to its desirable mechanical properties, solvent resistance, thermal stability, and creditable thermal insulation [1–3], epoxy is the most widely used thermosetting plastic with extensive manufacturing applications, including adhesives [4–7], electronic gadgets [8], laminates [9], encapsulations [10, 11], coatings [12–14], aquatic systems [5–17], and aerospace components [18–21]. Liquid epoxy resins, a family of highly reactive prepolymers with low molecular weight oligomers that include oxirane structures as an epoxy activity, can include aromatic, aliphatic, and/or heterocyclic backbone architectures [22]. Epoxy resins have a variety of physical properties due to their varied backbone architectures. A short-chain aliphatic epoxy resin, for example, possesses a low viscosity, whereas an aromatic epoxy resin has excellent thermal properties, such as a high glass transition temperature [23]. The most productive epoxy resin for industrial settings is the diglycidyl ether of bisphenol-A (DGEBA) [23]. Epoxy resins outperform polyester, phenolic, and melamine resins due to their low shrinkage and harmless loss during the curing process, as well as their inertness and chemical resistance, as well as their diversity in curing agents and circumstances [24]. A cross-linking reaction is a curing phase, or solidification of liquid epoxy resins with hardeners known as curing agents or catalysts, such as alcohols, acids or acid anhydrides, polyfunctional amines, thiols, and phenols, produce a stiff, insoluble, and infusible epoxy [25]. The qualities of the final epoxy finish are said to be influenced by the resins and curing chemicals used. In general, the high-temperature cured epoxy system achieves better stiffness, tensile strengths, and glass transition temperatures than the low-temperature cured epoxy method [26].

Epoxy nanocomposites have recently gained popularity owing to their distinctive physicochemical qualities that result from combining the individual properties of epoxy and nanoparticles in a single unit [27, 28]. The combination of better structural behavior with intelligent qualities such as sensing, actuation capabilities, and strain monitoring is termed novel multifunctional epoxy nanocomposites [29]. Numerous nanostructural materials, such as carbon nanofibers [5], iron and iron oxide nanoparticles [30], graphene [31, 32], carbon nanotubes [33, 34], silica [35, 36], nano clay [37, 38], polyaniline [39], alumina [40], zinc oxide [41–43], and were utilized to formulate epoxy nanocomposites to enhance the mechanical properties and realize new functionalities such as magnetic, electrical conductivity, and optical characteristics. Thus resulting into an epoxy with distinctive electrical [43, 44], anti-corrosive [45], magnetic characteristics [46], and optical [47] capabilities. Although numerous broad assessments exist concerning the thermal combustion, decomposition, and flame retardancy of epoxy nanocomposites with surface-modified silicon dioxide nanoparticles [23] and epoxy systems [22], there is a paucity of publications about multifunctional epoxy nanocomposites. The challenges and potential resolutions for creating epoxy nanocomposites are discussed in this chapter. The multifunctional epoxy nanocomposites and their usage are explored to present the necessary fundamental knowledge that might help expand their utilization in creative industrial applications.

2 Multifunctional Properties

2.1 Self-healing

Self-healing epoxy are epoxy materials capable of automatic recovery when damaged. They are inspired by biological systems such as the human skin, which are naturally able to heal itself. Existing self-healing epoxy can be classified into three groups: capsule-based, vascular, and intrinsic self-healing materials [48]. In capsule-based self-healing materials, small capsules comprising a liquid capable of filling and closing cracks are embedded under the material surface. In case the material is damaged, cracks trigger some capsules to rupture, releasing the liquid and closing the gap. For vascular self-healing materials, the capsules are substituted by a vascular structure comparable to a tunnel network, in which numerous functional liquids flow. These functional liquids will also fill the gap when a crack appears and breaks the vascular network. The material contained inside a capsule or a vascular network is known as a healing agent. The mechanism and behavior of healing agents are essential to the recovery process and restoration of mechanical properties.

Intrinsic self-healing materials heal through the inherent reversibility of chemical or physical bonding instead of structure design [49], such as the swelling of shape-memory polymers [50], the melting and solidification of thermoplastic materials [51], and increasing viscosities of pH-sensitive micro-gels [52]. Consequently, the healing mechanisms of intrinsic self-healing materials are fundamentally different from those of capsule-based and vascular self-healing composites.

Capsule-based and vascular self-healing structures are the main routes to building autonomous self-healing structures. Healing mechanisms, healing performance, and fabrication techniques for producing capsules and building vascular networks have been summarized and analyzed. Capsule-based self-healing materials can heal small cracks, while vascular systems are more suitable for healing larger damaged areas. The healing performance varies from 24 to 121% depending on the types of healing agents, different healing, and damage conditions.

2.2 Shape Memory

Shape-memory epoxy resins are an emergent category of polymers with applications covering numerous areas of daily life. Some of these applications include, for example, smart fabrics [53, 54], heat-shrinkable tubes for electronics or films for packaging [55], self-deployable sun sails in spacecraft [56], self-disassembling mobile phones [57], intelligent medical devices [58], or implants for minimally invasive surgery [59, 60]. These examples cover only a tiny number of the possible applications of shape-memory technology, which shows potential in numerous other applications.

Shape-memory epoxy resins are dual-shape materials belonging to the group of ‘actively moving’ polymers [61]. They can actively adjust from a shape A to a shape B. Shape A is a temporary shape that is obtained by mechanical deformation and subsequent fixation of that deformation. This procedure also defines the change of shape shift, resulting in shape B, which is the permanent shape. In shape-memory polymers stated so far, heat or light has been employed as the stimulus. Using irradiation with infrared light, application of electric fields, alternating magnetic fields, or immersion in water, indirect actuation of the shape-memory effect has also been realized. The shape-memory effect only depends on the molecular architecture and does not necessitate a specific chemical structure in the repeating units. Therefore, intrinsic material properties, e.g., mechanical properties, can be altered to the need of specific applications by variation of molecular parameters, such as the type of monomer or the comonomer ratio.

2.3 *Magnetic*

Magnetic epoxy nanocomposites are typically created by incorporating magnetic nanoparticles into the epoxy matrix. Consequently, epoxy is widely used in microwave adsorption [62–64], magnetic resonance imaging [65], flexible electronics [66], and electromagnetic interference shielding [66]. Owing to their distinctive physicochemical properties, such as high coercivity and integral active chemical catalysis with their minute size and high specific surface area, magnetic nanoparticles, such as cobalt, iron, nickel, and their alloys among them or others, have recently attracted significant consideration in various chemical and physical domains [67], owing to their distinctive physicochemical properties containing high coercivity and integral active chemical catalysis with their minute size and high specific surface area, which are unlike the bulk materials [68]. In magnetic hysteresis loops, the intensity of the applied external magnetic field is essential to return the material to zero magnetization once it has become saturated, and the remnant magnetization is the magnetization that remains after the applied external magnetic field has been detached. Diverse magnetic domains, wherein atoms’ magnetic moments are aligned in an identical direction, make up bulk magnetic materials. However, when the size of a magnetic substance shrinks, the number of magnetic domains shrinks as well, perhaps to only one. These nanoparticles’ magnetic characteristics are no longer consistent with bulk magnetic materials [69]. Magnetic nanoparticles have added proficient interactions with the polymer matrix on the nanoscale, which influences the surface energy at the interface between the magnetic nanoparticles and the matrix [70]. Magnetite (Fe_3O_4) is the strongest magnetic substance of all-natural minerals on Earth [71], out of all the magnetic nanoparticles. Park et al. [72] studied the magnetic characteristics and wear rates of silane-modified Fe_3O_4 /epoxy nanocomposites. The modified Fe_3O_4 /epoxy nanocomposites’ saturation magnetization was found to be higher than that of the unmodified Fe_3O_4 /epoxy nanocomposites. However, because pure magnetic metal nanoparticles are easily oxidized and flammable in air, the

majority of reported magnetic nanocomposites are based on magnetic metal oxide [73].

2.4 Thermal and Electrical Conductivities

The unprecedented growth of the semiconductor electronic sector, particularly wireless telecommunication, necessitated the development of new multifunctional nanocomposites to meet the demands of electronic gadgets [74]. As a result of their ecologically acceptable and cost-effective process/materials and ease of large-scale fabrication adaptation, epoxy-based nanocomposites with electrical and thermal conductivities have advanced [75]. Nanoparticles are typically superior to micron-sized particles in electrically and thermally conductive applications because they have a higher specific surface area, which improves electrical and thermal properties, such as a lower percolation threshold and increased electrical and thermal conductivity [76]. Epoxy materials with good thermal conductivity can effectively reduce heat and solve heat dissipation issues in electronic devices [77].

Because of their exceptional conductivity [78] and extensive range of applications in electronics [79], supercapacitors [80], electrodes for electrodeposition [81], and conducting polymers have gotten increased attention in recent decades. A doping procedure can usually be used to adjust the conductivity of conducting polymers [82]. Zhang and Guo et al. [83, 84] have produced pure conducting polymers as conducting nanofillers to increase the electrical conductivity of epoxy. The addition of a 10.0% (w/w) loading of nanofiller to the epoxy resulted in the electrical conductivity rise by 5–6 orders of magnitude.

The extremely mobile electrons in pure metallic nanoparticles result in outstanding electrical conductivity. Nevertheless, because of their easy oxidation and flammability in air, it is difficult for metal oxide nanoparticles to be extensively utilized in production, and most of the indicated effort focuses on them [73]. To maintain pure iron nanoparticles, Zhu and Zhang et al. proposed a protective shell made of metal oxide [31] and carbon [70] thin layers. In conclusion, the electrical conductivity of metallic nanoparticle/epoxy nanocomposites might be up to seven orders of magnitude greater than pure epoxy, which might be advantageous for the manufacture of electrically conductive epoxy nanocomposites in large quantities.

Owing to its great adhesive strength, low cost, and good chemical and corrosion resistance, epoxy is now one of the most extensively utilized electrically conductive adhesives for microelectronic packaging such as printed circuit board to flip-chip integrated circuit package assembly [84]. Electrically conductive adhesives typically contain an organic polymeric binder as well as conductive fillers. Epoxy acts as a mechanical link between the interconnections, while the conductive fillers offer electrical conductivity by making physical contact with each other. Silver, gold, nickel, copper, and other carbon compounds could be employed as conductive fillers [74, 85, 86]. Silver flakes are the utmost utilized and commercially obtainable filler due to the nature of their conductive oxides and their high electrical conductivity. Although

nickel and copper are budget-wise, they can be oxidized easily at high humidity and temperatures. These issues decline the behavior of the device interconnections [87]. Electrically conductive adhesives possess several benefits compared with standard solder technology, including mild processing conditions, environmental friendliness, lightweight, and low stress on substrates. Nevertheless, numerous obstacles are to be addressed involving the minute and reduced conductivity at high temperatures and elevated humidity.

2.5 *Flame Retardancy*

Despite the fact that epoxy is the most common technical polymer, untreated epoxy is exceedingly flammable, severely limiting its applications. As a result, modifying epoxy to increase its flame retardancy is critical [88]. Reduced polymer flammability is usually achieved by combining intrinsically flame-retardant polymers with the chemical modification of existing polymers [89].

Nitrogen-, phosphorus-, and silicon-based materials [89] have been discovered to have flame-retardant characteristics in material compounds in recent decades. Green products are flame-retardants that are less harmful to the environment than halogenated chemicals [88, 90]. Silicon can normally enhance char formation in the condensed phase while trapping active radicals in the gas phase. The produced stable molecular compounds might prevent combustible gases from escaping due to breakdown caused by the nitrogen. Phosphorus could disrupt exothermic activities in the gas phase and promote char formation on the material surface as a barrier in the condensed phase [89]. The flame retardancy behavior of epoxy after mixing with various morphologies as nanofillers was investigated using these principles [83, 91]. The nanofiber morphology was shown to reduce the peak heat release rate of the epoxy in excess of the nanosphere morphology, owing to the increased specific surface area. Gu et al. [21] said that the phosphorus component has a role in the flame-retardant behavior of epoxy materials, implying that phosphorus can stimulate char yield production in the condensed phase.

Graphene is also considered a suitable halogen-free flame-retardant for epoxy, owing to the graphitized and layered structure. The graphene acts as a physical barrier to adsorb the degradation products and facilitate the development of char [92]. Due to its fragile thermal oxidation stability, obtained graphene usually decays in combustion, reducing its flame-retardant property. As a result, some modifications to the produced graphene are required in order to provide a desired flame-retardant property [93].

3 Applications

3.1 Aeronautics

The materials used in aerospace applications are typically subjected to harsh climatic situations such as high humidity, wide temperature swings, and a variety of mechanical loads such as tension, creep, compression, and torsion. Traditional materials such as titanium, steel, and aluminum are acceptable materials that meet all standards, but they have a significant disadvantage when it comes to the fundamental goal of low weight limits [94]. For efficient weight reduction, revolutionary polymer composites in aeronautic production have recently amplified dramatically as load-carrying elements of the innovative generation of adaptable airplanes [95]. Due to their outstanding mechanical behavior, electrical and chemical resistance, and low shrinkage on curing, epoxy-based thermosetting nanocomposites are one of the predominantly utilized aerospace materials in the aeronautical industry [18]. Multifunctionality has also become an important part of aircraft technology. The aerospace industry requires multifunctional epoxy nanocomposites with better mechanical and thermal properties as well as sensing/actuating capabilities [96]. For example, the electrical conductivity of structural sections for airplane fuselages must exceed 1–10 S/m [94] to effectively disperse lightning currents without the usage of conductive metal fibers or metal screens. As a result, new sophisticated epoxy nanocomposites with extra capabilities must be explored without jeopardizing structural integrity. Paipetis and Kostopoulos have written a comprehensive evaluation of the current state of the art in the aerospace composites industry [96].

3.2 Automotive

Epoxy resin is the predominant thermosetting resin in natural fiber composites for automotive applications because it has excellent performance and resilience to environmental deterioration [97]. In the automotive industry, epoxy-based matrix composites are commonly used as automobile bumper beams [98], the power transmission drive shaft [99], dashboards, headliners, seat backs, door panels, package trays, and interior parts [100], as well as an electrically conductive adhesive between a silicon chip and a package lead frame, and as a heat conductive adhesive between a silicon die and a lead frame or substrate [10]. Low-density natural fiber epoxy composites can often reduce the weight of a car by 10–30%. It is projected that a 25% reduction in automobile weight is equivalent to saving 250 million barrels of crude oil annually [98].

Natural fiber-epoxy composites, on the other hand, have low prices, reduced tool wear rates, low manufacturing energy needs, reduced safety and health risks, and good formability. They are less vulnerable than metals to the effects of stress concentration [101]. Carbon nanofibers and glass fibers were recently integrated into natural

fiber composites to produce hybrid fiber-reinforced epoxy composites, thus offering improved fatigue features because micron cracks in the resin will not spread easily like in metals and instead discontinue at the strong hybrid fibers [101]. Characteristics such as stacking sequences, fiber orientation angles, layer number, and layer thickness must be changed to achieve the required performance for automotive use [99].

3.3 *Anti-corrosion Coatings*

Epoxy resins are utilized in aquatic systems, the erection of new vehicular and pedestrian bridges, the strengthening and rehabilitation of structurally deficient bridges, as structural materials, and as anti-corrosion coatings in addition to aerospace and automotive applications [95]. Steel [102], iron [46], aluminum [14], and magnesium alloys [103] are now commonplace in automobiles, cellular phones, household appliances, guided weapons, large constructions, and computer industries. Metal corrosion, on the other hand, has become a growing problem in the metal finishing sector [104]. According to NASA [105], corrosion-related maintenance expenditures in the USA are estimated to be between 70 and 120 billion dollars per year. As a result, several efforts and inventive deterrence strategies to avert rusting were developed [106].

Lately, epoxy coatings have enticed much consideration because of their excellent adhesion, corrosion resistance, and environmental friendliness [107]. Epoxy coatings, in general, operate as a physical obstacle to keep harmful species at bay [108]. Nonetheless, pure epoxy cannot provide long-term anti-corrosive performance due to cavities and imperfections over the coating surface, subsequently to the curing progression, which causes them to be permeable to water, oxygen, and corrosive ions [109]. Inorganic nanofillers [110] and nanoclay [111] have recently been added into epoxy matrices to build epoxy nanocomposites and adjust the epoxy barrier effect to improve the epoxy coating's anti-corrosive qualities. According to reports, nanoparticles can fix cavities, micron fractures, and other imperfections of epoxy coatings, resulting in enhanced anti-corrosive behavior [112, 113].

3.4 *High Voltage*

Because of its superior electrical and mechanical qualities, excellent processability, and chemical stability, epoxy resin is one of the most often used thermosets in high-voltage equipment such as printed circuit boards, high-voltage capacitors, motors, generators, and transformers as insulation [114, 115]. When constructing epoxy insulation materials, the dielectric voltage breakdown strength is usually the essential peak metric [116]. As a result, increased heat stability is required for superior epoxy insulating materials to avoid electrical breakdown [117, 118]. As a result

of their extraordinary dielectric breakdown voltage and higher dielectric strength, epoxy composites reinforced with micron-sized inorganic fillers such as alumina, silica, and others have emerged as the ideal insulating materials for high voltage applications compared with pure epoxy [119]. Since nanocomposite insulation can offer higher performances such as reduced dielectric losses and elevated dielectric strength, tracking and erosion resistance, and surface hydrophobicity compared to traditional micro-sized epoxy composites [120], there has been a lot of interest in using nano-sized fillers as additives in epoxy matrices to form nanocomposites [121]. Over a wide range of frequencies, the dielectric permittivity of epoxy nanocomposites was lower than that of pure epoxy and epoxy with the micro-sized filler at low concentrations (depending on the filler type and size) [122]. Meanwhile, it has been discovered that the dielectric property of insulation is also highly connected to the accumulation of surface charge [123]. Nano-sized fillers on the surface of epoxy materials may cause fluctuations in electrical characteristics at the surface and prevent surface charge buildup, resulting in reduced dielectric behavior [124, 125].

4 Conclusion

This chapter provides a comprehensive summary of the characterization, manufacture, and properties of epoxy composites. Due to their exceptional heat and solvent resistance, high specific strength, high thermomechanical properties, lightweight, good adhesiveness, and reduced cost, epoxy composites are widely used in a variety of manufacturing industries, including aeronautic, automotive, aquatic, construction, and oil and gas. Epoxy composites are also used in electromagnetic shielding, printed circuit boards, supercapacitors, and other applications. Fibers, organic fillers, and inorganic fillers are commonly used in composites to obtain excellent performance. Furthermore, the addition of thermoplastic copolymers may cause the epoxy composites to phase split into multiple phase morphologies, allowing the performance of the epoxy composites to be tailored.

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