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Introduction to Epoxy Composites

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1.1 Introduction

In the last two decades, one can observe a great increase in the replacement of traditional materials with polymer composites in high-strength and lightweight applications [1–3]. This is due to its high strength/weight ratio, toughness, and thermal stability [4]. Several factors are associated with the composite performance, such as filler properties, filler geometry, matrix properties, filler–matrix interactions, filler orientation in the matrix, and the volume fraction of the filler [5]. The matrix component of the composites can be thermoplastic, thermoset, or rubber. Thermosetting polymers are widely used over others in engineering applications due to their versatility and high performance. The epoxy resin was marketed in the late 1940s, since then it is widely used for several industrial and commercial applications. Its low shrinkage, better rigidity, good chemical and corrosion resistance, remarkable adhesion properties, good thermomechanical properties, good dielectric strength, etc., make it widely useful in engineering applications [6, 7]. Unlike polyester resins, epoxy can retain its mechanical and physical properties under the influence of aggressive solvents. Also, epoxy resin will bond with almost all materials such as stone, wood, glass, plastics, ceramics, and metals [8].

Epoxy resins are low-molecular weight materials that comprise oxirane/epoxide rings as functional groups attached to their main chain [9]. The characteristics of the epoxy resin make it suitable for reactivity against a wide range of curing agents. Different types of epoxy resins are available such as diglycidyl ether of bisphenol-A (DGEBA), cycloaliphatic epoxy resin, triglycidyl *p*-amino phenol, tetraglycidyl diamino diphenyl methane, and novolac epoxy resins [10]. In addition, other modified epoxy systems are available such as biobased epoxy, fluorine-containing

Epoxy Composites: Fabrication, Characterization and Applications,
First Edition. Edited by Jyotishkumar Parameswaranpillai, Harikrishnan Pulikkalparambil, Sanjay M. Rangappa, and Suchart Siengchin.

epoxy, phosphorus-containing epoxy, and silicon-containing epoxy. While the curing agents are mainly catalysts or hardeners, the catalysts are tertiary amines or Lewis acids, and their function is to initiate polymerization of the epoxy resin to produce polyether structures [11]. The role of epoxy resin in the composite is to transfer the force uniformly onto the filler and protect the integrity of the entire composite system [12].

Epoxy resin with natural fibers, synthetic fibers, and other reinforced particles has been extensively studied in recent decades [13]. Synthetic fiber-reinforced epoxy composites are made of synthetic fibers such as glass, carbon, kevlar, and aramid. Due to their lightweight, good strength, and good modulus, synthetic fiber-reinforced epoxy composites are generally used in automobile and construction applications. However, the recyclability of the synthetic fibers from the composites after use is a concern. Recently, natural fibers are used in automotive and construction industries due to their advantages, such as biodegradability, easy availability, lightweight, cheap, simple processing, and good thermomechanical properties. Extensive study has been done on epoxy composites based on natural fibers such as kenaf, banana, jute, bamboo, and cotton [14–16]. Studies have shown that they can replace glass and carbon fiber (CF) in epoxy composites for semi-structural applications [14–17]. Furthermore, epoxy is the best resin that can be used with either synthetic fiber or natural fiber [16, 18–22]. On the other hand, the addition of micro- or nanofillers shows different behavior. For example, the addition of clay fillers limits the plastic behavior of epoxy due to the rigid clay behavior. Abdellaoui et al. [23] discussed the effect of clay loading on the deformation of epoxy composites. The strength of the composites decreased with the incorporation of clay. It was observed that at lower clay loading (5% and 10%), the epoxy–clay interactions are weak owing to poor distribution. On the other hand, at higher loading of 20 wt%, the clay particles agglomerate forming high-stress concentration zones, which further weaken the composite strength. Thus, they concluded that the incorporation of clay particles weakens the epoxy ductility and degrades mechanical properties. Similarly, carbon nanotubes (CNTs) in epoxy were reported to show poor dispersion with an increase in specific surface area. However, the dispersion of CNTs in the epoxy matrix can be improved by chemical functionalization, especially functionalization with amino group improved dispersion to a large extent [24].

1.2 Manufacturing Methods for Fabrication of Epoxy Composites

For the manufacture of epoxy-based composites, several methods were used in different fields of application with the requirement of the final shape and size of the components. Some of the most important methods used for the manufacturing of epoxy composites are hand layup, vacuum bagging, vacuum-assisted resin transfer molding, autoclave, compression molding, pultrusion, and filament winding. All these methods have their own advantages and disadvantages. The best selection of the

method gives the best result in any manufacturing industry. Different manufacturing techniques used for the preparation of epoxy composites are given in Table 1.1.

1.3 Experimental Techniques for the Characterization of Epoxy Composites

The detailed understanding of the epoxy composites is necessary for its effective utilization in various application areas. Several characterization techniques have been used to study the reinforcement effect of different fillers in epoxy matrices. Some of the characterization techniques used for the characterization of epoxy composites are universal testing machine, dynamic mechanical analysis (DMA), differential scanning calorimetry (DSC), rheology, thermogravimetry analysis (TGA), electron microscopy, contact angle, and water absorption studies [47–50].

The rheological measurement is very helpful in analyzing the state of dispersion and interfacial interaction of the nanoparticles with the epoxy matrix [51, 52]. Song et al. [52] studied the impact of dispersion of multi-walled carbon nanotubes (MWCNTs) on the rheological properties of the epoxy composites. The authors reported increased storage modulus, loss modulus, and complex viscosity with the incorporation of MWCNTs. This implies that the MWCNT-based composite exhibits a solid-like behavior. Kim et al. [53] studied the rheological properties of surface-modified MWCNTs in the epoxy composite. The rheological studies revealed that the modified MWCNTs in the epoxy matrix show higher storage modulus, loss modulus, and shear viscosity when compared with the untreated MWCNTs. This is because MWCNTs treated with acid, plasma, and amine introduce functional groups onto the surface that imparts good dispersion and strong adhesion between the MWCNTs and epoxy matrix. The least modulus and viscosity were observed for the neat epoxy system. Park et al. [54] studied the rheological properties of the acid-treated MWCNT-reinforced epoxy matrix composites. They reported that the surface-treated MWCNTs composite showed good dispersion and faster gel time. In another work, Zhu et al. [55] studied the fiber distribution and interfacial interaction of 3-aminopropyltriethoxysilane (APTES)-modified carbon nanofiber (CNF) in the epoxy composite. They observed a sharp increase in complex viscosity and storage modulus at high temperatures due to the in situ reaction of amine groups present in APTES with epoxy resin.

The DMA is used to study the viscoelastic properties of composites. Here, the change in viscoelastic property of a material with respect to temperature or frequency is measured to study the material behavior under dynamic conditions. The storage modulus, loss modulus, and tan delta are the parameters observed from the DMA measurements. These parameters are used to study the viscoelastic behavior of the composite material [56]. The transition of the material from glassy to rubbery, i.e. glass transition temperature, can also be measured using DMA. In a recent work, Yorseng et al. [50] studied the dynamic mechanical behavior of neat bioepoxy and kenaf/sisal fiber fabric-reinforced epoxy composites. The authors observed a rapid drop in the storage modulus at the T_g of the bioepoxy matrix. However, for

Table 1.1 Manufacturing techniques used in composite fabrication.

S. No.	Manufacturing methods	Remarks	References
1.	Hand layup	The advantages of using hand layup are design freedom and least expensive. The disadvantages are the need for a greater number of cycles for fabrication, skilled labor cost, risk of placement errors, molding of complex parts with thickness variation, and poor surface finish.	[25–28]
2.	Vacuum bagging	The advantages of vacuum bag molding are better finish, void free, and, possibility of using a heated oven to accelerated consolidation. The disadvantages include more complex and expensive compared to hand layup, need to design the vacuum bag according to component dimensions, and finally, the size of the final component is limited to mold size.	[29]
3.	Vacuum-assisted resin transfer molding	The advantages of VARTM are the ability to manufacture large complex parts, can be used to produce different component geometries, resin and hardener can be stored separately and mixed just before infusion, and low volatile organic compound emission. The disadvantages of the VARTM process are the difficulty in the reuse of bag, tube, sealing tapes, and other consumables after one cycle, pressure (both injection pressure and compressive pressure) is limited in between vacuum pressure and atmospheric pressure, leakage problems, less robustness, etc.	[30–32]
4.	Solvent casting	The advantages of solvent casting are simple fabrication process and no need for specialized equipment. This technique limits the use of any mechanical stress or high thermal processes to avoid any degradation or side reactions. However, the limitation of the solvent casting method is the use of an external solvent that may affect environment-friendliness and costs.	[33]
5.	Autoclave	The advantage is that it produces composites with closer control of thickness and lower void content. The limitation of this process is that the component size may be limited to the autoclave size.	[34]
6.	Compression molding	The advantages of compression molding are easy processing, low cost, and minimum waste. The disadvantage of using compression molding is it is limited to small-scale industries due to the time-consuming process. Also, the compression molding technique requires highly trained manpower to operate the processes.	[35, 36]
7.	Pultrusion	The advantages of pultrusion are the unlimited length of the products, smooth surface, and continuous production. The disadvantages include limited size in the transverse direction, reinforcement in only one direction, and expensive.	[37, 38]

(Continued)

Table 1.1 (Continued)

S. No.	Manufacturing methods	Remarks	References
8.	Filament winding	The advantages of filament winding are higher reinforcement levels (up to 70% or more to improve mechanical strength), tailoring orientation of fibers, and large component fabrication is possible. The disadvantages are heavy investments and limited design and shape.	[39, 40]
9.	Low shear liquid batch mixer	These are batch-type mixers that are versatile to be suitable for all types of processing conditions such as mixing sequence, mixing temperature, and mixing time. However, the limitation of these mixers is time consumption.	[41]
10.	Internal mixer		
11.	Rheo mixer (RMX)		
12.	Extrusion	The advantages of using extruders are low cost, good heat transfer, good mixing, high production, and good surface finish. The disadvantages are size variance and product limitations.	[42]
13.	Three-roll mill	The main advantage of the three-roll mill is good dispersion. The fillers can achieve highly intercalated or exfoliated structure.	[43–45]
14.	Resonant acoustic mixer	The main advantage of RAM mixers is uniform mixing, unlike the batch and continuous mixers where localized mixing near the region of mixing blade tip is observed.	[46]

the composites, the drop in storage modulus at the T_g is marginal due to reinforcement of sisal and kenaf fibers with bioepoxy matrix. Matykiewicz et al. [57] studied the thermomechanical properties of epoxy composites filled with glass fiber. The authors reported an improvement in the storage modulus of the epoxy composite with the incorporation of glass fiber, due to better dispersion of glass fiber in the epoxy matrix. In another work, Chateauminois et al. [58] studied the plasticization of unreinforced and epoxy/glass fiber-reinforced unidirectional composites using DMA. The samples of reinforced and unreinforced composites were both unaged and aged by immersion in water. The composite samples were dried in an air oven immediately after immersion. The results of the samples were compared for change in plasticization after aging. The authors observed a change in plasticization for reinforced composites after aging. This is due to the trapping of water in the voids generated at the fiber/matrix interface because of hygrothermal aging. In a similar work, Xian and Karbhari [59] investigated the moisture uptake and aging of a room temperature cured epoxy system using DMA. The plasticization was observed in the aged samples.

The DSC is mostly used for the measurement of T_g and the cure kinetics of the epoxy thermoset [60]. The cure kinetics of epoxy composites and the degree of cure

is dependent on the curing temperature [61, 62]. High cure temperature accelerates the curing reaction and hence decreases the cure time. The T_g behavior of composites with different filler loadings may be used to understand the interaction between the polymer and fibers. The addition of fillers in epoxy composites may have strong effects on the T_g [61]. Gojny and Schulte [63] reported that the T_g of the composites may vary with the addition of CNT, and the change is more noticeable with functionalization. Also, the composites with a strong filler polymer interface show improved T_g. Kang et al. [64] studied the DSC of functionalized nanosilica particles obtained using the sol–gel process in epoxy composites. An improvement in the T_g was observed for the composites with strong interfacial interactions.

The thermal stability of epoxy composites plays an important role in determining the maximum temperature up to which the material is safe for practical applications. In TGA, the mass of a sample is monitored against temperature using a thermo-balance [65]. The weight loss at a specific temperature determines the amount of degradation, and the temperature at which maximum weight loss is observed shows maximum degradation temperature. Also, TGA is useful for determining the composition of lignocellulosic biomass such as lignin, α-cellulose, and hemicellulose contents [66, 67]. TGA is also used for the fiber and void content analysis in composites. Yee and Stephens [68] showed a fast and precise method to study the graphite fiber content in epoxy composites using TGA. Nowadays, hydrogen fuel in automotive has attracted most of the people due to the depletion of fossil fuels. However, the storage of hydrogen fuel needs to be taken care of due to its very high pressure and flammability. Very recently, Zhang et al. investigated the thermal stability of CF-reinforced epoxy composites taken from the outer material of hydrogen fuel storage tank [69]. TGA and Fourier transform infrared analysis (FTIR) can be used to study the pyrolysis of epoxy composites. The TGA is used to analyze the weight loss at elevated temperatures, while FTIR is used to measure constituents and functional groups in the produced gases. They reported that the decomposition of epoxy composite takes place between 277 and 477 °C [70, 71].

FTIR spectroscopy is a form of the vibrational spectroscopic technique commonly used to determine the functional groups present in the composites [72]. FTIR is also used to measure the curing reaction, phase separation, and aging with the assessment of bands [73]. The FTIR peaks are obtained in the range between 4000 and 400 cm^{-1}. The oxirane ring in the epoxy resin is observed at 915 cm^{-1}, which corresponds to C–O deformation, and the peaks at 3050 cm^{-1} correspond to stretching of methylene groups in the epoxy ring. Table 1.2 shows characteristic FTIR peaks of DGEBA epoxy resin.

1.4 Properties of Epoxy Composites

1.4.1 Mechanical Properties

The mechanical properties of epoxy composites are an important topic in shaping its efficient use in any application area. The factors that affect the mechanical properties

Table 1.2 Characteristic bands of DGEBA.

Band (cm^{-1})	FTIR peak assignment
≈3500	O–H stretching
3057	C–H stretching vibrations of the oxirane ring
2965–2873	C–H stretching vibrations in epoxy resin
1608	C=C stretching vibrations of aromatic rings
1509	C–C stretching vibrations of aromatic rings
1036	C–O–C stretching vibrations of ethers
915	C–O stretching vibrations of oxirane group
831	C–O–C stretching vibrations of oxirane group
772	CH_2 rocking

Source: María González et al. [73]. IntechOpen. CC BY 3.0.

of filler-reinforced epoxy composites are volume fraction of filler, filler aspect ratio, filler orientation, and filler–matrix interfacial adhesion [74]. The mechanical properties of natural fiber composites can be improved when it is used along with synthetic fibers [75]. In other words, the hybridization of natural fiber and synthetic fiber leads to improved mechanical properties due to the synergetic effects of both the fibers. Fiore et al. [76] studied the effect of alkali (NaOH) treatment on kenaf fibers. They reported that the alkali treatment resulted in improved mechanical strength by reducing the polymer chain mobility and enhancing the stress transfer. However, the immersion time in NaOH had an unfavorable effect on the mechanical properties. The particle size of fillers may also affect the mechanical properties. For example, Wang et al. [77] showed the effect of particle size of graphene nanoplatelets on the mechanical properties of epoxy composites. Moderate increase in strength and modulus is observed when smaller particles are used. On the other hand, larger particles improve the modulus remarkably but reduce the strength. This is due to the reinforcement effect of larger particles, but they have poor interfacial interaction with the epoxy matrix. In an interesting work, Gojny et al. [24] schematically described several mechanisms during the failure of CNT-modified epoxy matrix as shown in Figure 1.1. The different failures occurring on the CNTs during the application of tensile force are pullout, breakage, pullout of inner tube, and bridging or partial debonding at the interfaces.

The impact strength/resistance of a composite is the energy needed to break any material. In other words, the impact strength of a material is its ability to resist the applied stress at high speed. Many factors such as voids, sharp edges of fillers, filler agglomeration, and weak filler–epoxy interface may lead to stress concentrated areas that may cause failures in the form of cracks by the application of applied stress [78, 79]. One way to improve the impact strength is by the addition of dispersants or coupling agents [80]. The addition of dispersants reduces filler agglomeration that could otherwise act as a stress concentration point. Devendra and Rangaswamy [81]

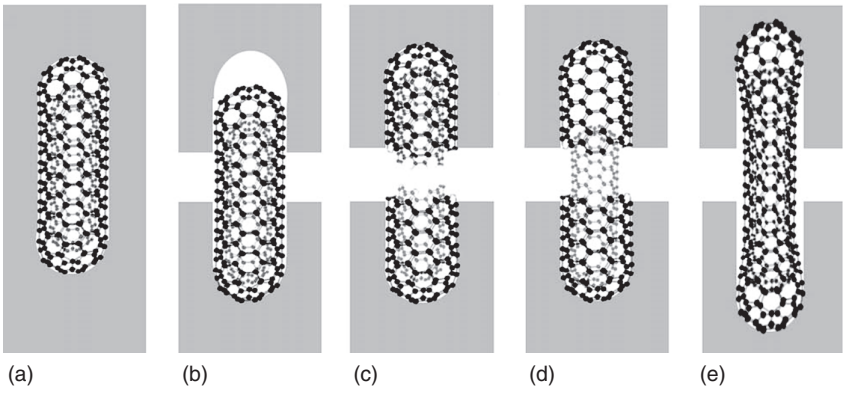

Figure 1.1 Schematic representation of failure types in epoxy/CNT composites: (a) undamaged CNT, (b) CNT pullout, (c) CNT breakage (very good CNT–epoxy interaction), (d) telescopic pullout damaging outer tube and pullout damaging inner tube, and (e) bridging and partial debonding at interface. Source: Gojny et al. [24]. © 2005, Elsevier.

reported that the filler content higher than optimum has an adverse effect on the impact resistance of a composite due to agglomeration of fillers.

The interfacial shear stress (IFSS) measures the degree of interfacial strength between the filler and the epoxy matrix. Wang et al. [82] studied IFSS measurements of Ag nanoparticles and graphene oxide (GO)-deposited CF-reinforced epoxy composites. The authors reported that the IFSS improved from 46.8 to 87.1 MPa for the epoxy composites. The presence of Ag nanoparticles was observed to increase the surface roughness of the fiber and the matrix, which provides better interlocking between the fiber and the matrix. While the incorporation of GO greatly improves the wettability and interfacial adhesion between the CF and polymer matrix that leads to improved shear strength (Figure 1.2). Godara et al. [83] studied the effect of CNTs on the IFSS of glass fiber-reinforced epoxy composites. It was observed that CNTs improve the IFSS irrespective of its location in the composites. However, as

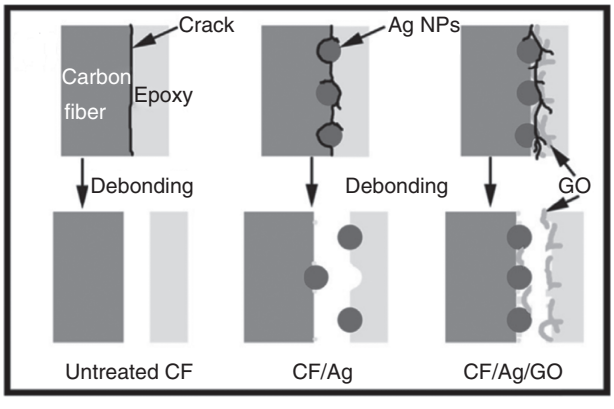

Figure 1.2 Scheme showing failure mode of untreated CF-modified epoxy, CF/Ag-modified epoxy, and CF/Ag/GO-modified epoxy. Source: Wang et al. [82]. © 2017, Elsevier.

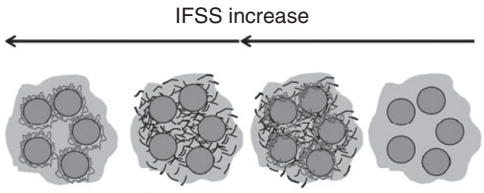

Figure 1.3 Schematic representation of CNTs on different locations in the composite and its effect on IFSS. Source: Godara et al. [83]. © 2010, Elsevier.

shown in Figure 1.3, the maximum improvement of IFSS is observed for composites with CNTs on the surface of the glass fiber.

1.4.2 Dielectric Properties

The dielectric constant and the dissipation factor are the two important parameters in measuring the dielectric properties [84]. The dielectric constant measures the ability of the material to store charge, while the dissipation factor is the energy dissipated by a dielectric. These are measured as a function of frequency of alternating current by placing the composite material between the plates of a condenser and measuring the impedance [85, 86]. The dielectric constant of epoxy resin is very low (<10) to be useful in practical applications [87]. Incorporating an adequate amount of fillers may improve the dielectric properties to some extent. However, higher loading may affect the mechanical properties of the composite [88–90]. In an interesting work, Singha and Thomas [91] studied the dielectric properties of inorganic filler (TiO_2, ZnO, and AI_2O_3)-incorporated epoxy composites. It was observed that the permittivity and tan delta values of the nanocomposites were lower than those of the micro-composites and unfilled composites. In another work, Kuo et al. [92] prepared epoxy composites using self-synthesized barium titanate ($BaTiO_3$), commercial $BaTiO_3$, and $Pb(Mg_{1/3}Nb_{2/3})O_3$ ceramic particles. It was observed that the self-synthesized ceramic particle $BaTiO_3$ exhibits a dielectric constant of 44 compared to 27 and 24 for commercial $BaTiO_3$ and $Pb(Mg_{1/3}Nb_{2/3})O_3$ composites. This is due to the large ceramic aggregates formed in the epoxy composites by self-synthesized $BaTiO_3$. In another study, Wan et al. [93] reported the dielectric properties of DGEBA–RGO/epoxy composites, where DGEBA–RGO was prepared by grafting DGEBA molecules on reduced graphene oxide (RGO) sheets. The DGEBA–RGO/epoxy composites showed an improved dielectric constant of ~32. This was attributed to better compatibility arising due to grafting of DGEBA and the better contact of RGO sheets making a pathway for suppressing the dielectric loss effectively. In one of the works, Jlassi et al. [94] reported that a very small amount of diazonium-modified clay-polyaniline nanofiller (B-DPA/PANI) in the epoxy matrix can improve the tensile strength (0.1 wt%) and dielectric constant with the incorporation as low as 0.5 wt%. This is due to the good dispersion of the nanofiller in the epoxy matrix.

1.4.3 Water/Moisture Absorption

Water absorption of a material maybe defined as the percentage of water uptake in a given unit time at a specific temperature. It is calculated by measuring the change

in weight with respect to its original weight after a given time. The weight gained at saturation is the final weight.

$$\text{Water uptake}\,(\%) = \frac{\text{Initial weight of sample-Final weight of sample}}{\text{Initial weight of sample}} \times 100$$

The rate of water uptake can be measured by calculating the diffusion coefficient of the composites [95]. The following equation can be used to calculate the coefficient of diffusion:

$$D = \pi\left(\frac{\text{kh}}{4\text{Mn}}\right)^2$$

One of the main limitations of epoxy resin and its composites is its high water absorption. The water uptake may adversely affect the T_g, modulus, strength, and toughness due to the degradation of the epoxy thermoset [73]. It also generates internal stresses due to swelling and causes delamination of the filler or other defects in composites. In general, the main concern with natural fiber composites is their high moisture intake due to the presence of hydroxyl groups in the fiber, which reduces the compatibility between the fiber and the epoxy matrix [96]. In fact, the fiber–matrix interfacial strength may be reduced, which in turn will decrease the mechanical performances of the composites. In few studies, it was observed that the hybridization of fibers in the composite may improve the mechanical and water absorption properties [97–99]. For example, Maslinda et al. [100] studied the effect of water absorption on the mechanical properties of woven kenaf, jute, and hemp fiber-based hybrid epoxy composites. The authors reported that the mechanical and water-resistant properties of the composites were improved with hybridization.

The water absorption is observed to be higher for natural fiber-reinforced composites when compared to synthetic fiber-reinforced composites [101, 102]. Therefore, the hybridization of natural fiber and synthetic fiber reduces the water uptake tremendously. Sanjay and Yogesha [102] studied the water absorption behavior of jute, kenaf, and E-glass woven fiber-reinforced epoxy composites with different layering sequences. The authors reported a reduction in water absorption behavior with the hybridization of natural and synthetic fibers. Venkateshwaran et al. [103] studied the water absorption rate of sisal and banana fiber composites. They observed a reduction in the rate of water absorption after hybridizing the sisal fiber (50%) with banana fiber.

The wetting of fibers or fillers plays an important role in reducing the water absorption because wetting improves the adhesion of the filler with matrix [104, 105]. The addition of a small amount of nanoclay (c. 3–5 wt%) in epoxy composites exhibits improved barrier properties [106, 107]. Becker et al. [108] studied water absorption in nanoclay-filled tetrafunctional tetraglycidyldiamino diphenylmethane (TGDDM) and DGEBA resin systems. It was evident from the results that nanoclay-filled composites showed lower water absorption when compared to neat epoxy resin. However, the rate of diffusion with the change in nanoclay concentration is observed to be unaffected. In an interesting work, Mohan and Kanny [109] reported the water barrier properties of sisal fiber-modified epoxy composites and nanoclay-filled sisal fiber-reinforced epoxy composites. After water

absorption, the tensile and wear properties of sisal fiber composites detrimentally decreased. However, after the addition of nanoclay to sisal fiber composites, the tensile and wear properties are least affected. This is due to the barrier property of nanoclay that stops the water from entering the composites.

1.4.4 Morphology

The morphology of composites plays an important role in identifying the failure mechanisms. For example, electron microscope is used to analyze the existence of voids, agglomeration, and dispersion of fillers [110, 111]. In an interesting study, Saba et al. [111] prepared hybrid epoxy composites containing kenaf and oil palm empty fruit bunch fiber (OPEFB) fillers that showed improved mechanical properties. The morphology study revealed that the addition of 3% OPEFB filler into epoxy/kenaf composites was observed to improve the interfacial bonding between the fiber and matrix. Also, the addition of OPEFB fiber reduces void contents, fiber pullout, and fiber protruding and tearing on the composites. Oksman et al. [112] studied the morphology of unidirectional sisal/epoxy composites. Figure 1.4a,b shows scanning electron microscopy (SEM) images of fractured surface of sisal/epoxy composites. Here, the fiber pullout and imprints are visible. Figure 1.4c,d shows the optical microscopy images of the composites. The figures show fiber distribution and horseshoe-shaped technical fibers. Atomic force microscopy (AFM) is also a powerful tool to characterize surface morphology and

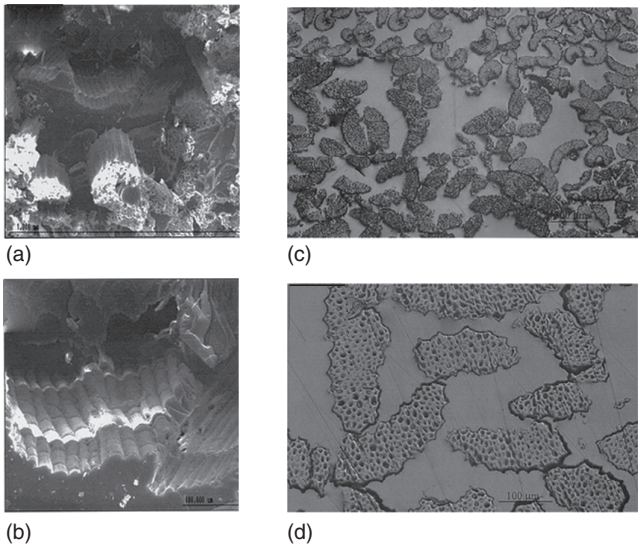

Figure 1.4 (a and b) SEM image of sisal/epoxy fracture surface shows fiber pullouts and imprint of the fiber on epoxy surface, (c and d) optical microscopy of sisal/epoxy composites shows horseshoe structure and voids in the fiber–epoxy interface. Source: Oksman et al. [112], Reproduced with permission from Wiley, License Number:4847180686936.

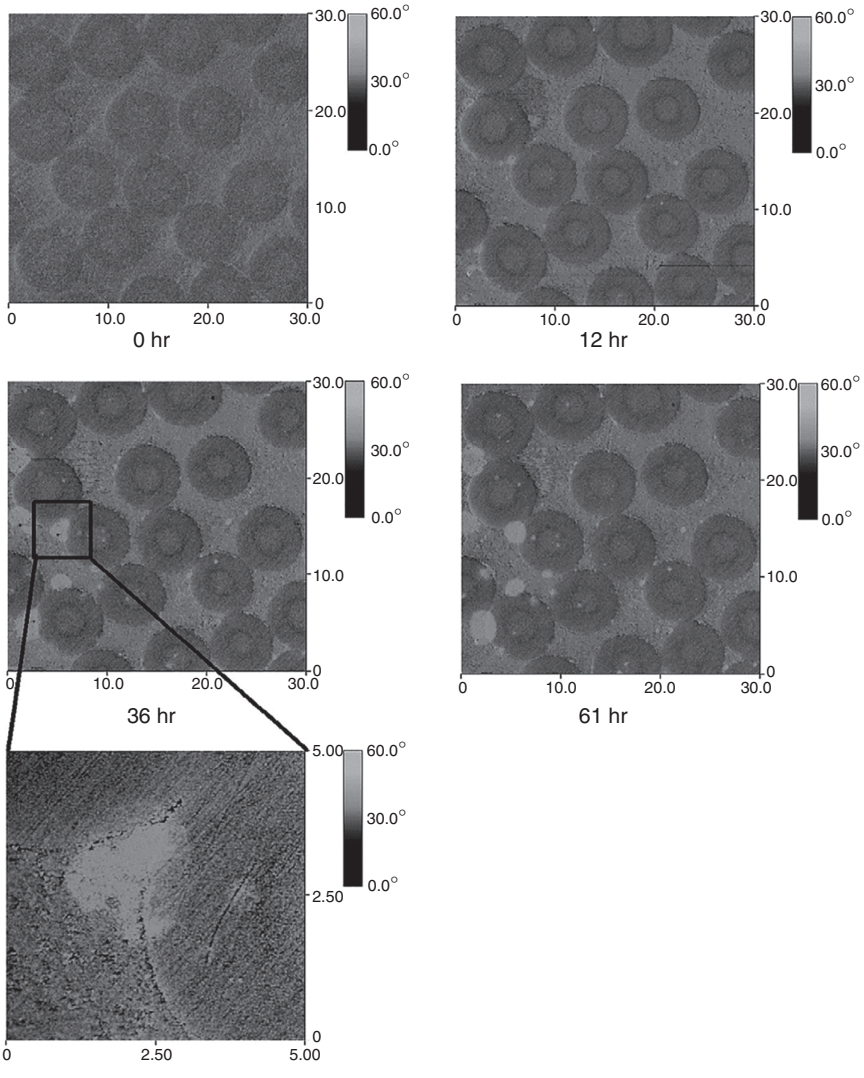

Figure 1.5 AFM image showing debonding occurred during hygroscopic treatments of carbon fiber-reinforced composite. Source: Wang and Hahn [114], Reproduced with permission from Elsevier, License Number:4847180982493.

thickness of nanosized fillers in epoxy composites. George and Verpoest [113] characterized the untreated and silane-treated fiber using AFM and observed that the surface of the treated fibers is rougher than that of the untreated fibers. In another work, Wang and Hahn [114] studied the effect of hygrothermal processes on the interfacial properties of CF-reinforced epoxy composites. The AFM was used to investigate the debonding of fibers. Figure 1.5 shows the AFM image of debonding in hygroscopic treated composites at different time intervals.

1.5 Conclusion

In this chapter, an overview of the manufacturing, characterization, and properties of the epoxy composites is briefly discussed. It is worth to point out that the applications of epoxy composites are widely accepted in all areas of manufacturing industries such as automotive, aerospace, construction, oil and gas, and marine owing to their excellent heat and solvent resistance, high thermomechanical properties, high specific strength, good adhesiveness, lightweight, and low cost. Epoxy composites also find applications in printed circuit boards (PCBs), electromagnetic shielding (EMI), supercapacitors, etc. The high performance of the composites is generally achieved by the incorporation of fibers, organic fillers, and inorganic fillers. Furthermore, the addition of thermoplastic copolymers may phase separate into different phase morphologies which may tailor the performance of the epoxy composites.

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