Chapter

Epoxy Composites for Radiation Shielding

Hayriye Hale Aygün

Abstract

Due to the increase in use of radiation energy in many industrial applications, radiation shielding has become a crucial topic in order to diminish its hazardous effects. Radiation shields can be of various weights depending on the materials from which they are produced and the area in which they are used. In this sense, polymer composites have taken attention by researchers because it is aimed to obtain shields with good processability, sufficient flexibility, low weight, and subsequent performance properties. Epoxy resin is one of the mostly used synthetic polymers as a matrix element in composite material production due to its improving characteristics by means of electrical insulation, chemical resistance, service life, bonding characteristic, and mechanical properties. Besides, epoxies have intermediate radiation shielding characteristics as well. By loading epoxy matrix with fibers and/or fillers having different radiation absorption rates or mechanical resistance properties, multifunctional shields can be produced to serve in numerous applications. This chapter focuses on radiation shielding efficiency of fiber-reinforced epoxy composites and the role of fillers and fiber-based materials on manufacturing of functional radiation shields.

Keywords: composite, epoxy resin, fiber, filler, radiation, shielding

1. Introduction

For protecting humans and the environment from the hazardous effects of radiation, various forms of shields have been used in different fields in which radiation has been utilized. Shielding materials manufactured from lead, stainless steel, and concrete are heavy and rigid structures and also not resistant to corrosion. These structures have been generally used as blocks for shielding against radiation and have not sufficient flexibility and comfort properties in order to be used in shielding garments (Figure 1). Therefore, researchers have been focused on the manufacturing of advanced materials with good shielding capability, lightweight, high modulus, and mechanical properties. At this point, composite materials have taken the attention of researchers due to manufacturing of a unique material from different materials with dissimilar characteristics.

Epoxy polymer is one of the most important thermoset polymers used in composite manufacturing due to its good wetting ability, low cure shrinkage, excellent chemical corrosion resistance, good dimensional stability, high tensile, fatigue, and compression strength. By courtesy of its use in composites, it contributes to
the properties of the whole composite by means of good mechanical strength, high stiffness, excellent chemical resistance, flame retardancy, and high electrical strength [1, 2]. Solid epoxy polymer is the output material obtained by reaction of curing agent and liquid resin. There are various types of epoxy-based liquid resin because the numbers of epoxide groups on its starting material can be variable. Diglycidyl ether of bisphenol A (DGEBA) has two epoxide groups in its structure, which is the most common starting material used in the manufacturing of epoxy-based liquid resin. For solidification, liquid resin is treated with small amounts of reactive curing agent and then a tridimensional network occurs as a result of crosslinking. The use of different types of starting materials and reactive curing agents results in various types of solid epoxy polymers with different characteristics. Thereby, the properties of epoxy resin are given a range of values as it is seen in Table 1. In case of being cured, the system exhibits brittle characteristic due to crosslinking mentioned above, and this case causes incomparable decreases in their relevant mechanical properties, especially in impact strength [3]. In addition to crosslinking occurred by reaction between the curing agent and epoxy resin, some additional structural changes are observed in case of irradiation of epoxy-based system. The color of epoxy resin alters from transparent to yellow and resin can be even degraded depending on exposing dose and starting material used for manufacturing epoxy resin. Even so, epoxies are addressed as assuring matrix elements with high radiation stability for composite manufacturing [4]. In order to
limit brittle characteristics and develop mechanical performance of epoxy-based systems, epoxy resins should be reinforced with flexible materials.

High strength-to-weight ratio is one of the advantages of fiber-reinforced composites. By increasing interactions between fiber and epoxy matrix, the resistance of the whole composite to many destructive forces is improved. The improvement can be successfully achieved by the incorporation of elastomeric/thermoplastic phases or by adding organic/inorganic particles into epoxy resins [5–7]. Gojny et al. dispersed carbon-based nanoparticles in epoxy resins and reported that fracture toughness of produced composites effectively improved at low nanoparticle concentration as well as stiffness [8]. In another study, carbon-based nanoparticles lead to the development of flexural strength and modulus of the epoxy composite [9]. There are numerous researches about the use of inorganic and organic particles in reinforcement of epoxies and improvement of composite properties in different ways [10–20].

2. Polymers and fillers used for radiation shielding

Polymers have been intensively used for fabricating radiation shields due to their lightness, low cost, and elasticity [21, 22]. However, polymers behave differently when they are irradiated. Under different radiation sources with variable frequency rays, crosslinking, chain scission or degradation may be observed in a polymer chain [23]. The behaviors of some irradiated polymers and classifications according to their radiation resistance are given in Table 2.

In order to delay the degradation of polymeric structures and diminish the hazardous effect of radiation on polymers, fillers are added to the structure during manufacturing process. The radiation shielding efficiency of a filler depends on its atomic number and the atomic structure of filler is a crucial factor in order to fabricate functional structures from polymer and filler for intended end-use. Fillers with high atomic number are generally used for gamma radiation shielding (Table 3). However, the use of fillers with low atomic number is preferable for neutron radiation shielding. When considering that there are generally low atomic number elements in a polymer chain, compatibility of polymer/filler combination has a significant effect on radiation shielding efficiency of fabricated composite material [25]. Many researches have been performed on the use of polymers [26–30] and fillers [31–33] for the manufacturing of radiation shields.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g cm$^{-3}$)</td>
<td>1.2–1.3</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>55–130</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>2.75–4.10</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2–0.33</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>50–80</td>
</tr>
<tr>
<td>Cure shrinkage (%)</td>
<td>1–5</td>
</tr>
</tbody>
</table>

Table 1. Typical properties of epoxy resin at room temperature.
Epoxy-Based Composites

3. Filler loaded epoxy composites for radiation shielding

There are many attempts for improving the shielding characteristics of epoxy or other polymer matrix with elemental particles. The researchers observed effects of particle loading via numerous trials by means of minimizing particle size, doping matrix with different particle concentration in weight, exposing composite specimens

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic number</th>
<th>Density (g/cm³)</th>
<th>Absorption edge (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium (Cd)</td>
<td>48</td>
<td>8.65</td>
<td>26.7</td>
</tr>
<tr>
<td>Tin (Sn)</td>
<td>50</td>
<td>7.30</td>
<td>29.2</td>
</tr>
<tr>
<td>Antimony (Sb)</td>
<td>51</td>
<td>6.69</td>
<td>30.5</td>
</tr>
<tr>
<td>Cesium (Cs)</td>
<td>55</td>
<td>1.87</td>
<td>26.0</td>
</tr>
<tr>
<td>Barium (Ba)</td>
<td>56</td>
<td>3.50</td>
<td>37.4</td>
</tr>
<tr>
<td>Gadolinium (Gd)</td>
<td>64</td>
<td>7.90</td>
<td>50.2</td>
</tr>
<tr>
<td>Tungsten (W)</td>
<td>74</td>
<td>19.30</td>
<td>69.5</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>82</td>
<td>11.36</td>
<td>88.0</td>
</tr>
<tr>
<td>Bismuth (Bi)</td>
<td>83</td>
<td>9.75</td>
<td>90.5</td>
</tr>
</tbody>
</table>

Table 3. Comparison of some elements used in radiation shielding [34].
to different radiation sources, analyzing microstructural changes under different radiation doses, and testing failure mechanism of composites. Radiation shielding properties of epoxy-based composite panels were tested by Al-Sarray et al. Epoxy resin was loaded with different barite concentrations of 0–50 wt %, and the linear attenuation coefficient of fabricated composites was tested by Co$^{60}$ and Cs$^{137}$ radioactive sources. Radiation shielding efficiency improved with the increase in barite concentration [35]. Ergin et al. compared the effects of lead oxide and barium oxide on the radiation shielding performance of epoxy composites. They reported that gamma radiation performance handled by lead oxide/epoxy composites could be obtained by the addition of barium oxide but the weight percentage of barium oxide must be two times more than lead oxide addition. Besides, addition of barium oxide at 40 wt % in epoxy resin exhibited better radiation shielding performance than gadolinium oxide/epoxy composites, concrete, and steel [36]. Li et al. dispersed micro- and nano-gadolinium oxide particles into epoxy matrix and evaluated both mechanical properties and radiation shielding characteristics of fabricated composites. Gadolinium oxide addition enhanced shielding efficiency due to dominating photoelectric effect of the gadolinium element. Nano-gadolinium oxide/epoxy composites exhibited better X-ray and gamma shielding characteristics and had similar flexural strength but higher flexural modulus with those of micro-gadolinium oxide/epoxy composites [37]. More et al. determined radiation shielding parameters of metal chloride/epoxy composites. Doping epoxy resin with higher weight ratios of metal chloride lead to increase in attenuation parameters of epoxy composite and test results were comparable with those of pure lead metal [38].

Mechanical properties, structural characteristics, and gamma shielding efficiency of epoxy composites were reported by Alavian et al. Epoxy resin was doped with inorganic nanoparticles such as lead, zinc, zinc oxide, titanium, and titanium oxide. Increasing nanoparticle loading enhanced shielding efficiency. 25 wt% Pb/epoxy nanocomposites showed better shielding properties but low mechanical strength than those of their counterparts [39]. Degradation of epoxy composite by high-frequency rays was investigated by Saiyad et al. They fabricated three different composite materials by loading graphite, boron nitride, and lead into epoxy resin. They irradiated epoxy composites by Am-Be neutron sources. They reported that linear absorption coefficients of composites were strictly dependent on the dispersion of filler and the highest shielding performance was observed in graphite/epoxy composites [40]. Aldhuhaibat et al. examined gamma radiation shielding performance of pure epoxy resin and epoxy-based nanocomposites with aluminum oxide or ferrium oxide nanopowder at different concentrations of 10–15 wt %. Specimens were irradiated by Cs$^{137}$ (1.05 kBq with single gamma-ray emission energy of 0.662 MeV) and Co$^{60}$ (74 kBq with two gamma-ray emission energies of 1.173 and 1.333 MeV) radioactive sources and linear attenuation coefficients of specimens were measured by NaI detector. They claimed that epoxy nanocomposites were potential gamma radiation shields with improved characteristics [41]. Another study was performed by Azman et al. Nano-sized tungsten oxide/epoxy composites had higher attenuation properties at 22–35 kV X-ray tube voltages used in mammography and radiography units. The particle size of tungsten was found as negligible by means of transmitted beam intensity at 40–120 kV tube voltages [42]. Cheng et al. studied the radiation degradation mechanism of tungsten/epoxy composites. They tested composites specimens under different activities of Co$^{60}$ sources. Loading with tungsten improved shielding characteristic of composites. However, measurements showed that an increase in radiation dose caused a decrease, then a slight increase and a sharp decrease in thermal and mechanical properties of composites [43].
4. Modification of epoxy resin with fibers/fillers for radiation shielding

In recent years, studies performed on radiation shields have focused on developing failure mechanisms and decreasing the weight of shield for supplying personal comfort. For this goal, researchers offered dissimilar alternative shields by studying various polymeric matrices with different fillers. Kim observed the effect of particle size and dispersibility of tungsten particles on radiation shielding performance of samples. For this aim, three types of tungsten-loaded HDPE shields were manufactured with identical thickness and sizes by doping nanoparticles, microparticles, and their mixture. It was claimed that sufficient protection was handled against low dose exposure notwithstanding particle size. But nanoparticle loaded HDPE sheets were more resistant to high-energy radiation. The shielding sheets produced with a mixture of different particle sizes of tungsten showed similar shielding performance as microparticle tungsten-loaded sheets [44]. Manufacturing and radiation shielding properties of nano gadolinium oxide/PMMA composites were searched by Shreef and Abdulzahara. Composite shields were fabricated with varying concentrations of gadolinium oxide (10−40 wt%). The thickness of composites was measured and shielding performance was tested with Co$_{60}$ and Cs$_{137}$ radiation sources. Test results showed that increasing nanoparticle concentration lead to an increase in thickness and improvement in attenuation coefficient but a decrease in half-value layer values of epoxy composites [45]. Zheng et al. fabricated S-glass fabric/epoxy composites with a ratio of 1:1. Composites were irradiated by Co$_{60}$ source and the effects of irradiation on properties of composites were compared. They claimed that gamma-ray irradiation caused negligible damage on S-glass fiber and possible degradation on epoxy resin. By increasing the exposing dose of gamma radiation, the color of composite altered from yellow to brown and tensile strength of composite reduced gradually. However, composite preserved its thermal and dimensional stability and exhibited excellent thermal conductivity after irradiation [46]. Li et al. tried to produce a novel radiation shielding composite with high mechanical strength. For this aim, they fabricated erbium oxide-loaded basalt fiber/epoxy composites by prepreg autoclave process and test shielding performance of composites by exposing them to X and gamma rays. They claimed that basalt fiber/erbium oxide/epoxy composites had high mass attenuation coefficient than aluminum at low photon energies ranging from 31 keV to 80 keV [47]. The fracture toughness of carbon fabric/epoxy composites was investigated by Phong et al. They produced micro/nano-sized bamboo fibrils and dispersed these fibrils into epoxy matrix. They reported that matrix cracking was delayed, crack growing was reduced, and fracture toughness of composites was improved [48]. Haque et al. reinforced epoxy matrix with layered nano silicate particles at very low concentrations (1 wt%) and claimed that flexural strength, toughness, decomposition temperature, and interlaminar shear strength of S2-glass/epoxy composites were improved due to enhanced fiber/matrix adhesion and reduced residual stresses [49]. Recycled PET fibers were used to mimic marble material. Nguyen et al. modified calcium carbonate particles with stearic acid in order to enhance compatibility between epoxy resin and calcium carbonate. They fabricated composites by positioning a single layer of recycled PET fiber mat in the core and by coating the front and backside of PET mat with epoxy/calcium carbonate mixture. They concluded that flexural properties, impact resistance, and thermal stability of epoxy composites were improved [50]. Saleem et al. presented an empirical approach and compared radiation shielding of lead nanoparticles loaded epoxy composites with glass or carbon fiber. The results showed that lead nanoparticles improved shielding
characteristics and lead to an increase in mass attenuation coefficients of composites. Mass attenuation coefficients were 0.2145 cm$^2$/g and 0.2152 cm$^2$/g for carbon and glass fiber reinforced epoxy composites at lead nanoparticle concentration of 50 wt%. But half-value length of epoxy composite with glass fiber was reported as 1.431 cm, which was lower than epoxy composites with carbon fiber (1.756 cm) [51].

Effects of radiation on neat epoxy resin and carbon fiber/epoxy composites were studied by Hoffman and Skidmore (2009). Front and back surfaces of plain woven carbon fabrics were treated with epoxy/hardener mixture (2:1). Prepared composites were exposed to mechanical and thermal testing and also analyzed by means of microstructural properties and radiation characteristics. After being irradiated, there were no remarkable changes in mechanical resistance of composites but significant variations were observed in thermal properties, spectroscopic analysis, and hardness value of neat epoxy samples as a result of gamma radiation [52]. Zhong et al. examined the cosmic radiation shielding properties of hot-pressed UHMWPE/nano-epoxy composites and they concluded that epoxy composites with the combination of continuous fibers such as UHMWPE and/or graphite nanofibers found as multifunctional hybrid systems by means of good structural properties, cost-effectiveness, and high radiation shielding performance [53]. In another study, UHMWPE/epoxy composites were fabricated by Mani et al. and test results showed that composites containing gadolinium and boron nanoparticles had good neutron shielding performance [54]. Condruz et al. suggested coating carbon/epoxy composites with different types of functional materials such as tantalum foil, babbitt and Monel for protecting hazardous effects of proton radiation. They impregnated 2 × 2 twill woven carbon fabric into epoxy resin and then coated polymeric substrates with zinc, Babbitt or zinc/ Monel particles by thermal spray technique. They concluded that the coating process reduced penetration depth of ion beam and produced composites were lightweight shields for proton radiation [55]. The effects of hybridization on mechanical, thermal and radiation shielding efficiency of composites were also examined and reported by Zagaoui et al. They blended epoxy resin (90 wt%) with benzoxazine resin (10 wt%) and reinforced bicomponent matrix with silane-treated glass and basalt fibers. Hybridization of different types of resins developed mechanical and thermal properties and excellent shielding characteristic was gained by integrating hybrid fibers into bicomponent matrix system [56].

5. Conclusion

Heavy concretes, lead plates, and stainless steel blocks or plaques are known as conventional radiation shielding materials but they are heavy and not suitable for individual protective equipment. Polymers are functional lightweight materials but do not supply adequate protection on their own. Thereby advanced radiation shields should be fabricated by the composition of polymer-based materials and substances with high radiation shielding activity. At this point, material selection has crucial importance on the efficiency of protection by which radiation source it is irradiated. The destructive effect of radiation on the material is related to the type of radiation source, exposing dose rate, exposure period, radiation absorption rate of material and strength of interbonding forces between components if a composite material is used. By taking into consideration the advantages introduced with composite manufacturing, the destructive effect of radiation can be limited by a combination of materials with high attenuation rates. At this point, the shielding efficiency of
composite material depends on how components in a composite behave in case of irradiation. Epoxies, the mostly used matrix elements in composite manufacturing, exhibit physical changes such as color transition and low shrinkage percentage and mechanical changes such as a decrease in flexural and impact strength due to crosslinking when they are irradiated. Despite these changes, they are known as reliable materials for being used as matrix elements in radiation shielding. Undesired physical and mechanical changes observed in irradiated epoxies tried to be eliminated by fiber and/or filler loading for handling effective radiation shields with long life. Fiber addition into epoxy matrix causes an increase in hardness, fracture toughness, impact resistance, flexural strength and modulus, and also consistency in dimensional stability and thermal properties with respect to neat epoxy. However, loading fillers into epoxy matrix outputs composite material with inconsistent mechanical and thermal properties, especially in heterogenic filler dispersion and inappropriate particle size. Modification of epoxy with fillers having high radiation absorption rate develops radiation shielding efficiency of the whole composite but not mechanical or thermal characteristics for long-term use of composite. Thereby epoxy-based composites, which are designed to be used for radiation shields, should contain both fillers and fibers. Epoxy-based radiation shields serve as effective protectors in the case of reinforcing with fiber-based structures and fillers having high radiation absorption rate and photoelectric properties.

Fiber and filler reinforced epoxy composites are functional engineering materials and compete with some conventional radiation shields by means of strength and modulus properties per unit weight. The functionality is improved by proper fiber/matrix combination, high interfacial bonding between these constituents, functional additive/filler loading, modification of fiber surface with an appropriate sizing agent, well-dispersed nano-sized filler addition, and suitable manufacturing technique. In this way, epoxy composite serves as a unique shielding material for which goal it is fabricated and in which field it is intended to be used. Moreover, there is a need to figure out the best alternative to be used in medical diagnostics and nuclear industry.

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References


[33] Engelmann HJ. Material for shielding from radiation; 2009. WO2009097833A1
Epoxy Composites for Radiation Shielding
DOI: http://dx.doi.org/10.5772/intechopen.104117


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erbium oxide. Composites Science and Technology. 2017;143:67-74


