Chapter 11
Summary and Concluding Remarks

Abstract The use of viable processing methodologies for designing new materials with advanced nanotechnology to enhance radiation shielding purposes in order to meet the safety requirements for use in medical X-ray imaging facilities has been achieved. However, very limited or little information is still available in this emerging research field. This leaves a wide scope for future investigators to make further advances in new materials design and processing.

11.1 Summary

11.1.1 Filler Dispersion Within Epoxy Resins by Melt-Mixing Method

- Epoxy composites filled with dispersed lead oxide (PbO and Pb_3O_4) particles of 1–5 μm for composites with filler loading of ≤30 wt% and 5–15 μm for composites with filler loading of ≥50 wt% have been successfully fabricated. The phase composition analyses proved that lead oxides used in this study were single-phase pure without impurity. Meanwhile, the microstructure analyses from OM and SEM illustrated that the fractured surfaces were quite rough, and the fillers (lead oxides) were well dispersed and firmly embedded in the epoxy matrix due to their relatively small particle size and good compatibility with the epoxy matrix. The attenuation ability of the lead oxide-epoxy composites was dependable on the filler loading and composite density. They showed good X-ray attenuation properties and could be considered as a potential candidate for radiation shielding in diagnostic radiology purposes. In addition, the lead oxide-epoxy composites in this study are superior to the lead oxide-isophthalate resin composite previously investigated by other researchers since with the same wt% of lead oxide; lead oxides-epoxy composite provides better attenuation on the Gamma-rays of energy 0.662 MeV emitted from Cs-137 point source than lead oxide-isophthalate. Hence, the usage of lead oxides can be minimal in the fabrication of lead oxide-epoxy composites to provide similar attenuation ability with the lead oxide-isophthalate, and thus reduce the health risks associated with lead oxides.

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- Epoxy composites filled with fairly dispersed $PbCl_2$, Bi_2O_3 or WO_3 have been successfully fabricated. Their attenuation ability was dependable on the filler loading and composite density. They also provide good X-ray shielding ability, and hence can be considered as candidate materials for X-ray shielding of radiological rooms. The 8 mm thick Bi_2O_3-epoxy composite with 70 wt% Bi_2O_3 is comparable to a 10 mm thick commercial lead glass which contains 56 wt% Pb while the 8 mm thick of 70 wt% $PbCl_2$- or WO_3-epoxy composites were not comparable with the lead glass unless they were prepared with a thickness greater than 10 mm. Both flexural modulus and hardness of composites increased with increasing filler loading, but the flexural strength decreased markedly when the filler loading was equal to or greater than 30 wt%.
- Epoxy composites filled with the dispersed WO_3 showed that for the same WO_3 loading, nano-sized WO_3-epoxy composite has better attenuation ability to attenuate the X-ray beams generated by lower tube voltages (25–35 kV) operated by mammography unit when compared to the micro-sized WO_3-epoxy composite. As the machine's tube voltage selected is greater than 40–49 kV, they attenuate similar amount of X-ray beams or in other word, the attenuation ability of the nano-sized and micro-sized WO_3 reinforced epoxy is indistinguishable. Meanwhile, the role of particle size in X-ray shielding was also insignificant at all tube voltage ranges (40–120 kV) for radiography unit.
- Epoxy composites filled with the dispersed WO_3 of different wt% showed that the size-effect on X-ray attenuation was profoundly dependent on the energy of synchrotron radiations. The particle size-effect was more obvious at lower synchrotron radiation energies (10–20 keV) since X-ray transmission in nano-sized WO_3-epoxy composite was less than their micro-sized counterparts. In contrast, this size-effect became insignificant at higher energies between 20 and 40 keV because the X-ray transmissions in both nano-sized and micro-sized WO_3-epoxy composites were very similar. The equivalent energy for mammography unit (25–49 kV) tube voltages are in the range of synchrotron radiation energies of 15–25 keV. Similarly, for radiography unit, the X-ray tube voltages 40–60 kV are equivalent to 25–40 keV energies. As the composite of the same WO_3 loading thickness increased, the size-effect on the X-ray attenuation tested with mammography and radiography unit was showing similar results as in (iii). Meanwhile, the effect of WO_3 loading on the mechanical properties showed an initial optimum improvement but further increase in the filler loading caused these properties to deteriorate.

11.1.2 Filler Dispersion Within Epoxy, Acrylic and Glass by Ion-Implantation Method

- Epoxy samples implanted with W, Au and Pb at various concentrations showed that the threshold of implanted ions above which the mass attenuation coefficient, μ_m of the ion-implanted epoxy composite is distinguishably higher than the μ_m of the pure epoxy is different for different ion types. The practical concentrations of W, Au and Pb in epoxy composite which could provide good X-ray attenuation properties and could be considered as candidates for effective X-ray shielding in diagnostic radiology by increasing the ion concentration than the one used in this work.
- Acrylic and glass implanted with W and Pb ions showed higher X-ray attenuation for the composite with the denser sample matrix and the composite having the higher RBS ion concentration. However, the number of implanted doses should be significantly increased so that this approach can be feasible for designing new shielding materials for the X-ray technologists. Even though glass provided the best results for both RBS ion concentration and X-ray attenuation, its usage as X-ray shielding needs extra care since it is easy to break. In contrast, implanted acrylic can be a good candidate for X-ray shielding but much time is needed when implanted acrylic with a very high nominal dose since it has a low melting point.

11.1.3 Filler Dispersion Within PLA Nanofibre Mats by Electrospinning Method

- PLA nanofibre mats dispersed with n-Bi_2O_3 and m-Bi_2O_3 showed that the electrospun n-Bi_2O_3/PLA nanofibre mats of all filler loadings (24–38 wt%) were found to be superior in attenuating X-rays compared to their micro-sized counterparts because the usage of n-Bi_2O_3 provides the fabrication of more uniform materials since the particle size can affect the microstructure and consequently the density and composition that will then modify the attenuation coefficient of the composite. However, the electrospun Bi_2O_3/PLA nanofibre mats with 38 wt% loading are not recommended for X-ray shielding because of higher porosity compared with the lower filler loadings. Meanwhile, the n-Bi_2O_3/PLA thin films are good X-ray shielding candidates only for the mammography unit at tube voltages of 22–35 kV when compared to the m-Bi_2O_3/PLA thin films. The particle size effect on X-ray attenuation diminished as the X-ray tube voltage exceeded 35 kV.

11.1.4 Effect of Starch Addition into PVA Composites

Starch offered better particle size effect for X-ray shielding ability than its micro-sized counterpart when being added into the Bi_2O_3–PVA composites. In addition, starch has improving the dispersion of nano-sized Bi_2O_3 particles within PVA matrix and also has helped to reduce the dependence of Bi_2O_3 particle size effect toward the density of PVA matrix.

11.2 Concluding Remarks

The use of viable processing methodologies for designing new materials with advanced nanotechnology to enhance radiation shielding purposes in order to meet the safety requirements for use in medical X-ray imaging facilities has been achieved. However, very limited or little information is still available in this emerging research field. This leaves a wide scope for future investigators to make further advances in new materials design and processing. Thus, some recommendations for further research are as follows:

1. Since the relationship between the mass attenuation coefficient and particle size of lead oxide remains unknown as mentioned in Chap. 3, further study should be done to reveal their relationship since lead oxide was the familiar compound used as radiation shielding in the past.
2. The dispersion of the nano-fillers by melt-mixing method was fairly homogeneous with some particle agglomerations with the use of only high-speed mixture. However, to get perfect dispersion for nano-fillers in polymer matrices are still challenging. Therefore, different ways of mixing as well as curing is required to be investigated deeply to improve the nano-filler dispersion by melt-mixing method.
3. Deeper testing of the physical and mechanical properties of the composites should be considered so that the composites are able to practically use as an X-ray shielding for long periods of time.
4. The practical concentrations of W, Au and Pb ions implanted into an epoxy, acrylic or glass composite should be increased higher than the concentrations used in order to provide good X-ray attenuation properties and could be considered as candidates for effective X-ray shielding in diagnostic radiology.
5. Since Bi has a greater atomic number, classified as non-hazardous and is also a relatively environmentally friendly compound compared to toxic Pb, the implantation of Bi ions into the epoxy, acrylic or glass should be considered to provide good X-ray attenuation properties and could be considered as candidates for effective X-ray shielding in diagnostic radiology.
6. Deeper investigations should be considered to characterize the implanted composites. However, the higher implanted ion concentrations are required so that the characterization analyses on the composites could be succeeded.
7. The fabrication of nanofiller-nanofiber polymer by electrospinning should be tested with different filler and polymer types that are also good candidates for attenuating X-rays.

8. Further investigations on the physical and mechanical properties of the electrospun nanofiller/nanofibre PLA should be considered for X-ray shielding practical purposes.
9. More studies on the effect of starch addition into polymer matrix should be done in order to support the preliminary results of starch helping in improvement of the dispersion of nano-sized particle within polymer matrix.