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Simulation of radiation attenuation in polymer matrix composite with epoxy resin, reinforced with carbon fiber and dispersion of bismuth oxide (Bi_2O_3) nanoparticles

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Abstract: The aim of this study was to simulate gamma radiation attenuation using a polymer matrix composite of an epoxy (DGEBA) resin that was reinforced with carbon fiber cloth fabric and then dispersed with bismuth (III) oxide (Bi_2O_3) nanoparticles. The quantitative methodology was used for this simulation with the software Topas MC (version 3.7). The mass ratios of the bismuth (III) oxide nanoparticles in the composite were approximately 0.163, 0.244, 0.325 and 0.407. The photon energy in the simulation was 100 keV, typical X-ray energy in Medical Imaging (Diagnostic Radiography). The mass ratio of 0.407 and the polymer matrix composite at a thickness of 2.29 mm provided 89.03% attenuation of the photon energy. However, for the lead plate, a thickness of 0.34 mm was necessary for similar attenuation. Nonetheless, the fabrication process of a composite plate is easier than that of a lead plate. In conclusion, a composite of an epoxy polymer matrix, with bismuth (III) oxide dispersion, reinforced with carbon fiber, is an excellent option as compared to a lead plate. The composite plate can attenuate photon energy and does not present an acute or chronic danger to the environment or to health. Also, it is non-carcinogenic, and does not cause reproductive toxicity, both clear advantages over lead. Finally, it should be noted that other applications of the composite would be production of an X-ray shield and aerospace industries, among others.

1. Introduction

Currently, there has been growing interest in the use of bismuth and bismuth oxide for radiation protection applications, due to their unique properties, such as non-toxicity and high density. Radiation shielding materials incorporating Bi_2O_3 have been introduced to provide equivalent or greater attenuation compared to commercial lead-based or lead-free materials (e.g. $BaTiO_3$, Bi_2O_3, Br_2, $CaWO_4$, among others). Recently, polymers loaded with powdered metallic compounds, such as Bi_2O_3, Gd_2O_3, $BaSO_4$, among others, have been developed to take advantage of their potentially useful attenuating capabilities [1], [2], [3], [4].

However, research that considers the mechanical properties of the composite and the radiation attenuation of bismuth trioxide are needed, but before of make a laminate it is better execute a simulation about radiation attenuation of the composite with a dispersion with Bi_2O_3.

This study shows the results of simulation of radiation attenuation of the dispersion of the Bi_2O_3 in a composite with epoxy polymeric matrix, reinforced with carbon fiber.

2. Methodology

For the simulation, the software Topas MC (version 3.7) [5] was used. It is a free distribution software, updated and user-friendly, which is based on the Monte Carlo method for simulating the interaction of radiation with matter [6]. There are several software that use the Monte Carlo methodology to simulate the interaction of radiation with material: ETRAN [7], ITS [8], EGS4 [9], PENELOPE [10], GEANT4 [11], MCNP6 [12], Topas [5], among others. Since all the mentioned software have the simulation results close to the results observed in practice, when photons are simulated.

For the simulation, a laminated plate measuring 100x100 mm was used, and the thickness of the laminate was 2.5, 5.0, 7.5 and 10 mm and such measurements were reproduced in practice and were determined due to the delimitation of the X-ray generator equipment [13].

The laminate of polymer matrix has 0.2 mm of carbon fiber. To finalize the thickness of the polymer matrix, epoxy resin is added with the dispersion of Bi_2O_3 to complete the total thickness of 2.5, 5.0, 7.5 and 10 mm. This separation between the polymeric matrix with dispersion and reinforcement is a simplification so that the simulation can be performed, since, in practice, the carbon fiber and the polymeric matrix interact in a microscopic way.

To perform the simulation of radiation attenuation, provided by the composite object of this research study, the percentage of each chemical element present in such material must be calculated, such percentages are presented in the following paragraphs.

Furthermore, it is known that the average molar mass of the cross-linked epoxy resin is approximately equal to 115594 $g.mol^{-1}$ [14]. That is, 24 chemical structures of epoxy resin bond with 4 chemical structures of amines thus forming the epoxy polymer matrix. This provides the following percentages: carbon 65.78%; oxygen 17.48%; Hydrogen 7.10% and nitrogen 0.14% [14], [15], [16]. Considering the dispersion percentages of bismuth trioxide (Bi_2O_3), object of this study and the composition for the production of the laminate, the percentages presented in Table can be concluded.

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Table 1. Mass composition of the chemical elements of the composite with a polymer matrix of epoxy resin with dispersion of bismuth trioxide (Bi_2O_3) particles, reinforced with carbon fiber fabric (estimate).

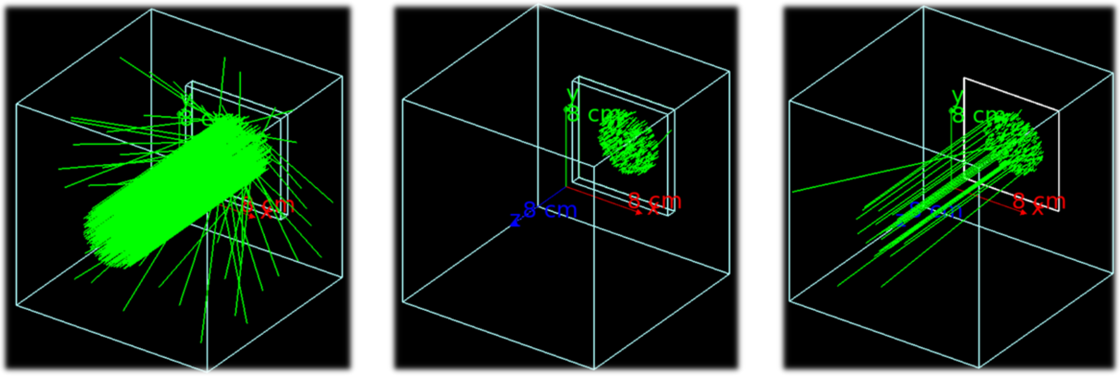
Identification		Carbon (%)	Oxygen (%)	Hydrogen (%)	Nitrogen (%)	Silicic (%)	Bismuth (%)	Specific mass ($g.cm^{-3}$)
A (Ep/FC)		73.40	18.37	6.92	0.14	1.17		1.21
$Ep/FC/Bi_2O_3$	B1	58.72	18.43	5.54	0.11	0.94	16.26	2.61
	B2	51.42	18.44	4.85	0.10	0.79	24.40	3.30
	B3	44.04	18.49	4.15	0.08	0.70	32.53	4.00
	B4	36.74	18.51	3.46	0.07	0.56	40.66	4.70

In Table , it can be seen that the formulation B4 with 40% by mass of Bi_2O_3 dispersion can increase by 288%, approximately, the specific mass of the composite without such dispersion. However, such specific mass still shows approximately 58.6% smaller in relation to lead (11.34 $g.cm^{-3}$). It is of the metals widely used for radiological protection for photons.

For the simulation, a gamma radiation source was used. The energy of such photons ranged from 50 to 125 keV. The radiation source is a circle of radius 30 mm. For the simulation of the gamma rays generation, a Gaussian distribution was used and 500 histories were generated for that simulation.

The photon energy detection occurred on the 2 largest surfaces of the laminate. The energy of the incident photons was detected on the surface closest to the radiation source, and on the surface furthest from the source. The energy of the photons that had already interacted was detected with the polymer composite.

3. Results and Discussions



(a) (b) (c)

Fig. 1. Comparison between the attenuation, result of computer simulation, of a 10 mm thick epoxy composite reinforced with carbon fiber without (a) and with Bi_2O_3 dispersion (b), and 0.5 mm thick lead plate (c), all with photons energy of 100 keV.

The Fig. shows a comparison between the attenuation, result of computer simulation, of a 10 mm thick plate of the composite object of this research study without dispersion of Bi_2O_3 (Fig. (a)); with dispersion of such oxide with a mass fraction of 40% (Fig. (b)) and with a lead plate of 0.5 mm of thickness, customarily used in Personal Protective Equipment – PPE, that use such metal (Fig. (c)), all with photons of 100 keV energy.

The green lines shown in Fig. , represent the photon trajectory with 100 keV energy. It can be seen that the composite plate with Bi_2O_3 dispersion practically attenuates the photons, being more efficient than the lead plate.

An estimative of tenth value layers (TVL) and specific mass, is show in Fig. . The horizontal axis is the mass bismuth ration, and vertical left axis is the TVL and right is the specific mass.

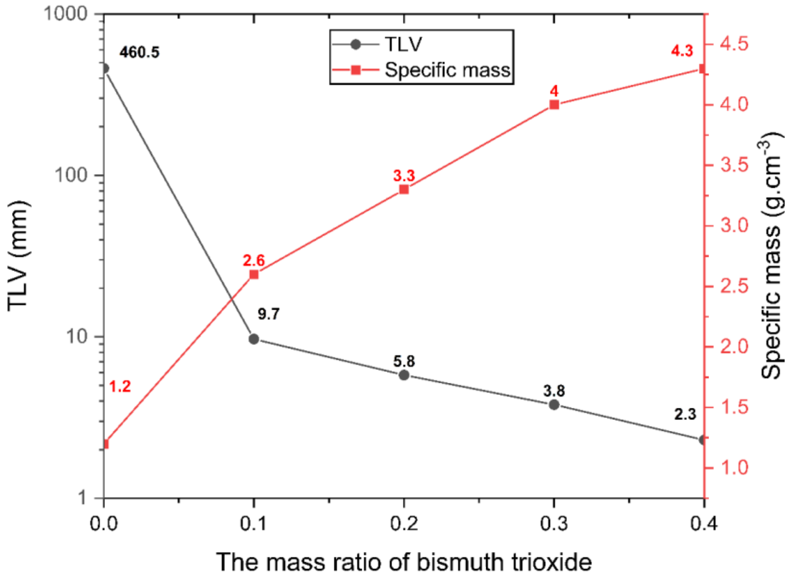


Fig. 2. Tenth value layers (TVL) and specific mass of composite epoxy with Bi_2O_3 dispersion and fiber plate in function of mass bismuth ration.

The mass ratios of the bismuth (III) oxide nanoparticles in the composite were approximately 0.163, 0.244, 0.325 and 0.407. The photon energy in the simulation was 100 keV, typical X-ray energy in Medical Imaging (Diagnostic Radiography). The mass ratio of 0.407 and the polymer matrix composite at a thickness of 2.29 mm provided 89.03% attenuation of the photon energy. However, for the lead plate, a thickness of 0.34 mm was necessary for similar attenuation.

The epoxy polymer composite with Bi_2O_3 dispersion and carbon fiber fabric, can be used as radiological protection for photons, such as X-rays, and such composite proves to be commercially attractive when compared to the lead (specific mass 11.34 $g.cm^{-3}$), metal customarily used for such radiological protection.

4. Conclusions

The composite of an epoxy polymer matrix, with bismuth (III) oxide dispersion, reinforced with carbon fiber, is an excellent option as compared to a lead plate. The composite plate could attenuate photon energy and does not present an acute or chronic danger to the environment or to health. Also, it is non-carcinogenic, and does not cause reproductive toxicity, both clear advantages over lead. Therefore, the applications of the composite could be in the production of an X-ray shield and aerospace industries, among others.

The mass ratio of 0.407 (Bi_2O_3 nanoparticles) and the epoxy composite at a thickness of 2.29 mm provided 89.03% attenuation of the photon energy (100 keV). So, the production of a polymer composite with an epoxy matrix and bismuth (III) oxide dispersion, reinforced with carbon fiber fabric is an innovation. In addition to the simulation, it is necessary to reproduce such a simulation in practice.

Credit author statement

Pedro Marcio Munhoz: Conceptualisation; Methodology; Formal Analysis; Writing – original draft. **Fernando Codelo Nascimento:** Resources; Writing – review. **Leonardo G. A. Silva:** Resources; Writing – review. **Bruno Caravelas Gary:** Resources; Writing – review. **Wilson Aparecido Parejo Calvo:** Resources; Supervision; Writing – review.

Declaration of Competing Interest

The authors declare no conflict of interest.

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