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Investigation of radiation attenuation properties of Al-Cu matrix composites reinforced by different amount of B_4C particles

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ABSTRACT

In recent years, B_4C particle reinforced Al matrix composite materials have been excessively used for gamma and neutron shielding regarding their neutron absorption and lightweight. In this paper, linear and mass attenuation coefficients using 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV,1332 keV) and 2000 keV(high energy) gamma energies for B_4C (5-15 wt%) particle-reinforced Alumix 13 and Alumix 231 (which contains special alloy elements such as Cu and Mg) aluminum matrix composites were theoretically calculated with XCOM platform. Pair production, coherent scattering, photoelectric absorption and incoherent scattering processes besides the total attenuation coefficients for B_4C (5-15 wt%) particle-reinforced Alumix 13 and Alumix 231 matrix composite materials were evaluated separately. On the other hand, half-value thickness (HVL) values and one-tenth thickness values (TVL) were also calculated to evaluate the radiation shielding effectiveness of this material excluding coherent scattering values that are frequently used in gamma ray transport theory as well as the total attenuation coefficients. Gamma attenuation curves for Al composite materials against 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) gamma energies were theoretically calculated and plotted for B_4C (5-15 wt%) particle-reinforced Alumix 13 and Alumix 231 matrix composite materials. According to the obtained results for this material, radiation attenuation properties and the ability of shielding of materials were investigated. Therefore, this study is original from a variety of aspects, and its results may be used not only in nuclear technology but also in other technologies such as nano and space technology.

1. Introduction

People are consistently exposed to background radiation from cosmic rays and the sun in the atmosphere, inherently happening radioactive materials within earth, houses, food and their bodies. Therefore life and radiation are not separable and radiation is important in our daily life. Radiation could be described as non-ionizing and ionizing regarding its energy. Ionizing radiation described with alpha particles, X and gamma rays, beta particles have high energy and ionize atoms of the interacting matter. When a gamma ray interacts with the matter, there are main processes as photoelectric absorption, pair production and Compton scattering which take place. Therefore radiological measurements and radiation protection are significant nuclear studies specifically for accelerators, nuclear power plants, detector manufacturers and other widespread use of radioactive isotopes in many fields [1-4]. The shielding, which is implemented naturally or is composited materially, is widely and effectively used for protection from hazards of radiation. Recently, Novel multifunctional composite materials have been studied to improve gamma ray shielding materials. A lot of studies were about composite materials by using filler metal oxides or metal materials and various matrix to merge distinct characteristics of these materials on composite radiation shielding [5]. As result, these radiation shielding materials were frequently significant to defend life and other materials from the degrading effect of these harmful radiations emitted from unshielded radioactive sources. These materials decrease the danger dosage by interacting with radiation itself and reducing radiation energy. High-density materials such

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as metal, concrete, metal alloys, lead bricks and multilayers of single slabs of pure elements (Pb, Al, Cu, Fe) are used for this aim [6]. The amount and type of shielding required depends upon the activity of radiation, type of radiation, the dose rate and source that is satisfactory for the outside shielding material. Good shielding material should induce a major energy loss in a short penetration length emission of more dangerous radiation. Moreover, these materials must have a great absorption cross-section for radiation and effects on their mechanical and optical properties of irradiation may be small. The radiation shielding for any material can be determined in terms of linear attenuation coefficients μ (cm^{-1}). It is one of the significant characteristics that needs to be studied and determined prior to using a material in radiation applications. Since the accurate attenuation coefficient values of materials are very necessary parameters in radiation dosimetry, nuclear and radiation physics, spectrometry, medicine, environment and industry, biology and agriculture [5]. It qualifies the diffusion and penetration of gamma radiation in the matter and represents the probability per unit path-length of gamma radiation that gamma ray will have in interaction with absorber atom. It is the basic parameter to acquire several other parameters related to dosimetry and shielding, such as effective atomic numbers, mass energy absorption coefficient, electron densities, atomic, electronic and molecular cross-sections, tenth-value and half-value layer thickness for shielding effectiveness [7-9].

Aluminum composites are important materials for several engineering applications such as armor, nuclear power plants, marine components, aerospace parts and automobile parts owing to high strength-to-weight ratio and their excellent low-temperature properties [10]. Aluminum (Al) based matrix composite materials are being considered as a type of innovative advanced materials for high specific modulus, its lightweight, and good wear resistance properties. Aluminum oxide (Al_2O_3), boron carbide (B_4C) and silicon carbide (SiC) particles are enormously hard reinforcement elements with superb mechanical properties; they are extensively used in Al-based matrix composites as reinforcement materials [11]. Today, various shielding materials manufactured by adding boron and boron compounds added to distinct materials have been investigated in various studies [12,13]. Boron carbide (B_4C) particle reinforced Al matrix composites have excellent structural performance such as stiffness and high strength, low density, erosion resistance and good wear [14,15]. By using certain additives, it is more suitable for production or manufacturing.

In the pre-alloyed Al-Cu alloys, specifically Al-Cu-Si-Mg alloys have lately attracted the attention of scientists because of their advantageous specific features in composite production. In this study, pre-alloyed Al-Cu alloy powder, with a commercial brand of Alumix 13 and 231 and the nominal composition of Al-4.5Cu-0.5Mg-0.1Si (wt%) and Al-14Si-2.5Cu-0.5 Mg (wt%) respectively, were preferred as matrix material in the design of the composite sample. Boron carbide was chosen as a reinforcement particle. Aluminum reinforced with B_4C composite materials is used neutron and gamma application owing to its ability to absorb gamma and neutron. In this way, increase in the quantity of B_4C in these composites not only increase the strength of aluminum reinforced particles with B_4C composite increases the absorption of gamma rays and neutrons [16].

In this work, gamma attenuation behaviors by using 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) gamma energies for B_4C (5-15 wt%) particle-reinforced Alumix 13 and Alumix 231 matrix composites were theoretically evaluated with XCOM program. The mass and linear attenuation coefficients, tenth-value (TVL) and half-value layers (HVL) of these matrix composites were calculated. All the calculated values from XCOM computer code for these composite materials were compared with each other.

2. Materials and metods

2.1. Materials

Commercial pre-alloyed Alumix 231 and Alumix 13 powder and reinforced B_4C (5-10-15 wt%) powder were used as the starting material for theoretically calculation of Al matrix composites. The physical properties and chemical compositions of these matrix materials and reinforced particle are shown in Table 1 and Table 2, respectively.

The size distribution of these powders was measured using Malvern Master Sizer-E (a laser light scattering machine) and the particle size distribution graphic are given in Figure 1, 2 and 3. Alumix 231 powder with an average size of about 22 µm at $D_{10,}$ ~75 µm at D_{50}, and ~190 µm at D_{90} and Alumix 13 powder with an average size of about ~26 µm at D_{10}, ~91 µm at D_{50}, and ~206 µm at D_{90} were produced by inert gas atomization. B_4C, which has an average size of about ~4.60 µm at D_{50}, ~2.65 µm at D_{10}, and ~8.25 µm at D_{90}, was used as reinforcement particles. Theoretical densities of composites were calculated according to the rule of mixture. Alumix 231 reinforced B_4C (5 wt%) with 2,66 g/cm^3 (density), Alumix 231 reinforced B_4C (10 wt%) with 2,65 g/cm^3 (density), Alumix 231 reinforced B_4C (15 wt%) with 2,64 g/cm^3 (density), Alumix 13 reinforced B_4C (5 wt%) with 2,76 g/cm^3 (density), Alumix 13 reinforced B_4C (10 wt%) with 2,75 g/cm^3 (density), Alumix 13 reinforced B_4C (15 wt%) with 2,74 g/cm^3 (density) composites materials are defined as A1, A2, A3, B1, B2 and B3, respectively.

Table 1. Physical properties for Ecka Granules Alumix 13 and Ecka Granules Alumix 231 samples.

Material	Density (g/cm^3)	Melting point (°C)
Alumix 231	2.67	577
Alumix 13	2.78	610
B_4C	2.52	2450

Table 2. The chemical compositions for Ecka Granules Alumix 13 and Ecka Granules Alumix 231 samples.

	Alumix 13 (wt%)	Alumix 231 (wt%)
Mg	0.40 – 0.60	0.50 – 0.80
Cu	4.2 – 4.8	2.4 – 2.8
Si	0.05 – 0.25	14 - 16
Al	Balance	Balance

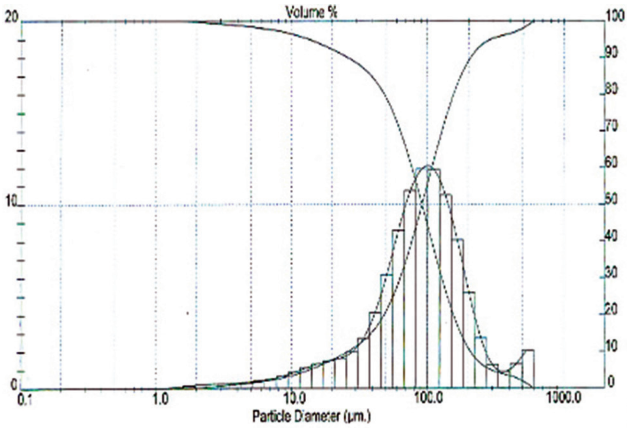

Figure 1. Particle size distribution plot for Alumix 13 powder.

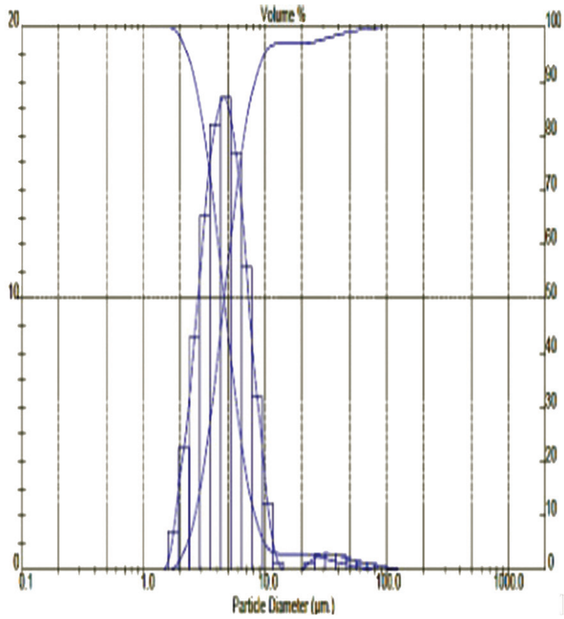

Figure 3. Particle size distribution plot for B_4C powder.

2.2. Methods

According to Lamber–Beer law, gamma rays collimated into a narrow beam are decreased through a shield

$$I = I_0 e^{-\mu x} \quad (1)$$

Where I, I_0, μ and x are the transmitted intensities, incidents intensities, the linear attenuation coefficient and the thickness of shielding material, respectively.

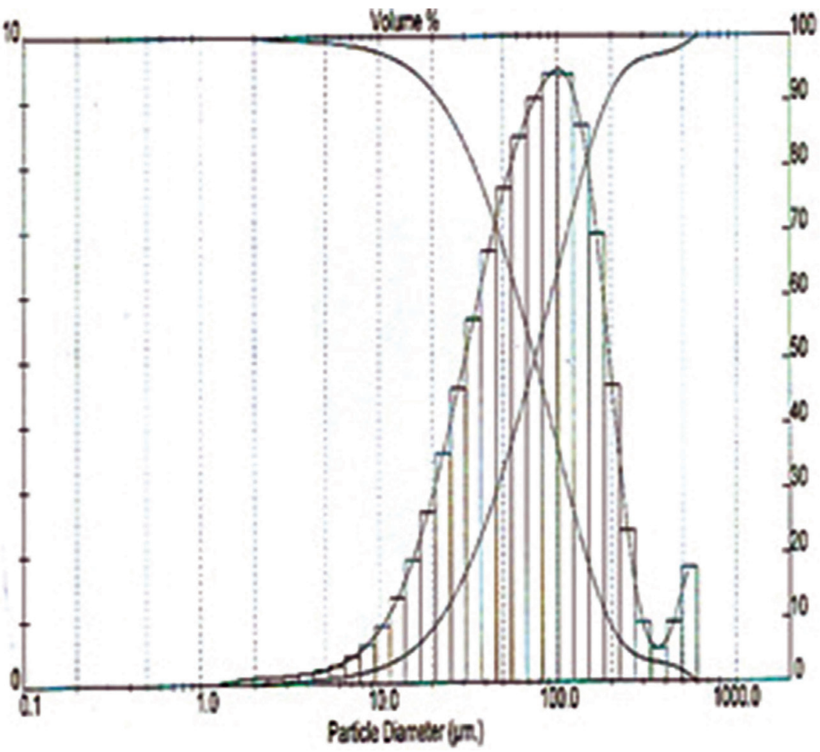

Figure 2. Particle size distribution plot for Alumix 231 powder.

The absorber density depending on the physical state of the material is proportional to linear attenuation coefficients. But it is habitual to use the mass attenuation coefficient removing density dependence. Thus, mass attenuation coefficient (μ_m (cm^2/gr)) is more useful than linear attenuation coefficient and it is defined as

$$\mu_m = \frac{\mu}{\rho} \qquad (2)$$

Where ρ is the sample density [17]. It was attained thanks to a proportional relationship with the total photon interaction cross-section per atom σ , the latter value being computed from theoretical models of interaction processes of gamma rays with matter for each element.

$\frac{\mu}{\rho}$ (Total mass attenuation coefficients) is defined as

$$\frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \qquad (3)$$

Where $(\mu/\rho)_i$ and w_i are the mass attenuation coefficient of the constituent element (i) and weight fraction, respectively. μ/ρ was computed by using XCOM program code. This program calculates attenuation coefficients and cross-sections for compound, any element or mixture, from 1 keV to 100 GeV energies [18,19].

The half value (HVL) and the tenth value layers (TVL) of shielding materials are necessary to determine the strength of gamma rays shielding. HVL and TVL are thicknesses of sample that will decrease the intensity of primary photon beam in order of half and tenth. These values can be computed as [17]

$$HVL = \frac{\ln 2}{\mu} \qquad (4)$$

$$TVL = \frac{\ln 10}{\mu} \qquad (5)$$

Linear attenuation coefficients, mass attenuation coefficient, HVL and TVL of A1, A2, A3, B1, B2 and B3 composite materials with 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) energies as a function of the weight fraction of B_4C are computed by using XCOM program code.

The program provides total cross-sections and attenuation coefficients as well as partial cross-sections for the following processes: coherent scattering, incoherent scattering, pair production and photoelectric absorption in the field of the atomic nucleus and in the field of the atomic electrons. For compounds, the quantities tabulated are total and partial mass interaction coefficients, which are equal to the product of the corresponding cross-sections times the number of target molecules per unit mass of the material [17].

3. Result and discussion

As seen Table 3, μ/ρ decreases with increasing of weight fraction of B_4C compound in A and B composite materials with an increase in energy (80 keV, 356 keV, ^{137}Cs (662keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy)).

The interaction cross-sections increase with the decrease in the gamma rays energies. As seen Figure 4 and Figure 5, in most absorbing materials, the cross-sections of photoelectric interactions are sufficiently high, energies lower than 500 keV while cross-sections of Compton scattering are important from 100 keV to 10 MeV energies and pair-production process becomes dominant above 2 MeV energies [20,21]. The incident gamma photons which interact are completely absorbed only in photoelectric-absorption and as many photons are straight away removed from the incident flux. Where photons are not completely absorbed, it is not the case in pair-production and Compton scattering, [20,21].

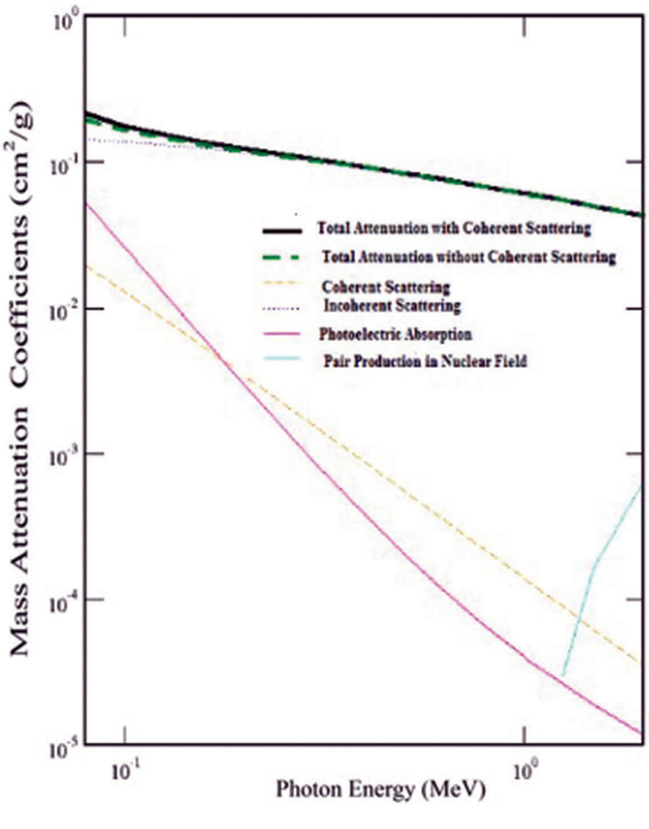

Figure 4. Photon interaction mechanisms of B3 at 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) energies from XCOM results.

Table 3. The linear attenuation coefficients, the mass attenuation coefficients, HVL and TVL of A1, A2, A3, B1, B2 and B3 composite materials at different gamma ray energies.

Energy (keV)		A1	A2	A3	B1	B2	B3
80	Linear attenuation coefficients(cm^{-1})x10^{-1}	5.173	5.088	5.000	5.572	5.472	5.373
	Mass attenuation coefficients (cm^2/g)x10^{-1}	1.945	1.920	1.894	2.019	1.990	1.961
	HVL (cm)	1.339	1.362	1.386	1.243	1.266	1.290
	TVL (cm)	4.541	4.525	4.605	4.132	4.207	4.285
356	Linear attenuation coefficients (cm^{-1})x10^{-1}	2.567	2.554	2.541	2.265	2.639	2.626
	Mass attenuation coefficients (cm^2/g)x10^{-2}	9.653	9.639	9.625	9.609	9.598	9.586
	HVL (cm)	2.700	2.713	2.827	2.613	2.626	2.639
	TVL (cm)	8.969	9.015	9.061	8.682	8.725	8.768
662	Linear attenuation coefficients (cm^{-1})x10^{-1}	1.982	1.972	1.962	2.045	2.036	2.026
	Mass attenuation coefficients (cm^2/g)x10^{-2}	7.453	7.443	7.432	7.413	7.405	7.397
	HVL (cm)	3.496	3.514	3.532	3.387	3.403	3.419
	TVL (cm)	11.614	11.674	11.735	11.254	11.307	11.360
1173	Linear attenuation coefficients (cm^{-1})x10^{-1}	1.510	1.503	1.495	1.558	1.551	1.544
	Mass attenuation coefficients (cm^2/g)x10^{-2}	5.679	5.672	5.664	5.648	5.642	5.636
	HVL (cm)	4.588	4.611	4.635	4.446	4.467	4.488
	TVL (cm)	15.242	15.319	15.390	14.771	14.840	14.910
1332	Linear attenuation coefficients (cm^{-1})x10^{-1}	1.416	1.409	1.402	1.461	1.455	1.448
	Mass attenuation coefficients (cm^2/g)x10^{-2}	5.326	5.318	5.311	5.297	5.291	5.285
	HVL (cm)	4.895	4.919	4.943	4.744	4.763	4.786
	TVL (cm)	16.261	16.341	16.423	15.760	15.825	15.901
2000	Linear attenuation coefficients (cm^{-1})x10^{-1}	1.152	1.145	1.139	1.189	1.153	1.176
	Mass attenuation coefficients (cm^2/g)x10^{-2}	4.331	4.323	4.315	4.308	4.302	4.295
	HVL (cm)	6.016	6,050	6.024	5.840	5.858	5.889
	TVL (cm)	19.986	20.099	20.213	19.365	19.468	19.565

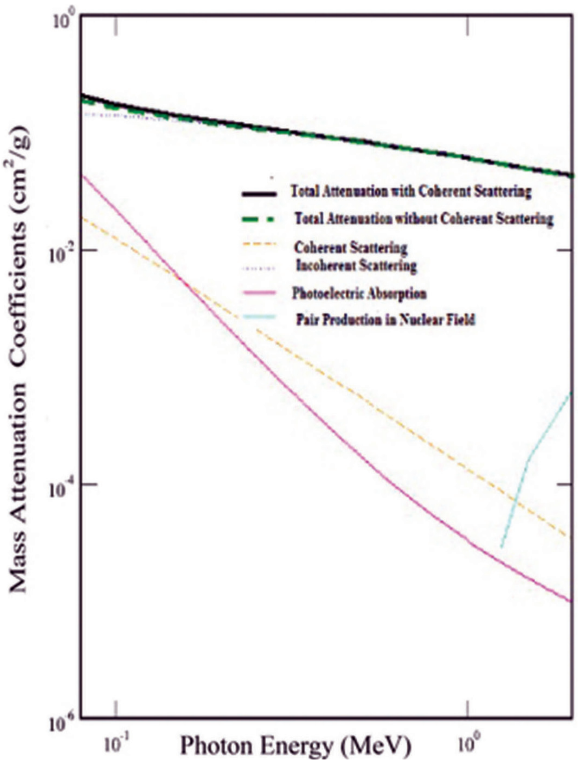

Figure 5. Photon interaction mechanisms of A3 at 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173keV, 1332keV) and 2000keV (high energy) energies from XCOM results.

As shown Figure 4, Figure 5 and Table 3, A and B composite materials are used as a shielding material. But, photon-interactions at B3 composite materials is more dominant than A3 composite materials. This is attributed to the ability of the composite for attenuation and the decrease in permeability. In addition, linear attenuation coefficient values of B composite material with the same weight fraction B_4C are more than linear attenuation coefficient values of A composite material with the same weight fraction B_4C. B composite materials are most likely to interact with photons. Consequently, it is implied that B composite materials show better attenuation performance than A composite materials owing to much interaction probability between photons.

As seen in Figure 6 and Table 3, as incident photon energy increase mass and linear attenuation coefficients for A and B composite materials decrease and the calculated of mass and linear attenuation coefficient significantly increase with decreasing the weight fraction B_4C (wt%) of A and B composite materials using 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) energies owing to density and variations in the chemical composition of these materials. In generally, total mass attenuation

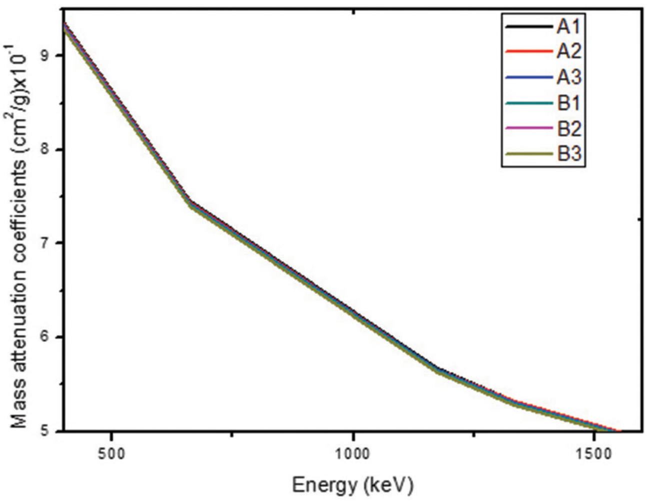

Figure 6. Mass attenuation coefficients – energy graphs for A and B composite materials against 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) energies.

coefficients of A1 and B1 composite materials are higher in the 80 keV and 356 keV energies. Thus, the computed values of total mass attenuation coefficients are a good consistency.

HVL -%B_4C and TVL-%B_4C graphs for A and B composite materials are shown in Figure 7 and Figure 8. HVL and TVL values for 80 keV, 356 keV^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) increase with increasing %B_4C ratio in these composite materials. But, HVL and TVL values of B composite materials are smaller than A composite materials. This is attributed to density and variations in the chemical composition of these composite materials. In addition, HVL and TVL values of B composite material with the same weight fraction B_4C are smaller than HVL and TVL values of A composite material with the same weight fraction B_4C. Consequently, considering the fact that composite materials with B_4C have high gamma absorption cross-section, these materials can absorb effectively a wide range of gamma rays.

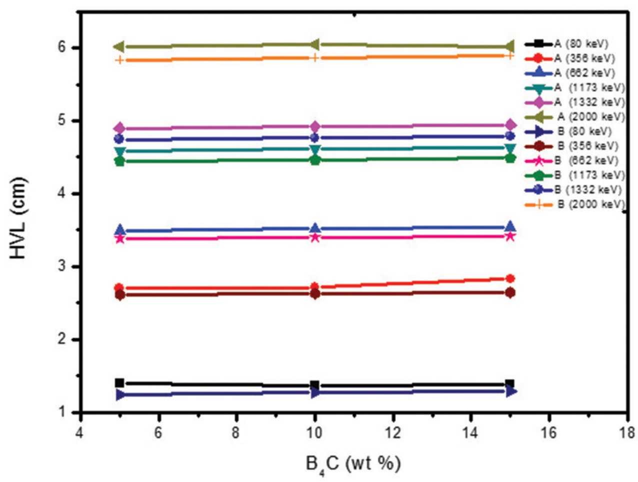

Figure 7 The half-value layers (HVL) - % B_4C graphs for A and B composite materials against 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) energies.

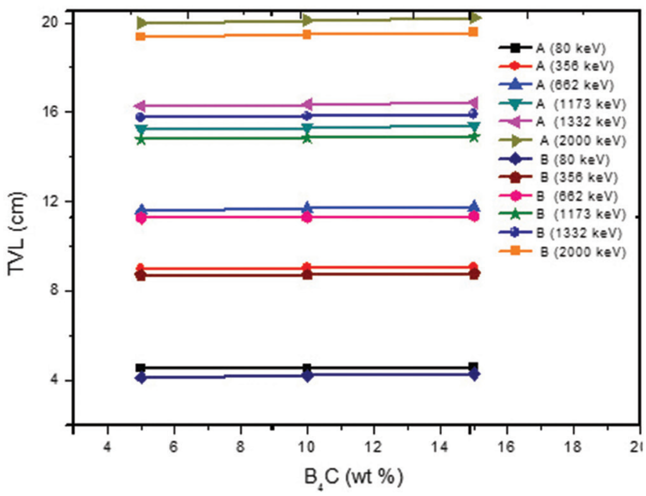

Figure 8 The half-value layers (TVL) - % B_4C graphs for A and B composite materials against 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) energies.

4. Conclusion

Linear and mass attenuation coefficients for A and B composite materials were theoretically investigated against 80keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) gamma energies by using XCOM computer code. Apart from these, HVL and TVL were computed to evaluate the radiation shielding effectiveness of these materials excluding coherent scattering values that are frequently used in gamma ray transport theory as well as the total attenuation coefficients. The calculated HVL, TVL and Linear and mass attenuation coefficients for A and B composite materials were compared with each other. The effects of B_4C percentage in A and B composite materials on gamma rays were determined. It is concluded that increase of B_4C (wt%) ratio in A and B composite materials cause smaller Linear and mass attenuation coefficients. Besides, increase of B_4C reinforcing ratio in these composite materials result in higher macroscopic gamma cross-section values. In addition, it is shown that density and variations in the chemical composition of the materials affect linear and mass attenuation coefficients and half-value and one tenth thickness for A and B composite materials against 80 keV, 356 keV, ^{137}Cs (662 keV), ^{60}Co (1173 keV, 1332 keV) and 2000 keV (high energy) gamma energies. Consequently, A and B composite materials with B_4C absorb gamma radiation, increase the gamma shielding ability and the hardness of composite materials.

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