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Gamma, X-ray and neutron interaction parameters of Mg–Gd–Y–Zn–Zr alloys

L. Seenappa[a,d], H.C. Manjunatha[a,*], B.M. Chandrika[d], K.N. Sridhar[b], Chikka Hanumantharayappa[c]

[a] Department of Physics, Government College for Women, Kolar 563101, Karnataka, India
[b] Department of Physics, Government First Grade College, Kolar 563101, India
[c] Vivekananda Degree College, Bangalore 560055, Karnataka, India
[d] Research and Development Centre, Bharathiar University, Coimbatore 641046, India

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ABSTRACT

The X-ray and gamma interaction parameters such as mass attenuation coefficient, linear attenuation coefficient, Half Value Layer (HVL), Tenth Value Layer (TVL), effective atomic numbers, electron density, exposure buildup factors, relative dose, dose rate and specific gamma ray constant are studied in the Mg–Gd–Y–Zn–Zr alloys of different composition such as Mg-8.2Gd-3.8Y-1.0Zn0.4Zr, Mg-8.2Gd-4.3Y-1.0Zn0.4Zr, Mg-8.2Gd-4.8Y-1.0Zn0.4Zr, Mg-8.2Gd-5.3Y-1.0Zn0.4Zr, Mg-8.2Gd-5.8Y-1.0Zn0.4Zr, Mg-8.2Gd-6.3Y-1.0Zn0.4Zr, Mg-8.2Gd-6.8Y-1.0Zn0.4Zr, Mg-8.2Gd-7.3Y-1.0Zn0.4Zr and Mg-8.2Gd-7.8Y-1.0Zn0.4Zr. It is also studied the neutron shielding properties such as coherent neutron scattering length, incoherent neutron scattering lengths, coherent neutron scattering cross section, incoherent neutron scattering cross sections, total neutron scattering cross section and neutron absorption cross sections in the same Mg–Gd–Y–Zn–Zr alloys. A detail analysis of X-ray/gamma and neutron interaction in the Mg-based alloys reveals that the Mg-based alloy Mg-8.2Gd-7.8Y-1.0Zn0.4Zr is good absorption of both X-ray/gamma and neutron radiation. Hence we may suggest that this alloy can be used for the shieldding for X-ray/gamma and neutron radiation.

1. Introduction

The study of photon interaction with different alloys has become a topic of prime importance for radiation physicists. The parameters such as mass attenuation coefficient and its derivables such as effective atomic number, electron density, exposure buildup factors, dose rate and specific gamma ray constant are helps in the basic understanding of photon interactions with alloys. Mg alloys exhibit low density, high specific strength and good damping capacities, having great potential in automotive and aerospace applications. The addition of heavy rare earth elements such as Gd and Y into Mg alloys leads to obvious age-hardening response and remarkably improved strength. Nogami et al. (2006) studied the characteristic and mechanism of microstructure evolution in the Mg-Gd-Y-Zn-Zr alloys. Yamada et al. (2006) studied the effects of zinc addition on microstructure evolution and mechanical properties of Mg-Gd-Y-Zn-Zr alloys. Zhou et al. (2017a) studied the compression behavior and mechanical properties of the Mg-Gd-Y-Zn-Zr alloy filled with intragranular long-period stacking ordered phases. Zhou et al. (2017b) studied the effect of long period stacking ordered phases on the dynamic recrystallization of the compressed Mg-Gd-Y-Zn-Zr alloys. Xue et al. (2015) studied the flow stress model and processing map of homogenized Mg-Gd-Y-Zn-Zr alloy during thermomechanical processes. Rimma et al. (2016) studied the structure and mechanical property variations in Mg-Gd-Y-Zn-Zr alloy depending on its composition and processing conditions. Xia et al. (2014) studied the characterization of hot deformation behavior of as extruded Mg–Gd–Y–Zn–Zr alloy. Yu et al. (2017) developed an as extruded Mg–Gd–Y–Zn–Zr Alloy with an excellent strength ductility balance by pre-annealing and hot extrusion and studied the effects of pre-annealing on microstructure and mechanical properties. Xu et al. (2015) studied the improving strength and ductility of Mg–Gd–Y–Zn–Zr alloy simultaneously via extrusion. Singh and Badiger (2014) studied the gamma and neutron shielding properties of some alloy materials. Chen et al. (2015) studied the shielding effectiveness and mechanical properties of Mg–Zn–Cu–Zr alloys. In our previous work (Manjunatha, 2015, 2016; Seenappa et al., 2017; Manjunatha et al., 2017a, 2016; Rudraswamy et al., 2010), we have measured the X-ray and gamma interaction parameters in some compounds of dosimetric interest. We

* Corresponding author.
E-mail address: manjunathhc@rediffmail.com (H.C. Manjunatha).

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also reported theoretical studies on the X-ray and gamma interaction parameters of biological samples (Manjunatha and Rudraswamy, 2013, 2011a; Suresh et al., 2008; Manjunatha, 2014). In our previous work (Manjunatha et al., 2012), we have reported shielding parameters for beta and bremsstrahlung radiation in concretes. In the previous work, we have also estimated energy exposure build up factors using GP fitting method (Manjunatha and Rudraswamy, 2012a, 2011b, 2012b).

In the present paper, we have studied the X-ray and gamma radiation shielding parameters such as mass attenuation coefficient, mean free path, half value layer (HVL), tenth value layer (TVL), effective atomic number, electron density, exposure buildup factors, dose rate and specific gamma ray constant are studied in alloys such as Mg-8.2Gd-3.8Y-1.0Zn0.4Zr, Mg-8.2Gd-4.3Y-1.0Zn0.4Zr,Mg-8.2Gd-4.8Y-1.0Zn0.4Zr, Mg-8.2Gd-5.3Y-1.0Zn0.4Zr, Mg-8.2Gd-5.8Y-1.0Zn0.4Zr, Mg-8.2Gd-6.3Y-1.0Zn0.4Zr, Mg-8.2Gd-6.8Y-1.0Zn0.4Zr, Mg-8.2Gd-7.3Y-1.0Zn0.4Zr and Mg-8.2Gd-7.8Y-1.0Zn0.4Zr. It is also studied the neutron shielding properties such as coherent neutron scattering length, incoherent neutron scattering lengths, coherent neutron scattering cross section, incoherent neutron scattering cross sections, total neutron scattering cross section and neutron absorption cross sections in the same alloys.

2. Theory

2.1. Gamma/X-ray interaction parameters

In the present work, the mass attenuation coefficients (MAC) and photon interaction cross sections in the energy range from 1 keV to 100 GeV are generated using WinXCom (Gerward et al., 2004) and its composition. The total linear attenuation coefficient (μ) can be evaluated by multiplying density of compounds to mass attenuation coefficients.

$$\mu = \left(\frac{\mu}{\rho}\right)_c \times \rho \tag{1}$$

The total linear attenuation coefficient (μ) is used in the calculation of half value layer (HVL). HVL is the thickness of a interacting medium that reduces the radiation level by a factor of 2 that is to half the initial level and is calculated by the following equation

$$HVL = \frac{\ln 2}{\mu} = \frac{0.693}{\mu} \tag{2}$$

The total linear attenuation coefficient (μ) is also used in the calculation of tenth value layer (TVL). It is the thickness of interacting medium for attenuating a radiation beam to 10% of its radiation level and is computed by

$$TVL = \frac{\ln 10}{\mu} = \frac{2.303}{\mu} \tag{3}$$

The average distance between two successive interactions is called the relaxation length (λ). It is also called the photon mean free path which is determined by the equation:

$$\lambda = \frac{\int_0^\infty x \exp(-\mu x)dx}{\int_0^\infty \exp(-\mu x)dx} = \frac{1}{\mu} \tag{4}$$

The gamma interaction parameters such as linear attenuation coefficients μ(cm^{-1}), HVL (in cm), TVL (in cm) and mean free path λ are calculated using above Eqs. (1)–(4). The total molecular cross section $\boldsymbol{\sigma_m}$ [milli barn] is computed from the following equation using the values of mass attenuation coefficients [$(\mu/\rho)_c$]

$$\sigma_m(E) = \left(\frac{1}{N}\right)\left(\frac{\mu}{\rho}(E)\right)_c \sum_i n_i A_i \tag{5}$$

where n_i is the number of atoms of i^{th} element in a given molecule, $(\mu/\rho)_c$ is the mass attenuation coefficient of compound, N is the Avogadro's number and A_i is the atomic weight of element i. The effective (average) atomic cross section for a particular atom in the compound σ_a [milli barn] is estimated using the equation,

$$\sigma_a = \frac{\sigma_m}{\sum_i n_i} = \frac{\left(\frac{1}{N}\right)\left(\frac{\mu}{\rho}(E)\right)_c \sum_i n_i A_i}{\sum_i n_i} \tag{6}$$

The effective electronic cross section $\boldsymbol{\sigma_e}$ [milli barn] is computed from mass attenuation coefficient $(\mu/\rho)_i$ of i^{th} element in the given molecule using following equation,

$$\sigma_e = \left(\frac{1}{N}\right)\sum_i \left\{\left(\frac{f_i A_i}{Z_i}\right)\left(\frac{\mu}{\rho}\right)_i\right\} \tag{7}$$

where, f_i is the fractional abundance (a mass fraction of the i^{th} element in the molecule) and Z_i is the atomic number of the i^{th} element in a molecule. Finally the Z_{eff} is estimated as

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{8}$$

2.2. Secondary radiation during the interaction of gamma/X-ray

During the interaction of gamma/X-ray with the medium, it degrade their energy and produces secondary radiations through the different interaction process. The quantity of secondary radiations produced in the medium and energy deposited/absorbed in the medium is studied by calculating buildup factors. In the present work, we have estimated energy exposure build up factors (B_{en}) using geometric progression (GP) fitting method (Manjunatha and Rudraswamy, 2012a, 2011b, 2012b). We have evaluated the G-P fitting parameters (*b, c, a,* X_k *and d*) using following expression which is based on Lagrange's interpolation technique

$$P_{Z_{eff}} = \sum \left(\frac{\prod_{Z' \neq Z}(Z_{eff} - Z)}{\prod_{z \neq Z}(z - Z)}\right) P_z \tag{9}$$

where lower case z is the atomic number of the element of known GP fitting parameter P_z adjacent to the effective atomic number (Z_{eff}) of the given material whose GP fitting parameter $P_{Z_{eff}}$ is desired and upper case Z are atomic numbers of other elements of known GP fitting parameter adjacent to Z_{eff}. GP fitting parameters (*b, c, a,* X_k and *d*) for element adjacent to Z_{eff} are provided by the standard data available in literature (American National Standard ANS, 1991). The computed GP fitting parameters (*b, c,a,* X_k and *d*) were then used to calculate the exposure buildup factors (EBF) in the energy range 0.015–15 MeV up to a penetration depth of 40 mean free path with the help of GP fitting formula, as given by the equations;

$$B\left(E, X\right) = 1 + \frac{b-1}{K-1}\left(K^X - 1\right) \quad \text{for } K \neq 1 \tag{10}$$

$$B(E, X) = 1 + (b-1)X \quad \text{for } K = 1 \tag{11}$$

$$K\left(E, X\right) = CX^a + d\frac{\tanh\left(\frac{X}{X_K} - 2\right) - \tanh\left(-2\right)}{1 - \tanh(-2)} \quad \text{For penetration depth (X)} \leq 40 \text{ mfp} \tag{12}$$

Where X is the source-detector distance for the medium in mean free paths (mfp) and b is the value of build-up factor at 1mfp. K(E,X) is the dose multiplication factor and *b, c,a,* X_k and *d* are computed GP fitting parameters that depend on attenuating medium and source energy.

2.3. Specific Gamma Ray Constant

Specific gamma ray constant (Γ) is an exposure rate (in R/h) due to