

THE COMPARATIVE STUDY OF PHOTON SHIELDING PROPERTIES OF MONBCRVTi AND MONBCRZRTi ALLOY MATERIALS

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Abstract

In this work, the photon interaction properties of 2 alloys (MoNbCrVTi and MoNbCrZrTi alloy) have been studied by using the WinXCom program in the gamma ray energy range of 1 keV to 10³ MeV. The mass attenuation coefficients, partial interactions, effective atomic numbers, electron densities, and mean free paths were determined and compared. The results show that the mass attenuation coefficients, electron densities, and mean free paths of the MoNbCrVTi and MoNbCrZrTi alloys were close but the effective atomic number of the MoNbCrZrTi alloy shows a greater value than that of the MoNbCrVTi alloy. The MoNbCrZrTi alloy shows lower mean free path values compared with the MoNbCrVTi alloy; therefore, the MoNbCrZrTi alloy is better for radiation shielding than the MoNbCrVTi alloy. These results show the high potential of the MoNbCrVTi and MoNbCrZrTi alloys' shielding applications.

Keywords: Alloy, mass attenuation coefficient, partial interaction, mean free path

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Introduction

At present, the improving strength of large-sized bulk metallic material has become an interesting topic for the development of advanced structural materials (Li *et al.*, 2015; Appel *et al.*, 2000). Protection from radiation is at the cutting edge of nuclear engineering and design where radiation exposure is controlled by various passive and active techniques. Generally, lead-based radiation shielding is used widely to protect against exposure to ionizing radiation due to its physical-chemical properties and fabrication, ease of casting, and malleability. It takes many forms, including glass, powder metallurgy, lead impregnated rubber, and a lead-polyethylene-boron mixture for protection against gamma and neutron radiation and may be in the form of an impermanent or permanent arrangement of radiation shielding. In the past, there has been a lot of concern about the toxicity of lead. Lead toxicity in children and scientists has been studied and well recorded. Corrosion in the lead sheets of structural shielding walls has also been reported. In view of this, an environmentally friendly non-toxic "lead-free" material is a challenging requirement for radiation shielding and protection (Zou *et al.*, 2013; Singh and Badiger, 2016; Simsek and Dursun, 2019).

The goal of this study is to report the theoretical total mass attenuation coefficients, partial interactions, effective atomic numbers, effective electron densities, and mean free paths of MoNbCrVTi and MoNbCrZrTi alloys using the data that have been determined by the WinXCom program at 1 keV-10³ MeV gamma ray energies.

Methods

The mass attenuation coefficient (μ_m), in (cm²/g), was acquired using theoretical values of the material compound or mixtures that have been determined, and are given by the following equation (Chanthima and Kaewkhao, 2013):

$$\mu_m = \sum_i w_i (\mu_m)_i \quad (1)$$

where $(\mu_m)_i$ (cm²/g) is the individual mass attenuation coefficient which was received by WinXCom, and w_i is the fractional of the element by weight.

The total atomic cross section ($\sigma_{t,a}$) can be determined from the total mass attenuation coefficient by the following relationship (Khobkham *et al.*, 2016):

$$\sigma_{t,a} = \frac{(\mu_m)_{\text{alloy}}}{N_A \sum_i (w_i/A_i)} \quad (2)$$

where N_A is Avogadro's number and A_i is the atomic weight of an element in the alloy. The total electric cross section ($\sigma_{t,el}$) is given by the following relationship (Khobkham *et al.*, 2016):

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} (\mu_m)_i \quad (3)$$

where $f_i = n_i/\sum n_i$ is the mole fraction, Z_i is the atomic number of the composition element, n_i is the total number of atoms of the composition element in the molecule, and $\sum n_i$ is the total number of all atoms in the molecule. Then, n_i and A_i , are the total number of atoms and the atomic weight of the i^{th} element in the molecule, respectively.

The effective atomic number (Z_{eff}) is the number of the electrons that interacted with the photon per atom. It can be computed as the ratio of the total atomic effective cross section to the total electronic cross section (Khobkham *et al.*, 2016) by the following equation:

$$Z_{\text{eff}} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \quad (4)$$

The effective electron density (N_{e1}) is the number of electrons that interacted with the photon per unit mass. It can be computed as the

ratio of the total mass attenuation coefficient to the total electronic cross section (Khobkham *et al.*, 2016), as in the following equation:

$$N_{el} = \frac{\mu_m}{\sigma_{t,el}} \quad (5)$$

The mean free path (MFP) is the thickness of the shielding materials for 2 successive collisions. The intensity of the gamma ray reduces by various physical processes like complete absorption, partial absorption, energy reduction, and multiple scattering inside the medium. The MFP is the reciprocal of μ_{alloys} , having a dimension of length and given by the following relationship (Singh and Badiger, 2014):

$$MFP \text{ (cm)} = 1/\mu_{alloys} \quad (6)$$

where μ_{alloys} is the linear attenuation coefficient of the alloy.

Results and Discussion

The chemical compositions of the MoNbCrVTi and MoNbCrZrTi alloys are shown in Table 1. The densities (ρ) are 7.33 and 7.29 g/cm³, respectively. The results show that vanadium (V) and zirconium (Zr) are the main components in the MoNbCrVTi and MoNbCrZrTi alloys, respectively.

Table 1. The chemical composition (in at.%) of MoNbCrVTi and MoNbCrZrTi alloys (Xiang *et al.*, 2019)

Alloy	Mo	Nb	C	Zr	V	Ti
MoNbCrVTi	20.8	20.0	18.7	-	30.3	20.2
MoNbCrZrTi	19.4	19.5	20.7	21.7	-	18.7

The photon interactions in Figures 1 and 2 of the MoNbCrVTi and MoNbCrZrTi alloys, respectively, show that the same trends and the coefficient values in the 2 alloys were similar, as expected. The coherent scattering was found to be significant at a lower photon energy, and it decreases with an increase of the photon

energy. The incoherent scattering increases with an increase in the photon energy within the range 10⁻³ MeV to 2×10⁻¹ MeV, and after that it decreases. The incoherent scattering was found to be a significant interaction in the energy range 6×10⁻² MeV to 8 MeV. The photoelectric absorption was found to be the main interaction mechanism at a lower photon energy (10⁻³ MeV to 6×10⁻² MeV). The pair production in the nuclear field occurs at a photon energy of 1.25 MeV, and it increases with an increase in the photon energy. It was found to be the main interaction at a photon energy higher than 6 MeV. The pair production in the electron field occurs at about 3 MeV, which corresponds with the electron tunneling

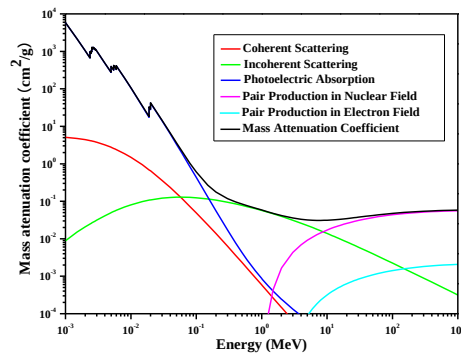


Figure 1. Total mass attenuation coefficient by WinXCom of MoNbCrVTi alloy at energy range 1 keV-10³ MeV

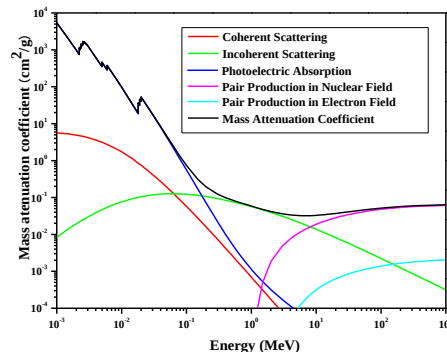


Figure 2. Total mass attenuation coefficient by WinXCom of MoNbCrZrTi alloy at energy range 1 keV-10³ MeV

energy of V and Zr, respectively. It increases with an increase in energy.

The mass attenuation coefficient values are shown in Figure 3; the coefficient values decrease when the photon energy increases and the coefficient values peak at the energy level that corresponds to the absorption edge of V ($K\ 5.47 \times 10^{-3}$ MeV) and Zr ($L_3\ 2.22 \times 10^{-3}$ MeV, $L_2\ 2.31 \times 10^{-3}$ MeV, $L_1\ 2.53 \times 10^{-3}$ MeV and $K\ 18.0 \times 10^{-2}$ MeV), respectively, as V and Zr are the major compositions of the 2 alloys.

The effective atomic number of the MoNbCrVTi and MoNbCrZrTi alloys have peaks, as shown in Figure 4, which correspond to the V and Zr X-ray absorption edges. The numbers drop to the values of 27 and 41, which

correspond to the atomic numbers of V ($Z = 23$) and Zr ($Z = 40$), respectively. The effective atomic number of the MoNbCrZrTi alloy is higher than that of the MoNbCrVTi alloy. The reason is that the Zr in the MoNbCrZrTi alloy has an atomic number higher than that of the V in the MoNbCrVTi alloy.

As in Figure 5, the effective electron densities of the MoNbCrVTi and MoNbCrZrTi alloys show similar values, in the range 2.6×10^{23} electron/gram to 3.5×10^{23} electron/gram. Also they show the peaks which corresponds to the X-ray absorption edges of V and Zr. The plot of the effective atomic numbers and that for the effective electron densities follow the same trend.

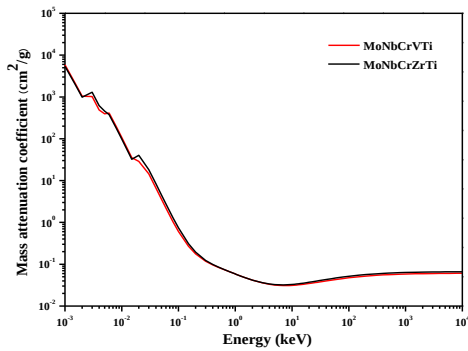


Figure 3. Mass attenuation coefficient of MoNbCrVTi and MoNbCrZrTi alloys at energy range 1 keV- 10^4 MeV

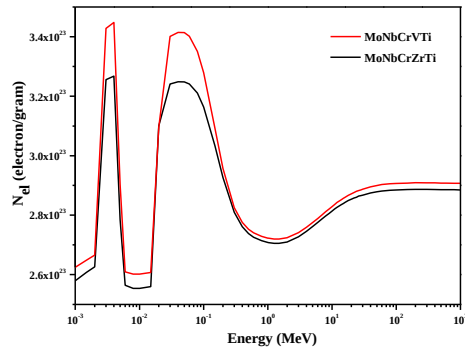


Figure 5. Effective electron densities of MoNbCrVTi and MoNbCrZrTi alloys at energy range 1 keV- 10^3 MeV

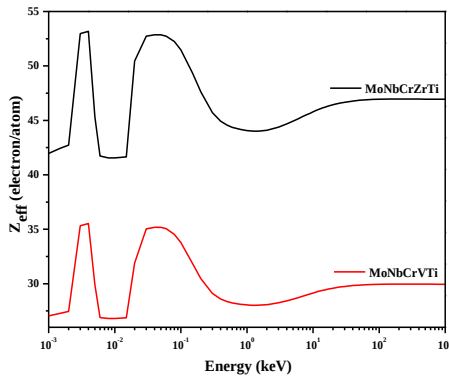


Figure 4. Effective atomic numbers of MoNbCrVTi and MoNbCrZrTi alloys at energy range 1 keV- 10^3 MeV

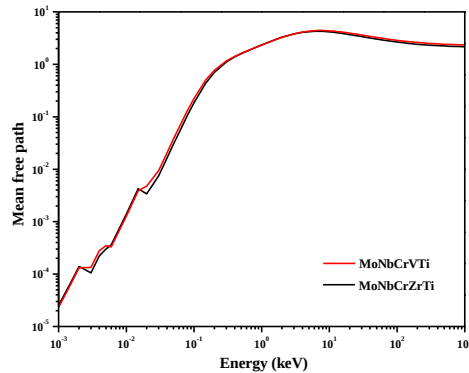


Figure 6. Mean free path of MoNbCrVTi and MoNbCrZrTi alloys at energy range 1 keV- 10^3 MeV

The MFP values with the gamma energy of the alloys are shown in Figure 6. It was found that the MFP values were low in the photoelectric absorption region and gradually become independent of photon energy in the incoherent scattering and pair-production region. It is to be noted that the MoNbCrZrTi alloy requires a thinner thickness compared with the MoNbCrVTi alloy in the entire region of interest of the energy. The MoNbCrZrTi alloy shows a lower MFP value compared with the MoNbCrVTi alloy; therefore, it can be concluded that the MoNbCrZrTi alloy is better at radiation shielding than the MoNbCrVTi alloy. The variation in the MFP of the alloys is dependent upon the Z of the elemental composition and densities. The MoNbCrZrTi alloy has a large composition of high-Z (Zr = 40) with a density of 7.33 g/cm³. The MoNbCrVTi alloy contains a large composition of low-Z (V = 23) and a density 7.29 g/cm³.

Conclusions

The photon interactions of the MoNbCrVTi and MoNbCrZrTi alloys have been studied with the WinXCom program for the photon energy range of 1 keV to 10³ MeV. The photon interaction results of the MoNbCrVTi and MoNbCrZrTi alloys show the same trends. The interaction coefficient values were close, as V and Zr are the main compositions for the MoNbCrVTi and MoNbCrZrTi alloys, respectively. The coherent scattering was found to be the main interaction at a lower photon energy. The scattering decreases with an increase in the photon energy. The incoherent scattering was found to be a significant interaction in the energy range of 6×10⁻² MeV to 8 MeV. The photoelectric absorption is a major interaction at a photon energy below 6×10⁻² MeV. The absorption value is not continuous due to the absorption edge of the V in the MoNbCrVTi alloy and Zr in the MoNbCrZrTi alloy. The pair production in the nuclear field occurs at the photon energy of 1.25 MeV and increases with an increase in the photon energy. It was found to be significant

at a photon energy higher than 6 MeV. The pair production in the electron field occurs at about 3 MeV, which corresponds to the electron tunneling energy of V and Zr, respectively. It increases with an increase in energy. The effective atomic numbers and effective electron densities of the MoNbCrVTi and MoNbCrZrTi alloys were found to follow the same trends. The numbers show the peaks which correspond to the gamma-ray absorption edges of V and Zr. The effective atomic number of the MoNbCrZrTi alloy was higher than that of the MoNbCrVTi alloy. However, the effective electron density values were similar in the range 2.6×10²³ to 3.5×10²³ electron/gram. The MoNbCrZrTi alloy shows a lower MFP value compared with the MoNbCrVTi alloy. These results suggest that the MoNbCrZrTi alloy has better properties for radiation shield applications than the MoNbCrVTi alloy.

Acknowledgments

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