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Using XCOM and FFAST Data to Calculate and Study Certain X-Ray Protection Criteria for Lead-Tin-Antimony Alloy

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Abstract. The coefficient of mass attenuation (μ/ρ) for lead-tin-antimony (Pb-Sn-Sb) alloys was calculated using various theoretical methods, accounting for different proportions of the constituent elements in each alloy. The first approach involved calculating the coefficients of mass attenuation for each specific element using the "FFAST" software, followed by the application of a "mixing method" to determine Mass attenuation coefficient for the entire alloy. These results were then compared with those obtained directly via the "XCOM" software, showing a high degree of agreement. Furthermore, other shielding properties were calculated for each alloy, namely: the Half-Value Layer (HVL) and the Mean Free Path (MFP). These values were compared to identify the optimal alloy for radiation protection, with an investigation into how the addition of antimony enhances these shielding characteristics, ultimately aiming to determine the most effective alloy for practical use. The study also compared these properties across four different alloys, contributing to improved X-ray shielding efficiency a matter of particular importance for individuals frequently exposed to X-rays in research facilities and diagnostic medical centers.

Keywords: Lambert-Beer law, shielding properties, the mixing rule, mass attenuation of compound

I. Introduction

The attenuation of X or gamma ray beam result from photons absorption and scattering therefore attenuation is the removal of photons from these rays when they enter into substance and the intensity of photons is lessen from original photon intensity beam. [1,2]. The linear attenuation coefficient (μ) is an important characteristic value which is used to expression properties of the shielding value of any substance compared to X-rays or gamma rays[3,4]. The coefficient of linear attenuation is the part of photons disconnected from beams of X or gamma rays per units thickness of material . In addition to the linear attenuation coefficient Knowledge of other shielding properties as coefficient of the mass attenuation , mean free path which is represented by the symbol (MFP),half value layer which is represented by the symbol (HVL) and is essential in fields involving radiation[5].

At a beam of monochromatic X-rays or gamma rays photons is weakened which inter matter on based on Lambert-Beer law[6,7]:

$$I/I_{\circ} = exp[-(\mu/\rho)] \quad \ldots\ldots (1)$$

Where $I_{\circ}$ is an intensity of an incident rays, I is an intensity of penetrating rays of mass thickness layer x with density ρ [8,9]. The attenuation coefficients of compounds (substances composed of two or more component) can be obtained as a weighted average (by mass) of the mass attenuation coefficients of these compounds components [10].That is, to study the attenuation coefficient of mass of any compound or mixture, we can use the attenuation coefficients of mass of its components, then by applying the mixing rule we obtain the coefficient of mass attenuation of compound the or mixture as a whole , as follows [2,8,10]:

$$\left(\frac{\mu}{\rho}\right)_{compound\ or\ alloy} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad \ldots\ldots (2)$$

since w_i and $\left(\frac{\mu}{\rho}\right)_i$ was the fraction of weight and the coefficient of mass attenuation of the all element in the compound or alloys, respectively [11,12].The half value layer is known as the thickness of a material necessary to lessen an incident radiation beam intensity original value to half, the thickness that causes the energy of incident X-rays or gamma rays to be reduced by half after they enter and pass through the material. It is expressed by the following relationship [11]:

$$HVL = \frac{0.693}{\mu} \ldots\ldots (3)$$

The (MFP) can be define as the average distance moved by a single X-ray or γ-ray particle before it interacts with the surrounding medium; it is expressed by the following equation: [11]:

$$MFP = \frac{1}{\mu} \ldots\ldots (4)$$

Since MFP and HVL are among the most important properties of materials used in the design of structural armor, calculating MFP and HVL is important in understanding many of the alloys used in this range[11,13].

II. Results and Discussion

Fine-grained lead-tin alloys have numerous applications in the electronics, energy storage, and nuclear energy industries. To improve their shielding properties, antimony is added to them. These properties are further enhanced after adding antimony in proportions that make them suitable for these applications[14]. To obtain the alloy properties after adding antimony, the alloy properties can be studied, interpreted, and predicted by studying the linear absorption coefficient and some shielding properties such as (μ/ρ), (HVL), and (MFP). In this research, we calculated the mass absorption coefficient using equation (2), which is the mixing rule, over an energy range of (30-300) keV.

Calculating the (μ/ρ) for all element in the alloy compo by us the FFAST program (*http://physics.nist.gov/PhysRefData/FFast/html/form.html*).FFAST program (Filter Fluorescence Attenuation Spectroscopy Tables) of NIST was designed for the purposes of X-ray diffraction and crystal interference, and it is also used to calculate both of coefficients of the mass attenuation and absorption coefficients for X-rays, and covers the energy range from threshold to 433 keV. The absorption coefficient of each alloy was compared with the absorption coefficient of the same alloy by calculating the coefficient of mass absorption for each alloy as a full using the XCOM program. The XCOM program, affiliated with NIST, is used to calculate the mass attenuation and absorption coefficients for X-rays for various elements, compounds, and alloys, over a wide range of energies extending from 1 keV to 100 GeV(*https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html*). The (HVL) and (MFB) of the incident X-rays were also calculated from equations (3) and (4) respectively. The coefficient of linear attenuation for each alloy was calculated from the relationship ($\mu = (\mu/\rho_{Alloy})\rho_{Alloy}$) where ρ_{Alloy} is the alloy density, which we extract from the following relationship:

$$\rho_{Alloy} = \frac{1}{\sum_i w_i/\rho_i} \ldots\ldots (6)$$

which is the inverse mixing rule[15]. We calculate it for each of the four alloys composed of lead, tin, and antimony . Where ρ_{Alloy} and ρ_i are are the alloy density and any element represent one of component of the alloy, respectively. The densities of the alloy components Pb,Sn and Sn are 11.342 g/cm³, 7.287 g/cm³, and 6.685 g/cm³ respectively [16].

Table 1, provided below, displays the density of the alloy sample used in this research calculated using Equation (6) along with the weight percentages of each constituent element of the alloy. All calculations were performed using the MATLAB software.

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Table 1: represent the alloying elements, weight fractions, mass, and density of the samples used in the study.

Sample code of alloy	Base material	weight fraction	Alloying element	weight fraction	Alloying Element	weight fraction	Alloy density (gm/cm^3)
A1	Pb	0.97	Sn	0.03	Sb	0	11.155764410520137
A2	Pb	0.965	Sn	0.03	Sb	0.005	11.117675503036997
A3	Pb	0.955	Sn	0.03	Sb	0.015	11.042272673292759
A4	Pb	0.945	Sn	0.03	Sb	0.025	10.967885754732986

Table .2: represent the values of $\mu/\rho(cm^2/g)$ for (A1,A2,A3 and A4) alloys for X- ray energy range (30-300KeV)

	A1		A2		A3		A4	
E(eV)	$\mu/\rho(cm^2/g)$ by mixing method	$\mu/\rho(cm^2/g)$ by XCOM	$\mu/\rho(cm^2/g)$ by mixing method	$\mu/\rho(cm^2/g)$ by XCOM	$\mu/\rho(cm^2/g)$ by mixing method	$\mu/\rho(cm^2/g)$ by XCOM	$\mu/\rho(cm^2/g)$ by mixing method	$\mu/\rho(cm^2/g)$ by XCOM
30	29.082192	30.64	28.9703765	30.530	28.7467455	30.3	28.5231145	28.74
40	14.784770	14.51	14.81749	14.540	14.88293	14.6	14.94837	13.76
50	7.3847370	8.121	7.400127	8.1370	7.4309085	8.169	7.4616895	7.564
60	5.2542520	5.066	5.264631	5.0750	5.2853905	5.094	5.3061495	4.636
80	2.2576340	2.438	2.26131	2.4410	2.2686635	2.449	2.2760165	2.158
100	5.4078490	5.433	5.3889335	5.4140	5.3511025	5.376	5.3132715	5.132
150	1.9719235	1.972	1.96503965	1.9650	1.95127195	1.952	1.93750425	1.836
200	0.8770735	0.9784	0.8743715	0.9751	0.8689675	0.9685	0.8635635	0.9012
300	0.4131542	0.396	0.4119185	0.3949	0.4094471	0.3925	0.4069757	0.3612

Table 2 displays the values of μ/ρ for the alloys which we selected with the weight ratios mentioned in Table 1 for the energy range of X-ray (30-300 keV), which were calculated as described previously, first by the mixing method given away in Eq. (2) by replacinge the attenuation coefficient values which calculated by the FFAST program for each of the alloy elements, and the second method directly by the XCOM program. Plotting the results as shown in Figures (1-4), the agreement of the results in the two methods is evident. From both methods, it appears that the X-rays mass attenuation coefficient decreases in the four alloys with increasing energy of the incident rays, with the appearance of a sharp edge in the attenuation coefficient curve at the energy of 80 keV for the four alloys. This edge is the absorption edge resulting from the photon energy being equal to the binding energy of an internal electron in the atom. The photon can suddenly eject this electron, i.e. the photoelectric effect occurs, as it occurs at low energies. The absorption increases sharply at this point, after which the curve increases again.

The figures (1- 4) show Mass attenuation coefficient versus the energy of the X-rays incident on each of the alloys used .

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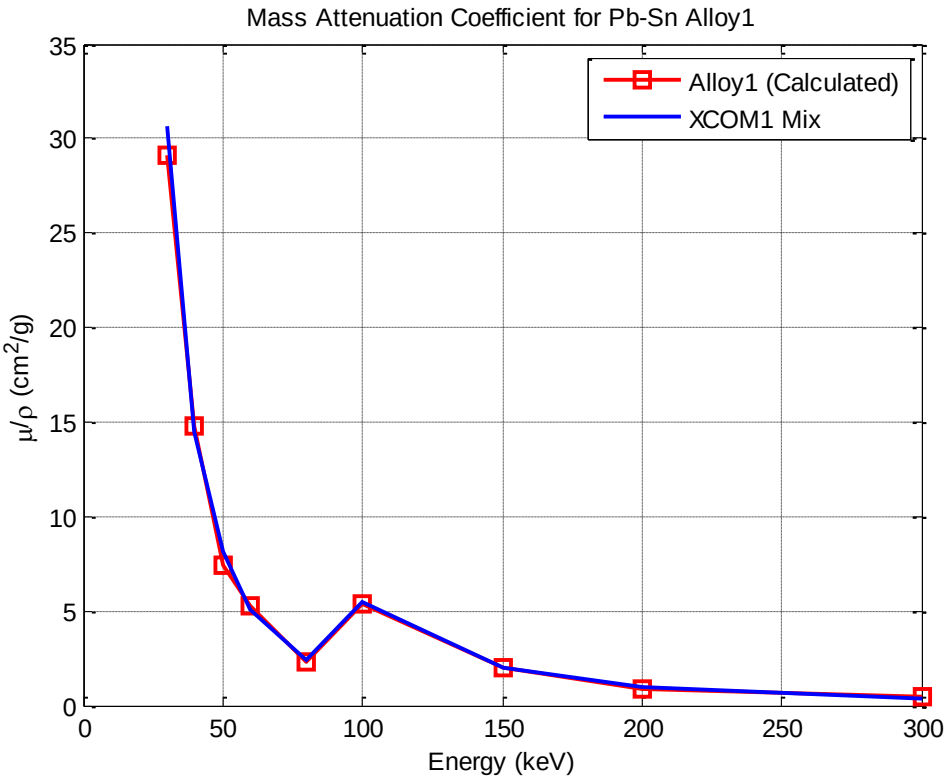


Fig.1: X- ray attenuation coefficient versus the energy in alloy A1.

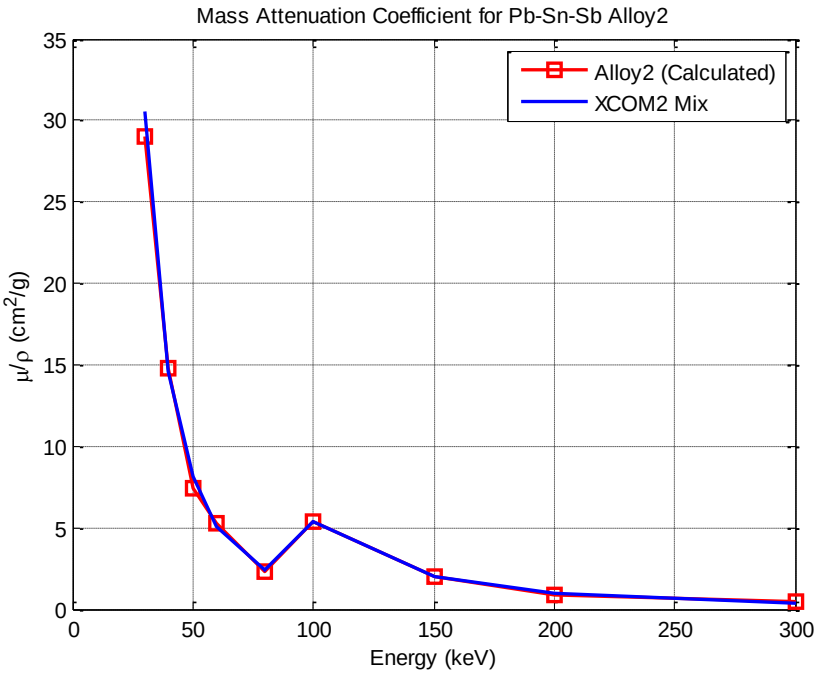


Fig.1: X- ray attenuation coefficient versus the energy in alloy A2.

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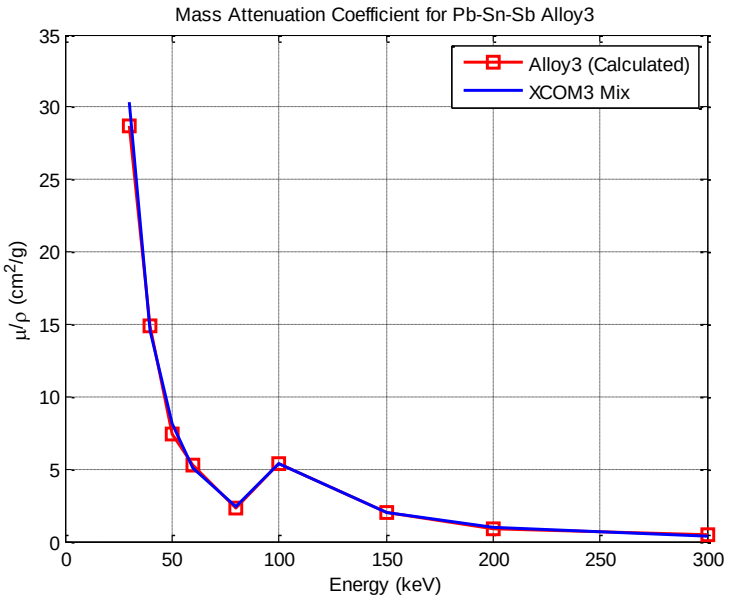


Fig.3: X- ray attenuation coefficient versus the energy in alloy A3.

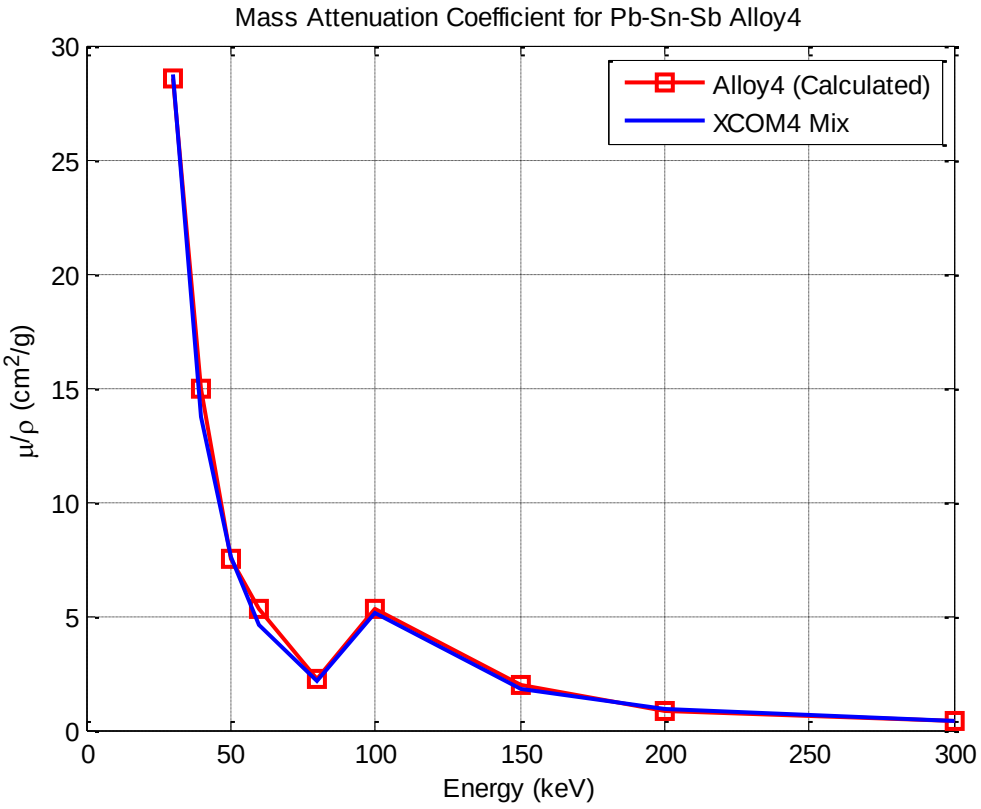


Fig.4: X- ray attenuation coefficient versus the energy in alloy A4.

From Tables 3 and 4, which display the values of HVL and MFP for the X-ray energy range (30-300) keV, and Figures 5 and 6, which show the relationship between the X-rays energy incident on the four alloys and HVL and MPF respectively, whose

values start low and rise with the rise in the energy of the incident photon, except in a region where a sudden drop occurs at the energy of 80 keV, which is, as we have shown, called the absorption edge, after which their values increase again for all four alloys. We also find that the effect of adding antimony led to an increase in both HVL and MFP, as is clear from the aforementioned tables and figures, as the highest value of HVL and MFP was in the A4 alloy, and their values were 0.155286629673726cm³ and 0.105580278709205cm³ at the energy of 300 keV, respectively, which is the alloy that contains the highest ratio of antimony and The lowest ratio of lead according to Table 1, while the lowest value of HVL and MFP appeared for the A1 alloy that does not contain antimony and was at the same energy 300 keV with a value of 0.150388267026836 cm and 0.102203242969016 cm respectively, thus the role of adding antimony to the alloy in increasing the radiation protection properties is clear. as it demonstrates that it is possible to reduce the percentage of lead in the alloy by adding this element while still achieving good shielding efficiency.

Table 3: represent the values of μ/ρ(cm^2/g) for (A1,A2,A3 and A4) alloys for X- ray energy (60-1500KeV).

E(eV)	HVL forA1(cm)	HVL forA2(cm)	HVL forA3(cm)	HVL forA4(cm)
30	0.00213648077671927	0.00215207462991400	0.00218362626643794	0.00221567265426450
40	0.00420253708058082	0.00420762303768800	0.00421772786329081	0.00422774421639987
50	0.00841377887294550	0.00842504568802500	0.00844743930683667	0.00846964816910503
60	0.0118253833567288	0.0118425026110010	0.0118765394058219	0.0119103098795285
80	0.0275215310155937	0.0275709206164780	0.0276692195860720	0.0277668834176313
100	0.0114895116621893	0.0115693415561180	0.0117306944780831	0.0118943450964449
150	0.0315091047664166	0.0317278138813680	0.0321698615861345	0.0326181915792470
200	0.0708418897080563	0.0713042594420200	0.0722376251682678	0.0731826725100184
300	0.150388267026836	0.151356184013848	0.153309544867717	0.155286629673726

Table 4: represent the values of μ/ρ(cm^2/g) for (A1,A2,A3 and A4) alloys for X- ray energy (60-1500KeV).

E(eV)	MFP forA1(cm)	MFP forA2(cm)	MFP forA3(cm)	MFP forA4(cm)
30	0.00308229022152749	0.00310478739619995	0.00315030678574490	0.00319653995054068
40	0.00606297940530594	0.00607031689040231	0.00608489507218886	0.00609934561514708
50	0.0121385170551348	0.0121547716333762	0.0121870787961838	0.0122191194116421
60	0.0170604219253635	0.0170851197886058	0.0171342245037016	0.0171829449986466
80	0.0397051763138689	0.0397764304461361	0.0399182458820939	0.0400591450075587
100	0.0165758614972765	0.0166910316893625	0.0169238147497141	0.0171599126852630
150	0.0454580291893601	0.0457735597448974	0.0464112997764006	0.0470581032341458
200	0.102203242969016	0.102870301491262	0.104216863595856	0.105580278709205
300	0.216964407047502	0.218360816084656	0.221178920101600	0.224031250546645

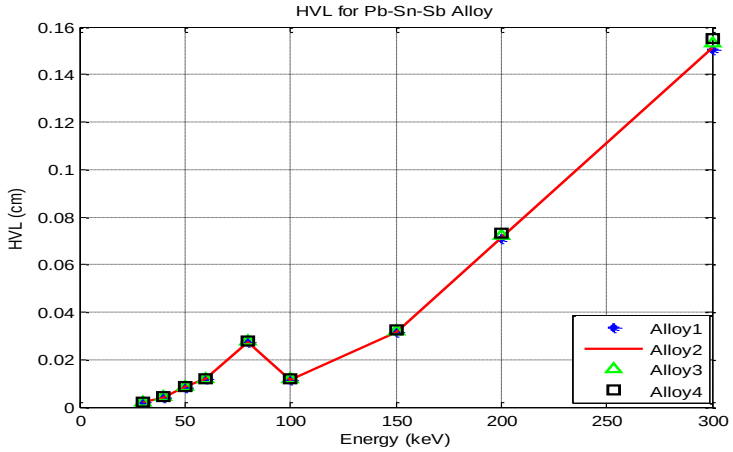


Fig. (5): HVL (cm) versus the energy of X- ray in (A1,A2,A3 and A4) alloys.

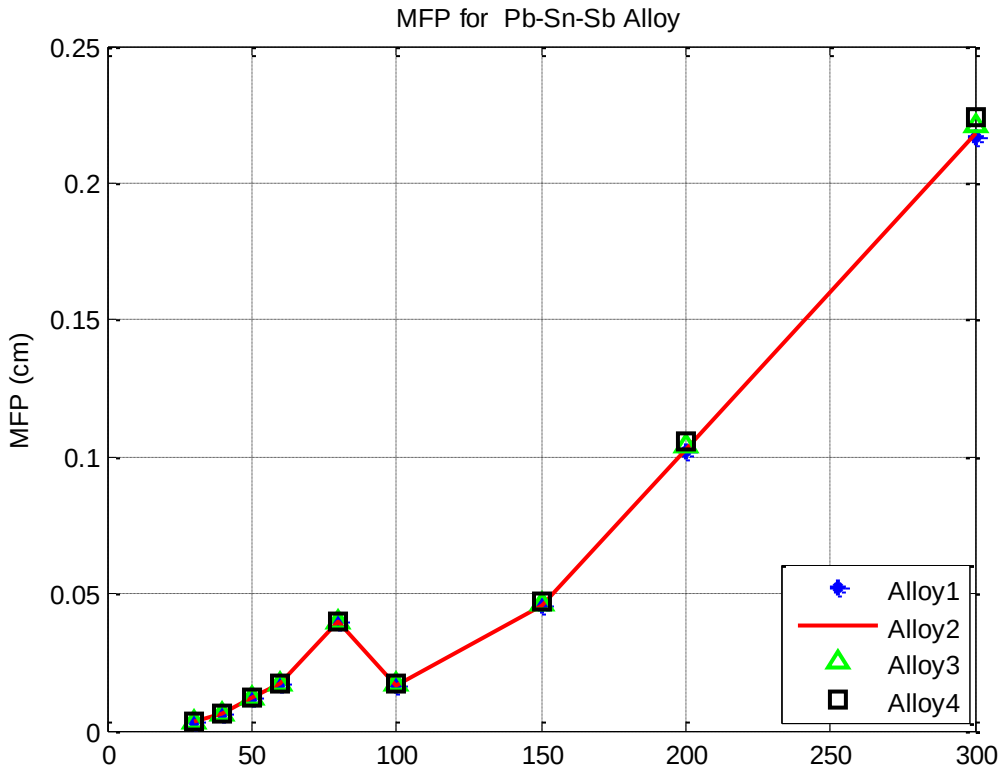


Fig. (6) : MFP(cm) versus the energy of X- ray (A1,A2,A3 and A4) alloys.

III. Conclusion

Through this research, which aimed to study an alloy of lead and tin after adding antimony to the alloy for the purpose of improving the shielding properties of this alloy, the effectiveness of this alloy can be predicted by calculating and discussing the shielding properties that included the mass absorption coefficient of X-rays (μ/ρ) , the (HVL) and the (MFP) to benefit from it as a shielding material for workers in the field of radiation and also to protect technicians and workers in the field of medical radiation and to benefit from this alloy as a suitable alternative to antimony-free alloys. By reducing the percentage of lead, we have reduced the effect of lead toxicity on workers. We conclude from this reserch that dependence of X-ray attenuation coefficients depend on occur interactions that within an alloy when such radiation enters it a process depende on the energy of the incident X-ray photons and the specific alloy atomic number of being used. It was further shown that, at interaction of X-rays with matter, the attenuation coefficient increases with higher photon energy, and dependence of this coefficient on the density of the alloy. Both (HVL) and (MFP) are affected by the increase in energy of photon and the increase in atomic numbers. The findings further illustrate the X-ray mass attenuation coefficients derived via the mixture method, the data from the FFAST program, and that calculated directly using the XCOM program.

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