Determination of effective atomic numbers and mass attenuation coefficients of wrought aluminium alloys 2014 and 2219 with multi energetic photons

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Abstract: *The total mass attenuation coefficients (μ_m) for wrought aluminum alloys 2014 and 2219 were measured at 59.5, 661.16, 1173, 1332keV photon energies. The samples were exposed to ^{137}Cs, ^{60}Co and ^{241}Am radioactive point sources using narrow beam transmission arrangement. The gamma-rays were counted by a NaI(Tl) detector with resolution of 8% of photon energy. Total atomic cross-sections (¯$_t$) and electronic cross-sections (□$_e$), effective atomic number (Z_{eff}) ,effective electron density (N_e) and photon mean free path(λ) have been determined using the values of μ_m for 2014,and 2219 aluminum alloys. The experimental values have been compared with theoretical values estimated from mixture rule and XCOM and the agreement is found to be good.*

Keywords: *mass attenuation coefficient, effective atomic number, effective electron number, total atomic, electronic cross sections*

1. INTRODUCTION:

In view of the extensive use of the radioactive sources in medicine, agriculture, industry etc., the study of photon atom interaction in different materials has gained importance in recent years. Since these interactions involve various compounds with different compositions, the effective atomic number of a material composed of several elements cannot be expressed by a single number. The (Z_{eff}) becomes an energy dependent parameter due to the different partial photon interaction processes with matter for which the various atomic numbers in the material have to be weighted differently. The effective atomic number (Z_{eff}) for the total and partial gamma ray interactions in alloys are equally important. In all materials, the absorption and scattering of gamma-rays are related to value of Z_{eff} of materials and the energy of photons. There is energy transfer from photon to matter in these interactions. Although the dependence on the photon energy is dominant in interaction with low energies, it can be negligible at high energies. A number of investigations on effective atomic number for total and partial photon interactions have been reported in the literature. Theoretical [1-10] and experimental [11-25] studies have been reported in a wide range of energies from a few keV up to several GeV. There was a study on few compounds in which the effective atomic number has been determined using the ratio of elastic-to-inelastic scattering [26, 27]. While the extensive and accurate data sets are available for elements [3-7] Similar studies have been carried out on various types of mixtures like alloys compounds and other composite materials including biological tissues, polymers and cements. In the present work, wrought aluminum alloys 2014 and 2219 have been subjected to attenuation studies at 59.5, 661.6, 1173, 1332keV photon energies to estimate the corresponding effective atomic number values for total photon interactions. Two different theoretical techniques, semi empirical approach and XCOM programme have been used for obtaining the calculated values.

2. EXPERIMENTAL:

Transmission experiments with the narrow beam (good-geometry) setup were used for measuring the incident and transmitted intensities to determine the attenuation coefficient. In the present work the total attenuation coefficient was measured at 59.5, 661.6, 1173, 1332keV photon energies using ^{137}Cs, ^{60}Co and ^{241}Am sources. The alloys studied in the present work were prepared by ingot metallurgy route. The alloys were melted in the air, in the induction furnace and cast iron moulds were used to obtain ingots. These ingots were subsequently homogenized at about 813K and hot rolled to obtain 12mm - 15mm thick plates. These alloy plates were precipitation strengthened by heat treatment (aging).

The alloy 6061 has been heat treated at 813K for solutionizing. It has been soaked at that temperature for 24 hours. For precipitation strengthening it has been water quenched. For aging, the alloy has been heat treated at 433K for 18 hours, and at 448K for 8 hours. Annealing has been done at 685K for 3 hours and has been allowed to cool naturally. The alloy 2219 has been heat treated at 805K for solutionizing and it was followed by cold water quenching. The alloy has been aged at 463K for 36 hours followed by cooling in air. Annealing has been done at 685K for 3 hours and has been allowed to cool naturally. For alloy 2014 solution heat treatment has been done at 807K followed by cold water quenching. Annealing has been done at 685K for 3 hours followed by cooling at the rate of 10K per hour down to 533K and then allowed to natural cooling.

The chemical compositions of the alloys 2014 and 2219 have been given in Table.1. In each case, the sample was shaped in to a cuboid for measuring the attenuation. The cuboid was stacked on the detector and the intensities of the transmitted photons were determined by choosing the counting time as 30 minutes. Counts were recorded under the photo peaks, as statistical uncertainty was to be kept as low as possible. The dimensions of the samples were measured with a screw gauge with tolerance of ±0.01mm.

The experimental setup in the present work is shown in Fig.1.The gamma rays are well collimated using collimators of cylindrical shape and a circular aperture of 6mm diameter between the source and the detector. The signal is detected by NaI (Tl) scintillation detector of 3×3 inch crystal and a high bias voltage of 1000 volts. The detector was shielded by a lead screen to reduce the radiation coming directly from the source and scattered from the surroundings. The attenuation measurements were made with multichannel analyzer.

The samples were exposed to 59.5, 661.6, 1173 and 1332keV photons emitted by 50mCi Am-241, 100mci Cs-137 and 10mCi Co-60 radioactive point sources, respectively. I_0 and I the intensities before and after attenuation were measured by a high resolution NaI(Tl) detector. The sample was placed between the source and the detector, the distance between the radioactive point source with sample and the sample to detector was 12cm and 4cm, respectively. The measurements for the sample were carried out five times for each energy value. For each sample and energy I_0 (un attenuated) and I(attenuated) intensities were obtained. In every case the photo-peak had Gaussian distribution. The peak areas have been calculated from the spectrum obtained for each measurement. The each spectrum was recorded for 30 minutes to accumulate an adequate number of counts under the photo peak. I_0 and I intensity measurements and μ_m calculations were carried out for the photon energies 59.5, 661.6, 1173, 1332keV.

The uncertainty in the measurement of the mass attenuation coefficients has been estimated from errors in intensities I_0, I and thickness(t) using the following relation

$$\Delta(\mu_m) = (1/\rho t)[(\Delta I_0/I)^2 + (\Delta I/I)^2 + (\ln(I_0/I))^2 (\Delta t/t)^2]^{1/2} \quad (1)$$

Where ΔI_0, ΔI and Δt are the errors in the intensities I_0, I and thickness (t) respectively. In this experiment, the intensities I_0 and I were obtained for the same time and under the same experimental conditions. It is found that error in these measurements is in between 2.5% to 3.5%.

3. ANALYSIS OF DATA:

The relations used in the present work are summarized in this section. The mass attenuation coefficients for wrought aluminum alloys 2014 and 2219 at different energies were determined by performing transmission experiments and the experimental values were compared by values obtained from following semi empirical relations.

$$I = I_0 \exp(-\mu_m t) \quad (2)$$

Where I_0 and I are the un- attenuated and attenuated photon intensities

$\mu_m = \mu/\rho$ (cm^2/g) is the mass attenuation coefficient

t (g/cm^2) is sample mass thickness (the mass per unit area)

The total mass attenuation coefficient μm for any chemical compound or mixture of elements is given by mixture rule.

$$\mu_m = \sum_i w_i (\mu_m)_i \quad (3)$$

where w_i is the weight fraction (the proportion by weight) $(\mu_m)_i$ is the mass attenuation coefficient of ith element

For a material composed of multi elements the fraction by weight is given by

$$w_i = \frac{n_i A_i}{\sum_i n_i A_i} \quad (4)$$

Where A_i is the atomic weight of the ith element and n_i is the number of formula units.

The total atomic cross-section σ_t for materials can be obtained from the measured values of μ_m using the following relation

$$\sigma_t = \frac{\mu_m N}{N_A} \quad (5)$$

Where $N_A = \sum_i n_i A_i$ is atomic mass of materials N_A is the Avogadro's number.

The total electronic cross-section σ_e for the element is expressed by the following equation

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i N_i}{Z_i} (\mu_m)_i = \frac{\sigma_t}{Z_{eff}} \quad (6)$$

Where fi denotes the fractional abundance of the element I with respect to the number of atoms such that f1+ f2 + f3 + f4 +……..fi =1,Z_i is the atomic number of i^{th} element

The total atomic atomic cross-section σ_t and total electronic cross-section σ_e are related to the effective atomic number (Z_{eff}) of the material through the following relation

$$Z_{eff} = \frac{\sigma_t}{\sigma_e} \quad (6)$$

The effective electron number or electron density N_e (number of electrons per unit mass) can derived by using the following relation

$$N_e = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e} \quad (7)$$

Finally, the average distance between two successive interactions, called the photon mean free path (λ), is given by

$$\lambda = \frac{\int_0^\infty x \exp(-\mu x) dz}{\int_0^\infty \exp(-\mu x) dx} = \frac{1}{\mu l} \quad (8)$$

where (μ_l) is the linear attenuation coefficient and x is the absorber thickness.

4. RESULTS AND DISCUSSION:

Mass attenuation coefficient (μ_m), total photon interaction atomic cross-section (σ_t) and total photon interaction electronic cross-section (σ_e) of wrought aluminum alloys 2014 and 2219 have been summarized in Table 2. It is evident from the table that the measured values of these parameters were in good agreement with those obtained theoretically and from values of XCOM. The experimental μ_m values for alloys 2014 and 2219 are smaller than theoretical values. This is due to the presence of other trace elements in the chemical composition of alloys 2014 and 2219. Further, this difference might be from experimental setup, counting and efficiency errors. It is clearly seen from Fig. 2a that variations of μ_m depend on the photon energy and chemical compositions of wrought aluminum alloys 2014 and 2219. The μ_m values of alloys 2014 and 2219 decrease with increasing photon energy. Experimental as well as theoretical values of effective atomic number have also been tabulated in Table.2 and are found to be in good agreement. Moreover it has been observed from Table.2 that the variation in effective atomic number as a function of energy for a given alloy is found to be negligible. The variation of Z_{eff} for each alloy is shown in Fig.2f. But the variation of $Z_{eff..}$ in these alloys is considerable. The variation is shown in Fig.2g. The linear attenuation coefficient (μ_l) is determined for these alloys by using μ_m of the alloys. From the Fig.2c. It is clear that the linear attenuation coefficient is inversely proportional to energy. This is because as energy increases, the transmitted photons increase and the absorbed photons decrease, and hence linear attenuation coefficient decreases. The linear attenuation coefficient is related to the mean free path which is the distance between successive interactions. Mathematically, mean free path is the inverse of the linear attenuation coefficient, the direct relation between it and energy is found, and it explains why the number of interactions becomes higher when the distance between the interactions gets smaller. The variation of impact parameter (λ) of these alloys as a function of energy is shown in fig.2b. Other important parameters that affect the transmission photons are atomic cross-section, and electronic cross-section. The variation in σ_t and σ_e with energy are shown in Fig.2d. and Fig.2e.

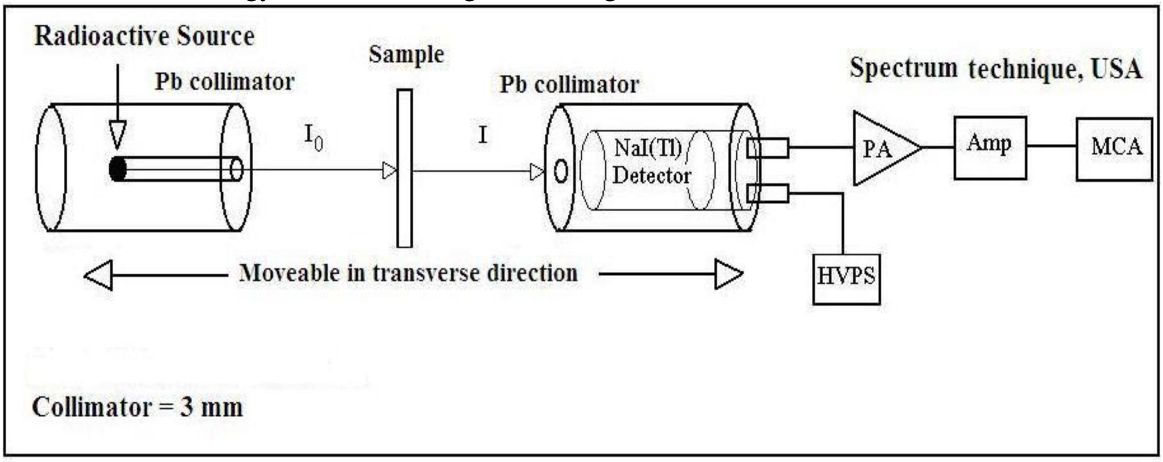

Fig.1. Block diagram of gamma ray absorption setup

Table.1. Chemical composition

	ALLOY	Al	Cu	Mg	Zn	Mn	Fe	Ti-V-Zr	Si	Cr
1	**2014**	93.5	4.4	0.5	-	0.8	-	-	0.8	
2	**2219**	93	6.3	-	-	0.3	-	0.4	-	

Table.2.mass attenuation coefficient, linear attenuation coefficient, mean free path, total atomic, electron cross sections , effective atomic number, effective electron number of wrought aluminum alloys 2014,2219,6061,7075 and 7095 at different energies

energy	**59.54kev**			**661.16kev**			**1173kev**			**1332kev**		
method	**x-com value**	**Emp-value**	**Exptl value**	**x- com value**	**Emp-value**	**Exptl value**	**x-com value**	**Emp-value**	**Exptl value**	**x- com value**	**Emp-value**	**Exptl value**
						μ_m $(10^{-2})gcm^{-2}$						
AL 2014	30.1	34.66	31.31±0.	7.47	7.46	7.24±0.23	5.67	5.67	5.23±0.2 3	5.39	5.310	5.17±0.2 3
2219	37.30	37.31	35.21±0.	7.47	7.45	7.29±0.23	5.66	5.66	5.48±0.2 3	5.30	5.30	5.16±0.2 3
						μ_l $(10^{-2})cm^{-1}$						
2014	84.28	97.06	87.67	20.91	20.88	20.28	15.88	15.86	14.65	14.89	14.87	14.49
2219	105.93	105.95	100.0	21.20	21.16	20.69	16.07	16.07	15.58	15.06	15.06	14.66
						λ in cm						
2014	1.19	1.03	11.41	4.78	4.79	4.93	6.30	6.30	6.83	6.72	6.73	6.90
2219	1.21	1.21	1.20	5	5	4.97	6.57	6.57	6.50	7.01	7.01	6.97
						$\sigma_t$$(10^{-24})$b/atom						
2014	13.89	15.99	14.45	3.45	3.44	3.34	2.62	2.61	2.41	2.45	2.45	2.39
2219	17.40	17.41	16.43	3.483	3.48	3.40	2.64	2.64	2.56	2.48	2.48	2.41
						σ_e (10^{-25}) b/atom						
2014	10.38	11.96	10.80	2.58	2.57	2.50	1.96	1.96	1.80	1.83	1.83	1.78
2219	12.88	12.88	12.15	2.577	2.57	2.52	1.95	1.95	1.89	1.83	1.83	1.78
						$Z_{effective}$						
2014	13.38	13.38	13.38	13.38	13.38	13.38	13.38	13.38	13.38	13.38	13.38	13.38
2219	13.52	13.52	13.52	13.52	13.52	13.52	13.52	13.52	13.52	13.52	13.52	13.52
						$N_{eff}(10^{23})$						
2219	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90

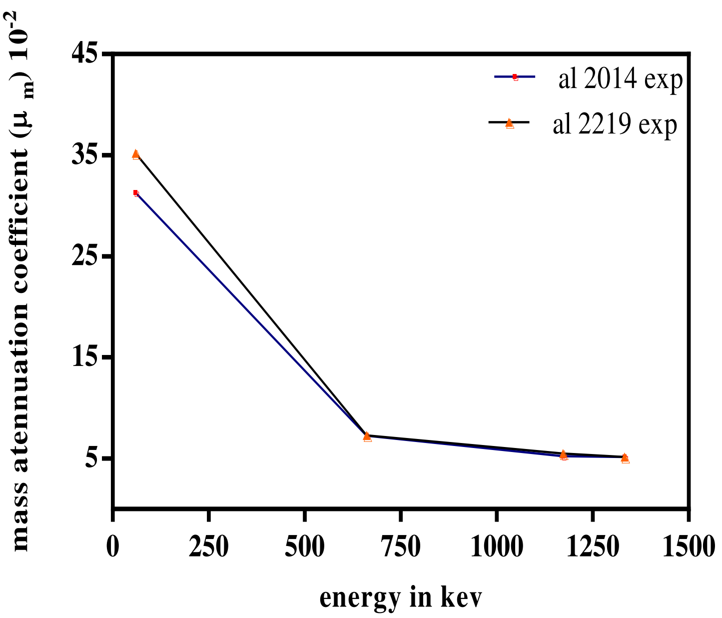

Fig.2a.mass attenuation coefficient of wrought aluminum alloys as a function of energy

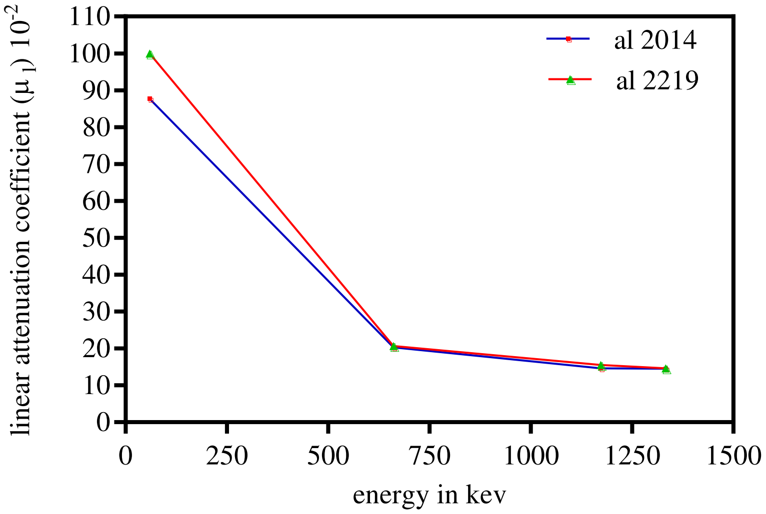

Fig.2b.Linear attenuation coefficient of wrought aluminum alloys as a function of energy

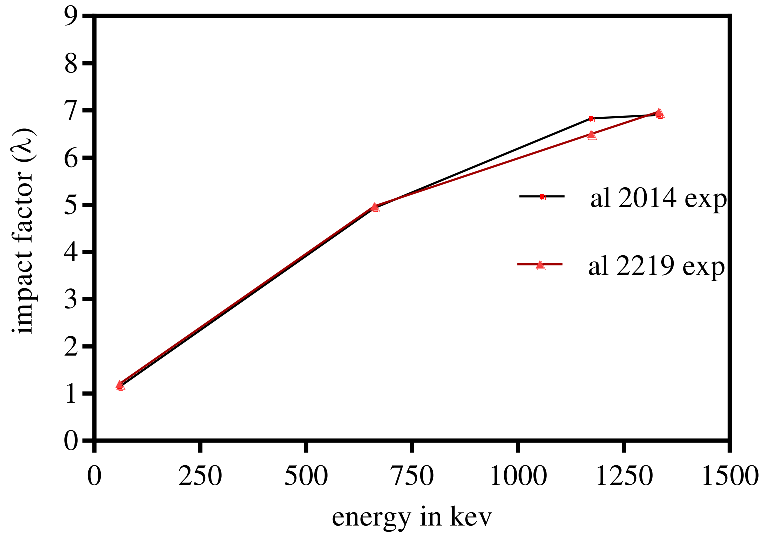

Fig.2c.Impact parameter of wrought aluminum alloys as a function of energy

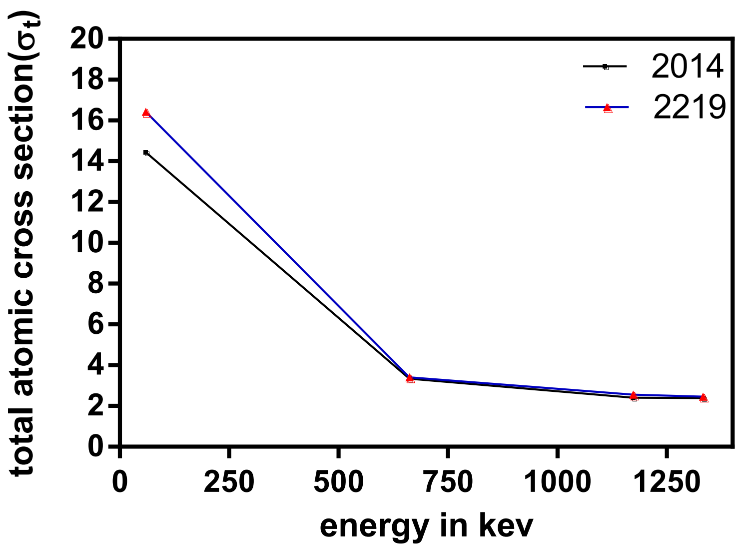

Fig.2d.Total atomic cross section of wrought aluminum alloys as a function of energy

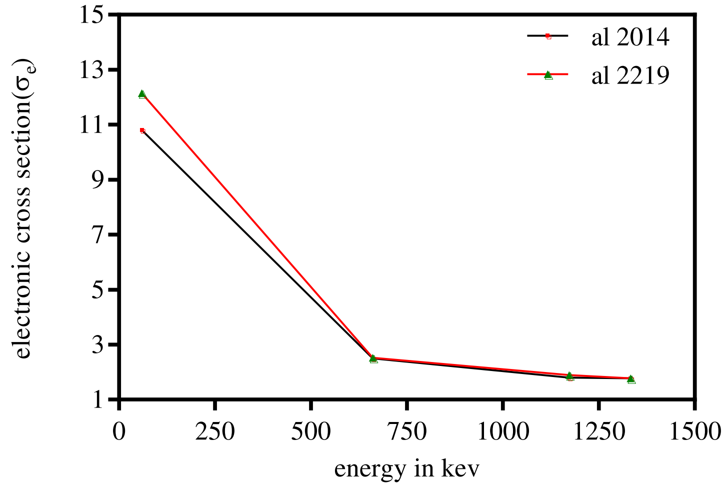

Fig.2e.Electronic cross section of wrought aluminum alloys as a function of energy

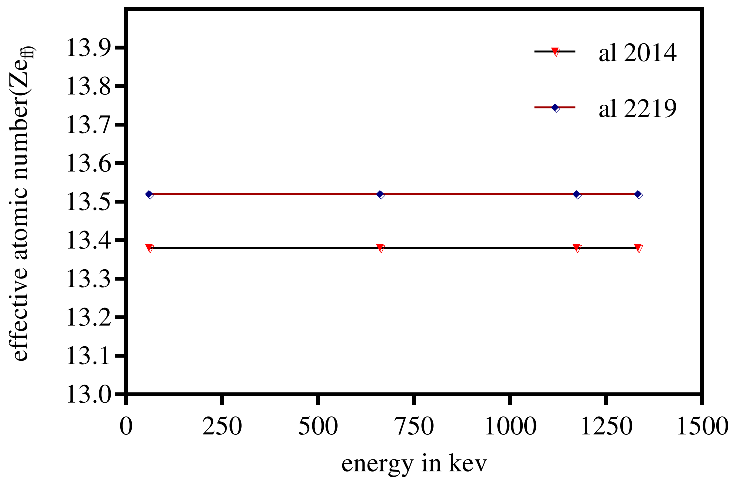

Fig.2f.Effective atomic number of wrought aluminum alloys as a function of energy

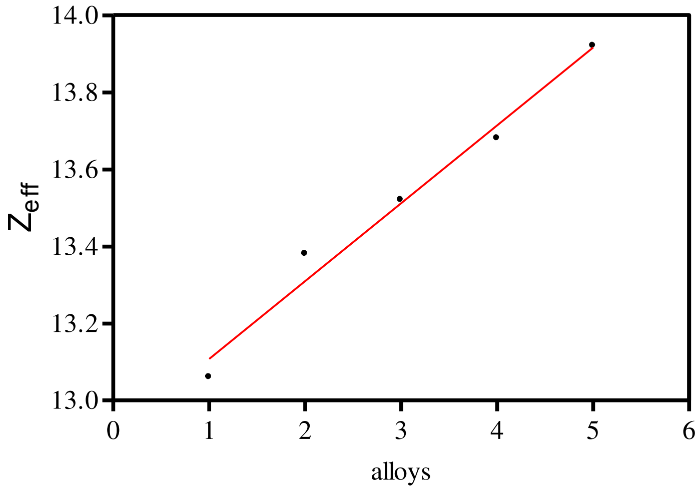

Fig.2g.variation of effective atomic number with alloy composition

5. CONCLUSIONS:

The present experimental study has been undertaken to obtain information on the μ_m and related parameters (Z_{eff}, N_{eff}, σ_t and σ_e) for wrought aluminum alloys 2014 and 2219 alloy. We have demonstrated that the μ_m is a useful and sensitive physical quantity to determine the Z_{eff} and N_{eff} for alloys. In the interaction of photon with matter, μ_m values are dependent on the physical and chemical environments of the elements in the sample. The μ_m values of these alloys decrease with increasing photon energy, also the variation of σ_t and σ_e with energy is identical to μ_m, in studied energy region, Z_{eff} values up to four significant digits shown in the table.2 for present alloys cannot vary with photon energy. It is also dependent on the spread in the atomic numbers of the elements of which the alloy is composed. The N_{eff} is closely related to the Z_{eff} and energy dependence of N_{eff} is the same as Z_{eff}. In the present study, it is indicated that the μ_m, Z_{eff} and N_{eff} are useful parameters for alloys. The results of this study will be helpful to understand better how mass attenuation coefficients change with variation of the atomic and electronic number for different alloy compositions. To our best knowledge, experimental and theoretical investigations of the μ_m, σ_t, σ_e, Z_{eff} and N_{eff} for wrought aluminum alloys 2014 and 2219 are not available in the literature. Moreover, the results of this work can stimulate both experimental and theoretical research for alloys.

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