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Investigation the Effective atomic number , electron density, Half value layer and mean free path of steel types304and 347 in the energy range 40KeV-130KeV

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Abstract:
Effective atomic number (Z_{eff}) ,electron densities (N_{el}) , half value layer(HVL)and mean free path (*mfp*) has been determined with the help of semi-empirical relations for Stainless steel of types: 304 and 347 at energy range 40-130keV .The effective atomic number and effective electron, densities and mean free path are found nearly remain constant as a function of energy.

Keywords :
Effective atomic number ,electron density, half value layer ,mean free path, Stainless steel ,cross section, mass attenuation coefficient, WinXCom.

Introduction

Among the parameters determining theconstitutive structure of material and the support of areasof application, such as medical radiation dosimetry,industry and radiation shielding, mass attenuationcoefficient, effective atomic number, effective electrondensity, and photon mean free path are the fundamentalparameters to study the interaction of photon with matter.These parameters are important for solving variousproblems in radiation physics[1]. The most relevant parameter determining the photon interaction in the material is the mass attenuation coefficient (μ/ρ) that is a measure of probability of interactions of incident photons with the thickness (g/cm^2) of target material is of importance in dosimetry, radiography, radiation shielding, computerized tomography, etc. [2]. It follows from the above that (μ/ρ) is a basic quantity used in calculations of the penetration of photons in biological, shielding and other materials [3].While the extensive and accurate data sets areavailable for elements [4–7], studies in composite materials suchas different alloys are meager due to difficulty in procuring targetsin suitable form for experiments [8].In composite materials like alloys, it is quite reasonable to define an effective atomic number, Z_{eff} to describe the properties of an alloy in terms of an equivalent element. Effective atomicnumber of an alloy, which is a very useful parameter for manyfields of scientific applications, is similar to that atomic number ofelements. However, on the basis of Hine's expression [9] that theeffective atomic number of a material composed of severalelements cannot be expressed by a single number, it can beconcluded that it is an energy-dependent parameter due todifferent partial photon interaction processes with matter for which the various atomic numbers in the material have to be weighted differently.Several investigators have contributed to find the effectiveatomic numbers in different alloys [10–13]. However, thesestudies seem to be restricted to a limited energy range and alsomost of them have focused on interpolation procedures and semi empiricalrelations. Thus, there needs to be some confirmation ofthe results in a continuous energy range by using a direct method.Also, while determining the effective atomic number of an alloy itshould be reasonable to take into account the absorption edges of elements constituting the alloys where there exists more than asingle effective atomic number. From this point of view, we foundit interesting to study the photon interaction in terms of effectiveatomic number for various alloys in an extended energy rangeincluding the K-absorption edges of elements present in thealloys.In the present study, the effective atomic numbers electron density ,mean free path and half value layer of various stainless steel have been calculated for total photon interaction at photon energies from 40keV to 130 keV using mass attenuation coefficients from WinXCom computer program [6,7].

Theroteical Basis :

The concept of cross section:

Photons interact with surrounding matter via four basic processes: materialization into an electron-positron pair in the electromagnetic field of the nuclei and surrounding atomicelectrons, incoherent (Compton) scattering with atomic electrons, photo-electric absorptionand coherent (Rayleigh) scattering with the molecules (or atoms) of the medium. The firstthree collision types transfer energy from the photon radiation field to electrons[14], one ofthem dominate depending on energy and the medium in which the transport takes place.The pair production

process[15,16]dominates at high energies. At some intermediate energiesincoherent scattering is the most important process, at low energies the photo-electric process dominates.The radiation cross section is the effective area of a target presents to a projectile, which determines the probability of the projectile interacting with the target. This cross section is not necessarily identical to the geometric cross section area of the target and cross section not only depends on the type of the target or the projectile interacting with it, but also on the nature of the interaction, i.e. whether it leads to particle scattering, absorption, emission of a secondary particle, etc. The cross section also depends on the energy of the projectile speak .In other words, a slower projectile spends more time in the proximity of the target, hence has a higher probability of interaction, while a swift particle can sweep through the target or its potential field without being affected much. The cross section for scattering can also vary depending on the angle of scattering, along with the energy of the projectile. Therefore, one can define a differential cross section, i.e. a cross section per unit solid angle, which varies from one angle to another. The amount of power re-radiated (or removed from the incident radiation) per unit incident flux (power per unit area) has dimensions of area, and is called the scattering cross section σ. This quantity reflects the area of the target intercepted by incident radiation .Since radiation may scatter in different directions (as measured from the direction of the incident radiation) at different powers, the cross section is determined per unit solid angle as dσ/ dΩ, where Ω refers to the solid angle. This cross section is called the differential, or angular, cross section.The cross section which indicates the probability of interaction has dimensionsof area, while the probability is a dimensionless quantity. In order to reconcilethese dimensional differences, let us consider one radiation particle encountering many targets, each with a cross section, σ, in an infinitesimal slab of thickness, dx.If there are N targets per unit volume, then Nd$x$is the number of targets per unit area, and σNd$x$is the probability of this single radiation particle interacting with the targets in a unit area. In other words, $\sigma$is the probability of interaction of a single radiation particle in an infinitesimally small slab containing one targetper unit area[17].

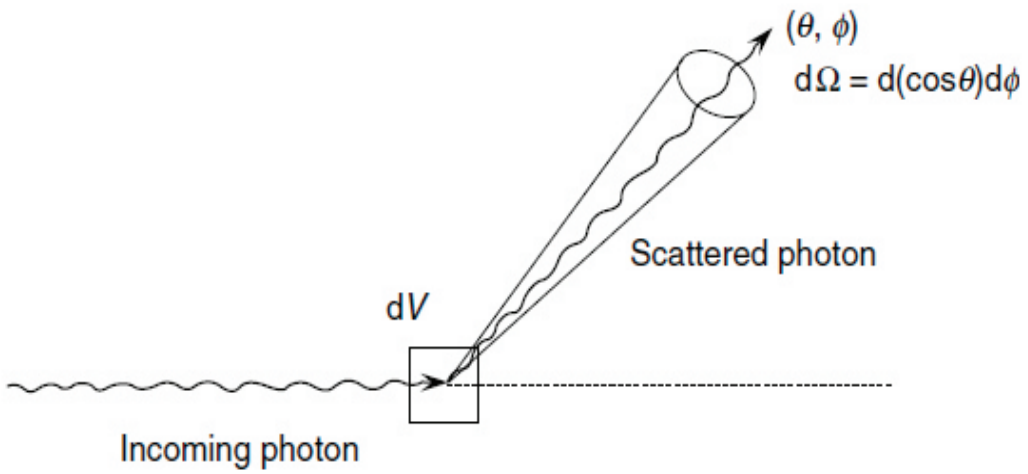

Fig.(1):Scattering angles and solid angle. A photon incident on a small volume element dV with one target entity per unit area normal to its direction of motion [17].

The mass attenuation coefficient(μ/ρ):

The total mass attenuationcoefficient $(\mu/\rho)_{Compound}$ for any chemical compound or mixture of elements represent a measure of the probability of interactions of incident photons with the thickness (g/cm^2)of the target material is of importance in dosimetry ,radiography ,radiation shielding ,computerized tomography ,etc.[2] .The quantity $(\mu/\rho)_{Compound}$ given by mixture rule [18]:

$$(\mu/\rho)_{Compound} = \sum_i w_i (\mu_i/\rho_i) \quad \text{.....(1)}$$

Where w_i and $(\mu/\rho)_i$ are the weight fraction and mass attenuation coefficient of the ith constituentelement, respectively. For a chemical compound the fraction by weight (w_i) is given by[19]:

$$w_i = \frac{n_i A_i}{\sum_j n_j A_j} \text{.....(2)}$$

Where A_i is the atomic weight of the ^{i}th element and $n_i$is the number of formula units. Due to the contribution of differenteffects in the attenuation process. Hence, thetotal attenuation coefficients may be expanded as[20]:

$$\mu = \omega + \tau + \sigma + \kappa + \zeta \text{.....(3)}$$

Where, ω: the probability of coherent scatteringτ: the probability of photoelectric absorption, σ:the probability of Compton scattering, κ: theprobability of pair production ζ .

The total atomic cross-sections (σ_a)

The total atomic cross-sections (σ_a) for materials can be obtained from the calculated values of $(\mu/\rho)_{Compound}$using the following relation[1]:

$$\sigma_a = \frac{N_i}{N_A}(\mu/\rho)_{Compound} \text{.....(4)}$$

Where N_i is the atomic mass of materials and N_A is the Avogadro's number.

The total electronic cross-section (σ_e)

The totalelectronic cross-section (σ_e) is given by the following formula[23]:

$$\sigma_{el} = \frac{1}{N_A}\sum \frac{f_i N_i}{Z_i}\left(\frac{\mu}{\rho}\right)_{Compound} = \frac{\sigma_a}{Z_{eff}} \text{.....(5)}$$

Where $f_i$denotes the fractional abundance of the element i with respect to the number of atoms such that$f_1 + f_2 + f_3 + \ldots + f_i = 1$, $Z_i$is the atomic number of ^{i}th element.

The effective atomic number (Z_{eff})

The common method of obtaining the effective atomic number(Z_{eff}) of the material consisting of different elements based on determination of the total attenuation cross section of atomic $\sigma_a$and electronicσ_{el} respectively ,which they are related through the following relation[23]

$$Z_{eff} = \frac{\sigma_a}{\sigma_{el}} \text{.....(6)}$$

The effective electron number or electron density,N_{el}, (number of electrons per unit mass) can be given by[23]:

$$N_{el} = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{(\mu/\rho)_{compound}}{\sigma_{el}} \text{.....(7)}$$

The mean freepath (*mfp*)

The average distance betweentwo successive interactions, called the photon mean freepath (*mfp*) is given by [1].

$$mfp = \frac{\int_0^\infty x e^{-\mu x} dx}{\int_0^\infty e^{-\mu x} dx} = \frac{1}{\mu} \text{.....(8)}$$

Where the mass absorption coefficient μ_m is defined as

$$\mu_m = \frac{\mu}{\rho} \text{.....(9)}$$

Where ρ is the mass density of the absorber.

TheHalf Value Layer (*HVL)*

The following relation relates half value layer to linear attenuation coefficient[24]:

$$HVL = 0.693 / \mu \quad \ldots\ldots\ldots\ldots\ldots(10)$$

The units of HVL is g/cm^2.

Results and Discussion

Crosssections,effective atomic numbers , electrondensities half value layer in additional to mean free path ; have been calculated with respect tothe mass attenuation coefficients.The experimental data of mass attenuation coefficient has been taken from [26]with the chemical composition of both types and densities of stainless steel in table (1).

Table(1):Chemical composition of both stainless steel 304 and 347[26].

Element Name	Density g/cm^3	Si	Fe	Cu	Zn	Al	Mn	Cr	Ni	C	Nb	Zr	Sn	U
Stainless steel type 304	7.90	0.5	71.4	a	a	a	1.0	17.3	9.8	a	a	a	a	a
Stainless steel type 347	7.91	0.4	69.3	a	a	a	1.2	17.9	10.4	a	0.8	a	a	a

Note: the letter "a" means the quantity less than 0.1% or negligible

Table(2)contains the experimental[25]and calculatedvalues of μ/ρ by using computer code of XCOM at photon energies of 40kev-130keV .The XCOM databases run on a personal computer and prepared by combining previously existing data bases for coherent and incoherent scattering ,photoelectric absorption ,and pair production cross sections. It uses chemical structure and atomic number of material as input for materials ,the values ofμ/ρ for the samples varied by reducing with the increasing photon energies for the same materials, because the mass of the material itself provides the attenuation, attenuation coefficients are often characterized by ρ is the material density. The values of μ/ρ are believed to be affected by the chemical , molecular and thermal environments .These phenomena lead to the deviation of the experimental μ/ρ values from that of the present calculated values ,since the evaluation of the theoretical value has been done by considering the cross section of an isolated atom .This deviation is termed as the breakdown or nonvalidity of the mixture rule[25].

The results given in the table 3 are the experimental and theoretical values of the atomic cross-sections of stainless steel calculated by using equation4 .The experimental values of present work are smaller than the theoretical values at low energies.This difference might be from experimental setup, counting and efficiency errors in comparison to the calculated results. The Iron and Nickel and on the other hand ,had a great contribution in various interaction with x-raydue to the size of their atoms(Fe and Ni)are sufficiently large which compose the compounds, so the electrons in the last shellare fewer bands to the nucleus; this pointincreases the interaction probabilities for such these atoms , rather than Mn-atom, C-atom, Si-atom in the two compounds.

The table4 represent the results ofexperimental and theoretical valuesof the electronic cross-sections and electron density of steel 304 calculated by using equations5 and 7 respectively.Values of electronic cross-sections inthe present work are smaller than their theoretical values. The difference might be from experimental setup, counting and efficiency errors. while the electron density are the same for both methods.

The table 5represent the results of experimental and theoretical values of the electronic cross-sections and electron density of steel 347 calculated by using equations 5 and 7 respectively. Values of electronic cross-sections and electron densities of experimental work are smaller than the theoretical values. The difference might be from chemical composition of two alloys.

Table (6) contains the effective atomic number Z_{eff} by employing the equation6.After finding the cross-section of the samples, the calculation of effective atomic number Z_{eff} and electron density becomes possible, the results are arranged in the table 5 below ,shows the effective atomic numbers to be constant as a function of energy of rang 40keV-130keV. This may be due to the dominance of photoelectric effect and Compton effect in their respective energy regions[27].The $Z_{eff}$and also the N_{eff} remains nearly constant(very close to each other)for different energies and are found to be independent of photon energy for a compound.The table 7 calculated mean free path and HVL of steel 304 and 347 obtained by application the equation 7,8 and 9.The mean free path is the average distance between the collisions and therefore it considered as a measure of the probability of a particular interaction. The quantity (*mfp*) inversely proportional to the cross section and the density of the material, that is Note that the definition of the mean free path depends on the type of cross section used in the calculation. The HVL physically represent the equivalence of the material thickness that is reduces the intensity

of radiation to half such a quantity reflect the fact that energetic photons has an ability to penetrates the steel as energy increases .

Conclusions

1-The effective atomic numbers of stainless steel have been calculated for total photon interaction in an extended energyrange of x-ray (40 keV–130 keV) by using mass attenuation coefficients from WinXCom .

2-Although both mass attenuation coefficient and effective atomic number depends upon the photon energies ,the electron density does not significantly depend upon photon energy .Small amounts from elements like: Cu,Zn,Mn, C,Sn ,Zr , and Nb in the alloys does not affect the be attenuation coefficient .

3-The author here does not compare the present results with other work like [28] because the elements concentration does not similar that stainless steel elements contents in present study.

4-Both the half value layer and mean free path are increasing with increasing the incident photon energy and decreases with increasing the density of matter.

5-All theevaluated parameters has a physical meaning and allows many characteristics of a material to be visualized with an abstracted numbers.

6-The linear attenuation coefficientμ of a material depends on the photon energy , the atomic numbers Z of the elements that compose the material, and the material density.

Table2:Thecalculated and experimental[25] mass attenuation coefficient of steel304 and 347.

Energy (KeV)	μ/ρ (Cal. 304) (cm^2/g)	μ/ρ (Cal.347) (cm^2/g)	μ/ρ (Exp.304) (cm^2/g)	μ/ρ (Exp.347) (cm^2/g)
40	2.45	3.464	3.393	2.57
45	1.80	2.477	2.426	2.09
50	1.51	1.843	1.804	1.65
55	1.25	1.416	1.387	1.30
60	0.968	1.119	1.096	1.04
65	0.811	0.9055	0.888	0.943
70	0.712	0.7501	0.7353	0.772
75	0.607	0.6325	0.6204	0.597
80	0.544	0.5424	0.5324	0.577
85	0.527	0.4722	0.4638	0.524
90	0.449	0.4166	0.4095	0.468
95	0.406	0.3721	0.366	0.423
100	0.352	0.3359	0.3307	0.395
110	0.303	0.2818	0.2776	0.323
115	0.288	0.2609	0.2575	0.316
120	0.279	0.2435	0.2404	0.283
125	0.262	0.2341	0.2380	0.260
130	0.231	0.2158	0.2134	0.250

Table3.The calculated and experimental[25]atomic Cross section, of steel304 and 347.

Energy (KeV)	$\sigma_a \times 10^{-24}$ (Cal. 304) (cm^2/atom)	$\sigma_a \times 10^{-24}$ (Exp.304) (cm^2/atom)	$\sigma_a \times 10^{-24}$ (Cal.347) (cm^2/atom)	$\sigma_a \times 10^{-24}$ (Exp.347) (cm^2/atom)
40	44.112	62.3633	34.986	25.957
45	33.084	44.589	25.0177	21.109
50	27.7538	33.084	18.6143	16.665
55	22.975	25.493	14.3016	13.130
60	17.7918	20.1444	11.3019	10.504
65	14.906	16.32144	9.1550	9.5243
70	13.0865	13.5148	7.576	7.7972
75	11.1566	11.402	6.388	5.9792
80	9.998	9.7855	5.478	5.8277
85	9.686	8.5246	4.769	5.2924
90	8.2526	7.5266	4.207	4.726
95	7.4626	6.727	3.758	4.726
100	6.4697	6.07826	3.3925	3.989
110	5.569	5.102	2.8440	3.2623
115	5.29344	4.7328	2.635	3.1916
120	5.128	4.4185	2.4593	2.858
125	4.3	4.152	2.3088	2.575
130	4.245	3.9222	2.1795	2.525

Table 4: The calculated and experimental[25]electronic cross-sections and electron density of steel 304 .

Energy (KeV)	$\sigma_{el} \times 10^{-25}$ (Cal. 304) (cm^2/elect.)	$N_{el} \times 10^{23}$ (Cal.304) (cm^2/elect.)	$\sigma_{el} \times 10^{-25}$ (Cal.304) (cm^2/elect.)	$N_{el} \times 10^{23}$ (Exp.304) (cm^2/elect.)
40	8.673	2.8248	12.01122	2.824858
45	6.372	2.8248	8.5880	2.824871
50	5.345	2.825	6.3720	2.831136
55	4.425	2.82485	4.9099	2.82490
60	3.426	2.82485	3.8798	2.82488
65	2.870	2.82487	3.1435	2.824876
70	2.520	2.82539	2.6629	2.76127
75	2.148	2.82588	2.1962	2.8248
80	1.92576	2.82485	1.8846	2.82485
85	1.8655	2.82497	1.64185	2.82486
90	1.58946	2.82485	1.44963	2.82485
95	1.4372	2.824937	1.2650	2.89190
100	1.2460	2.82504	1.1706	2.8250
110	1.0726	2.8249	0.9827	2.8248
115	1.01952	2.82485	0.9155	2.8126
120	0.9876	2.8250	0.8510	2.84249
125	0.82836	2.82485	0.79968	2.82487
130	0.81774	2.8266	0.75543	2.82488

Table 5: The calculatedand experimental[25] electron densities electronic cross-section coefficient of steel347.

|Energy (KeV)	$\sigma_{el}\times 10^{-25}$ (Cal. 347) (cm^2/elect.)	$N_{el}\times 10^{23}$ (Cal .347) (cm^2/elect.)	$\sigma_{el}\times 10^{-25}$ (Exp.347) (cm^2/elect.)	$N_{el}\times 10^{23}$ (Exp.347) (cm^2/elect.)
40	12.505	3.994	9.2777	2.1396
45	8.9419	3.8873	7.5449	2.4336
50	6.6532	3.448	5.9565	2.58945
55	5.11176	3.2	4.693	2.64771
60	4.03959	3.266	3.7533	2.66805
65	3.2724	3.15853	3.4042	2.9998
70	2.7078	2.976	2.7869	2.8990
75	2.2833	3.396	2.15517	2.71833
80	1.958	2.8165	2.0829	3.0615
85	1.7046	2.53122	1.8916	3.19152
90	1.50392	2.9985	1.68948	3.22841
95	1.3432	2.58942	1.528	3.3582
100	1.21259	2.69582	1.42595	3.37433
110	1.016576	2.62539	1.166	3.28686
115	0.94184	2.559	1.1407	3.45166
120	0.879	2.46557	1.0216	3.32549
125	0.82524	2.775966	0.9205	3.188775
130	0.7790	2.63898	0.9025	3.30937

Table 6:The calculated and experimental [25]effective charge(dimensionless) of steel 304 and 347.

Energy (KeV)	Z_{eff} (Cal. 307)	Z_{eff} (Exp.304)	Z_{eff} (cal.347)	Z_{eff} (Exp.347)
40	5.086129	5.1488	2.79776	2.797783
45	5.192090	5.1920121	2.7977805	2.797783
50	5.192478	5.19209	2.797796	2.7980
55	5.192478	5.1921627	2.797783	2.797783
60	5.19209	5.192123	2.797783	2.797783
65	5.193169	5.19211	2.797640	2.797808
70	5.193728	5.1922086	2.7978432	2.797804
75	5.193055	5.1916947	2.797705	2.774351
80	5.19394	5.1923485	2.797752	2.797877
85	5.1918782	5.1920699	2.797723	2.797843
90	5.19273	5.192083	2.7966913	2.797310
95	5.192272	5.19243	2.797796	2.79783
100	5.19245	5.1924	2.797138	2.797531
110	5.192375	5.191818	2.79762	2.797855
115	5.19205	5.16963	2.797715	2.797783
120	5.19205	5.1292126	2.797838	2.797572
125	5.191355	5.192076	2.797731	2.7973927
130	5.191136	5.19200	2.797817	2.797839

Table7:The calculated mean free path(cm)and half value layer(g/cm^2)of steel 304 and 347.

Energy (KeV)	mfp (cal 304)	mfp (cal.347)	HVL (cal.304)	HVL (cal.347)
40	0.0517513	0.036532	0.035804	0.0252917
45	0.0704394	0.0510888	0.04873	0.0353696
50	0.0839674	0.0686636	0.0580937	0.0475369
55	0.1014327	0.113089	0.0701772	0.0618718
60	0.1309823	0.139638	0.0906214	0.078392
65	0.1563389	0.168753	0.1081646	0.0782936
70	0.1780771	0.20013	0.12320	0.0967538
75	0.2088812	0.233374	0.1445165	0.1167985
80	0.2330715	0.2680692	0.161252	0.1385148
85	0.2405899	0.3038460	0.1664544	0.1615240
90	0.282385	0.340183	0.1953708	0.185537
95	0.312292	0.376845	0.216596	0.2102991
100	0.360201	0.44951	0.2699122	0.235449
110	0.4184518	0.44950	0.289501	0.260823
115	0.4402462	0.485171	0.30458	0.310896
120	0.4544477	0.519895	0.3144140	0.335801
125	0.5418415	0.553728	0.37650	0.359797
130	0.548878	0.586572	0.3797468	0.3832485

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