Shielding parameters for cobalt free steel alloys

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Abstract. Steel alloys are widely used for radiation shielding in nuclear applications since Cobalt is an expensive element, this leads to the steels may be expensive, so it is preventing wider application and selection. So the important direction of this research is preparing cobalt-free maraging stainless steel as shielding to reduce the production cost. Therefore, seven different free-cobalt steel alloys were prepared by using an electro slag re-melting technique. Steel compound ratios were calculated by using the software WinXCOM program for Monte Carlo simulation, at energies of photon 662, 1173 and 1332 keV. The attenuation properties of these alloys were studied. Furthermore, the total of removal macroscopic cross-section, transmission number and mean free path were determined using Geant4 code for fast neutrons radiation shielding. Therefore, shielding parameter variations are applied to the steel alloys to investigate the superior shielding properties to gamma rays than other materials.

Keywords. Free cobalt stainless steel, Coefficients of mass attenuation, Fast neutrons, Removal cross-section

1. Introduction
Gamma and neutron radiation are employed in many applications like high-energy physics, material analysis, and nuclear plants [1-24]. According to this purpose; using the radiations increases every day in technology, and the need for electrical energy increases, leading to more and more new nuclear power plants [2–3]. According to this purpose; different types of stainless steel were developed, containing of heavy elements such as iron, barium, or titanium in their structure [4–5]. This steel has well mechanical properties at high temperatures, so it may be used for radiation protection in many applications in nuclear energy reactors. The steel is that the protected material within the transfer of heat system within the core of the reactor and also the neutron modulation system. The coefficient of attenuation is a very dominant parameter which distinguishes between the spread and gamma rays and penetration of neutrons with the matter, and depends on alloys chemical compositions with falling energy [22]. The scattered and absorbed radiation is relevant to the electron effective density and the matter density. Using 137Cs and 60Co sources for gamma rays to calculate linear mass attenuation coefficients at energies of photon from 662 keV to 1.33 MeV [6-20]. Therefore,
the aim of the present work is producing cobalt-free alloys composite capable of use as a nuclear radiation shield, which is better than other alloys. From the result, the total removal cross-section, transmission number and mean free path values of studied steel alloys are a good type of stainless steel for shielding specially (0.032 % Ni, 0.009 % Mo, 0.087 % Cr, 0.948 % Mn, 0.002 % Ti, 0.005 % V, 97.01 % Fe, 0.3 % C, 0.035 % P, 0.012 % S with minor elements to reach 100% of the composition) with density 8.28 g/cm$^3$ compared with the different steel alloys used in a convenient material shielding in the field of nuclear.

2. Methods and materials

2.1 Preparation sampling of the Material Shielding

The preparation samples of free cobalt stainless-steel done by induction the furnace of pilot plant electro-slag re-melting technique (ESRT). We used Chromium and titanium instead cobalt element to outdo the issue of austenitic retained. The percentage content of nickel reduced to 14 % by weight. Materials mixed for 15min and became a homogeneous mixture; it heated at 350°C and pelletized pressure at 600 MPa. The formed samples pellet annealed at 820 °C for one hour and repeating this process for two hours at 1300 °C [7-12], and then annealed studied samples of steel alloys were hardened by the faster cooling process.

2.2 Mass Attenuation Coefficient

By using the method of gamma transmission, we used a detector (HPGe) with relative efficiency 25% relative to the NaI(Tl) detector for measuring the coefficient of mass attenuation for gamma radiation with a collimated narrow beam. The sample located among the standard source of gamma radiation and detector. Repeat this process once with the sample and once without it for 5 minutes. The samples irradiated by emitted photons from (137 Cs and 60 Co) sources radioactive from 662 keV to 1.33 MeV [6-14]. Using the Lambert-Beer law for gamma-ray photons mono-energetic parallel beam was attenuated with the matter [15].

\[ I(x) = I_0 \exp(-\mu x) \] (1)

Where $I_0$ is the density of initial photon, $I(x)$ is the collimated beam which photons are penetrated thickness $x$ and $\mu$ is the total linear attenuation coefficient. So the equation may be written for the collimated beam by:

\[ \frac{\mu}{\rho} = \frac{\ln(I_0/I)}{x} \] (2)

The mass attenuation coefficient $\mu/\rho$ for mixtures of elements can be calculated by eq.[16-17]

\[ \frac{\mu}{\rho} = \sum w_i \left( \frac{\mu_i}{\rho_i} \right) \] (3)

Where $\rho$ is partial density, $(\frac{\mu}{\rho})_i$ is the mass attenuation of the $i^{th}$ constituent and $w_i$ is the weight fraction of $i^{th}$ constituent. Also, the half-value layer (HVL) can be calculated:

\[ HVL = \frac{\ln(2)}{\mu} \] (4)

2.3 Monte Carlo simulation codes Geant4

Geant4 is a software tools for the simulation of the particles movement through matter and it used by a huge number of projects and experiments in several application fields such high energy physics, astrophysics and space science, medical physics, and radiation protection. Its operation and modeling capabilities continue to be extensive, while its performance enhanced. An overview of recent developments in diverse areas of the toolkit is presented. These include performance optimization for complex setups; improvements for the propagation in fields; new options for event biasing; and additions and improvements in geometry, physics processes and interactive capabilities [19]. The simulation Geant4 code is depend on the targeted material type, the particle geometry and various energies of photon. The simulation experimental setup explains what is happening between targeted material and
radiation. It used in high energy physics, nuclear applications and in the, materials research, medical physic and particle accelerator [8-13].

2.4 Theoretical basis

2.4.1 The effective removal cross-section of Fast neutrons (ΣR) cm⁻¹

The effective removal cross-section is called also attenuation coefficient of neutron (ΣR) for homogenous mixtures or compounds, and it can be determined by using Kaplan eq. [18].

\[
\Sigma_R/\rho = \frac{\text{Ln}(\Sigma_{R}^{0}/\rho)}{\rho x} = \Sigma W_i (\Sigma R/\rho) _i
\] (5)

\[
\Sigma_R = \frac{\text{Ln}(\Sigma_{R}^{0}/\rho)}{\rho x} = \Sigma \rho_i (\Sigma R/\rho) _i
\] (6)

Where \(W_i\) is the percentage weight, \(x\) is the alloy thickness, \(\rho_i\) is the partial density and \((\Sigma R/\rho) _i\) is the fast neutron mass attenuation coefficient of the \(i^{th}\) constituent.

2.4.2 The Total macroscopic cross-section (Σj) cm⁻¹

The total of macroscopic cross section is a very significant parameter for neutron shielding particles, and this theoretically values was calculated for energy 4.5 MeV fast neutrons by using simulation of Monte Carlo Geant 4 code. The results are showed in Table 4. The cross-section used for explain the reactions possibility among neutrons and target material in particle physics and nuclear physics [9-12], how a particle or a neutron can be interacting with the material target categorized by the cross-section. Neutron reaction probability with the light ions (alpha particles) or nucleus by a microscopic cross-section (\(\sigma\)) and the interaction probability with the heavier materials are calculated by the macroscopic cross-section. Neutrons can interact with the target material such as absorption, scattering, fission, capture, etc.. So the total macroscopic cross-section (\(\Sigma_j\)) can be determined by equation [9-10].

\[
\Sigma_j = N\sigma
\] (7)

Where \(\sigma\) is the microscopic cross-section unit with m⁻¹ and \(N\) is the atomic density of target material which given by:

\[
N = (\rho/A).NA
\] (8)

As \(\rho\): density target material, \(NA\) : Avogadro number.

\[
\Sigma\text{ Total} = \Sigma\text{ scattering} + \Sigma\text{ absorption} + \Sigma\text{ capture} + \Sigma\text{ fission} ...
\] (9)

Materials that have large total cross-section are excellent moderators for neutrons that means the high possibility interaction with the target materials [9-10].

The mean free path \(\lambda\) is the path traveled by a neutron among two collisions or interactions with the target material and the collision probability \(P(x)\) at a distance \(x\) taken by a neutron in the material target can be determined [13-15].

\[
p(x)dx = \Sigma_t \exp^{-\Sigma x}dx
\] (10)

\(\Sigma_t\): The distance of neutrons this can be taken in the material without any interaction. The mean free path \(\lambda\) may be calculated by using:

\[
\lambda = \int_0^\infty x p(x)dx = \frac{1}{\Sigma_t}
\] (11)

\(\Sigma_t\): The interaction possibility of neutron per unit length [11], transmission number of neutron that passing and incoming is explained by transmission 100,000 fast neutrons which sent to each material and the numbers of neutrons passing through the materials can be calculated by (Geant 4 code) Monte Carlo simulation.

3. Result and discussion

In this research, the seven new different samples of high-alloyed steel were produced, the chemical compositions of them showed in table 1.
Table 1: Chemical compositions and densities of produced alloys.

| Sample | Elements (wt. %) | Density (g/cm³) |
|--------|-----------------|----------------|
|        | Ni  | Mo  | Cr  | Mn  | Ti  | V   | Fe  | C   | P   | S   |
| s1     | 0.032 | 0.009 | 0.087 | 0.948 | 0.002 | 0.005 | 97.01 | 0.3   | 0.035 | 0.012 | 8.28 |
| s2     | 12.655 | 5.565 | 5.15 | 0.258 | 0.0045 | 0.033 | 75.03 | 0.05  | 0.014 | 0.009 | 7.93 |
| s3     | 12.61 | 5.76 | 5.3  | 0.275 | 0.0075 | 0.037 | 74.62 | 0.04  | 0.013 | 0.005 | 7.91 |
| s4     | 13.48 | 3.915 | 9.04 | 0.2865 | 0.1165 | 0.0735 | 71.42 | 0.02  | 0.015 | 0.005 | 7.8  |
| s5     | 12.225 | 5.305 | 5.74 | 0.31  | 0.414  | 0.052 | 74.26 | 0.03  | 0.01  | 0.005 | 8.12 |
| s6     | 10.46 | 4.585 | 17.03 | 0.491 | 0.0165 | 0.0735 | 63.97 | 0.02  | 0.015 | 0.011 | 7.67 |
| s7     | 11.825 | 3.595 | 13.24 | 0.371 | 0.097  | 0.097 | 67.55 | 0.02  | 0.015 | 0.011 | 7.77 |

The gamma rays attenuation coefficient of the prepared different steel alloys observed with energy range 622 - 1333 keV. The intensities of gamma rays that transmitted through the steel alloys samples was determined and given as samples thickness function. The curves of attenuation were used to find the linear attenuation coefficients average values and hence the coefficients of experimental mass attenuation (μ/ρ)Exp. also found. These values of (μ/ρ)Exp. tabulated in Table2 and it compared with the theoretical coefficients of mass attenuation (μ/ρ)Theo. which completed by using WinXCOM software computer [24]. It observed that the coefficient of mass attenuation has nearly the same behavior for all investigated steel alloys. Also the coefficients of mass attenuation have nearly the same values for all the prepared samples. This behavior was mainly due to the balance in the high value of different Z-elements (Cr, Ni, Mn and Fe) of the steel grades.

Table 2: The mass attenuation (μ/ρ)Exp and (μ/ρ)Theo for the studied alloy with different thickness (t).

| Sample | Energy line (keV) | Mass attenuation (μ/ρ)Exp (cm²/gm) | Mass attenuation (μ/ρ)Theo (cm²/gm) |
|--------|------------------|-----------------------------------|-----------------------------------|
| S1     | 662              | 0.0734±0.009 t = 0.43 cm          | 0.0735                            |
| S1     | 1173             | 0.0551±0.001 t = 0.868 cm         | 0.0553                            |
| S1     | 1333             | 0.0518±0.001 t = 1.308 cm         | 0.0518                            |
| S2     | 662              | 0.0734±0.009 t = 0.43 cm          | 0.0733±0.009                       |
| S2     | 1173             | 0.0551±0.001 t = 0.868 cm         | 0.0552±0.001                       |
| S2     | 1333             | 0.0518±0.001 t = 1.308 cm         | 0.0547                            |
| S3     | 662              | 0.0734±0.009 t = 0.43 cm          | 0.0734±0.009                       |
| S3     | 1173             | 0.0551±0.001 t = 0.868 cm         | 0.0555±0.001                       |
| S3     | 1333             | 0.0518±0.001 t = 1.308 cm         | 0.0518                            |
| S4     | 662              | 0.0734±0.009 t = 0.43 cm          | 0.0734±0.009                       |
| S4     | 1173             | 0.0551±0.001 t = 0.868 cm         | 0.0552±0.001                       |
| S4     | 1333             | 0.0518±0.001 t = 1.308 cm         | 0.0518                            |
| S5     | 662              | 0.0734±0.009 t = 0.43 cm          | 0.0734±0.009                       |
| S5     | 1173             | 0.0551±0.001 t = 0.868 cm         | 0.0552±0.001                       |
| S5     | 1333             | 0.0518±0.001 t = 1.308 cm         | 0.0518                            |
| S6     | 662              | 0.0734±0.009 t = 0.43 cm          | 0.0734±0.009                       |
| S6     | 1173             | 0.0551±0.001 t = 0.868 cm         | 0.0552±0.001                       |
| S6     | 1333             | 0.0518±0.001 t = 1.308 cm         | 0.0518                            |
| S7     | 662              | 0.0734±0.009 t = 0.43 cm          | 0.0734±0.009                       |
| S7     | 1173             | 0.0551±0.001 t = 0.868 cm         | 0.0552±0.001                       |
| S7     | 1333             | 0.0518±0.001 t = 1.308 cm         | 0.0518                            |
**Figure 1.** The relation among mass attenuation (exp. and theo) with different energies for sample 1.

**Figure 2.** The relation among mass attenuation (exp. and theo) with different energies for sample 2.
**Figure 3.** The relation among mass attenuation (exp. and theo) with different energies for sample 3.

**Figure 4.** The relation among mass attenuation (exp. and theo) with different energies for sample 4.
Figure 5. The relation among mass attenuation (exp. and theo) with different energies for sample 5.

Figure 6. The relation among mass attenuation (exp. and theo) with different energies for sample 6.
Figure 7. The relation among mass attenuation (exp. and theo) with different energies for sample 7. The observed variations in the coefficients of mass attenuation as shown in the previous figures (1: 7) of different seven studied samples and can be explained by photon energy and Z-dependency of an interaction elements cross-section. There were two different regions observed in the behavior of the coefficients of mass attenuation. First region is a sharp decrease of coefficients of mass attenuation in the energy range up to 622 keV because of the dominant reaction among gamma rays and the investigated alloys grades is the photoelectric effect. Second region is a slight decrease in the coefficients of mass attenuation from 911.2 keV up to 1333 keV, which may be considered this process of Compton scattering [19]. Additionally, it is excellent agreement among the experimental results of coefficients of mass attenuation and corresponding theoretical data which determined by the WinXCOM software. Half value layer is the required thickness to half the intensity of coming radiation. It observed in table 3 the sample number 1 has the smallest “HVL” among samples that examined. Samples that have smallest value of “HVL” means that have more ability for absorption the radiation.

Table 3: Half value layer at different thickness of studied samples.

| Sample | Energy line (keV) | HVL |
|--------|------------------|-----|
|        |                  | t = 0.43 cm | t = 0.868 cm | t = 1.308 cm |
| S₁     | 662              | 1.140 | 1.14 | 1.71 |
|        | 1173             | 1.518 | 1.51 | 2.27 |
|        | 1333             | 1.616 | 1.61 | 2.43 |
| S₂     | 662              | 1.188 | 1.19 | 1.79 |
|        | 1173             | 1.576 | 1.58 | 2.39 |
|        | 1333             | 1.682 | 1.69 | 2.55 |
| S₃     | 662              | 1.213 | 1.19 | 1.79 |
|        | 1173             | 1.616 | 1.58 | 2.38 |
|        | 1333             | 1.725 | 1.69 | 2.55 |
| S₄     | 662              | 1.208 | 1.21 | 1.82 |
|        | 1173             | 1.593 | 1.58 | 2.39 |
|        | 1333             | 1.709 | 1.71 | 2.58 |
| S₅     | 662              | 1.158 | 1.16 | 1.74 |
|        | 1173             | 1.541 | 1.54 | 2.32 |
|        | 1333             | 1.647 | 1.64 | 2.48 |
Also a total macroscopic cross-section ($\sum t$) cm$^{-1}$ for fast neutrons, mean free path ($\lambda$) was determined by simulation of Monte Carlo Geant 4 code as shown in Table 4.

**Table 4:** Total macroscopic cross-section ($\sum t$) and mean free path ($\lambda$).

| Sample no. | Total macroscopic cross-section ($\sum t$) cm$^{-1}$ | Mean free path ($\lambda$) cm |
|------------|---------------------------------------------------|-------------------------------|
| $S_1$      | 0.1871                                            | 5.344                         |
| $S_2$      | 0.1697                                            | 5.893                         |
| $S_3$      | 0.1677                                            | 5.963                         |
| $S_4$      | 0.1638                                            | 6.105                         |
| $S_5$      | 0.1721                                            | 5.809                         |
| $S_6$      | 0.1608                                            | 6.217                         |
| $S_7$      | 0.1632                                            | 6.129                         |

**Figure 8:** Total macroscopic cross section data of the seven studied alloys at different energies. The macroscopic cross section of studied seven samples at different energies shown in Fig. 8 and it is clear that the macroscopic cross section range of seven samples is about range 0.1608 to 0.1871 and it was considered a good type of stainless steel alloys for shielding of fast neutrons radiations. According to different thickness (0.43-0.868-1.308 cm) the transmission amount dose which passes calculated by Simulation of Monte Carlo Geant 4 code and as tabulated in table 5.

**Table 5:** Transmission number with different thickness.

| Thickness(cm) | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ |
|---------------|-------|-------|-------|-------|-------|-------|-------|
| 0.43          | 92269 | 92963 | 93043 | 93199 | 92865 | 93318 | 93224 |
| 0.868         | 85008 | 86303 | 86454 | 86747 | 86121 | 86970 | 86794 |
| 1.308         | 78289 | 80094 | 80305 | 80715 | 79838 | 81028 | 80781 |
According to thickness of samples; the neutron transmission changed. 100,000 fast neutrons with energy 4.5 MeV was sent for each neutrons number and thickness was determined which passing through the material. It observed in Fig.9 that as all sample's thickness increases and the neutrons number which passed was obviously reduced. Clearly, the new high alloys stell are perfect as material shielding ability radiation for fast neutron.

4. Conclusion

In this work, the Mass attenuation coefficient (cm²/g) was calculated at three different energies of gamma-ray for new steel samples, and half values layer (HVL) was calculated for the seven samples. Total macroscopic cross-section, transmission number and mean free path values determined for 4.5 MeV particles fast neutron. Neutron transmission numbers at 0.43 cm material thickness were calculated and obtained that there is decreasing in the neutrons number for all new alloys. From the result; it observed that both of the total cross-section, transmission number and mean free path of the stainless-steel highly alloyed samples were considered a good type of stainless steel alloys and promising for use as shielding alloys for gamma-ray and fast neutrons radiations especially sample 1 (0.032 % Ni, 0.009 % Mo, 0.087 % Cr, 0.948 % Mn, 0.002 % Ti, 0.005 % V, 97.01 % Fe, 0.3 % C, 0.035 % P, 0.012 % S).

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