Attenuation Effectiveness of Double Phase Stainless Steel Alloys for Fusion Reactor System

Noha M. Ali, Aly Saeed, R. M. El Shazly, S. A. Al-Fiki, M. M. Eissa, S. U. El-kameesy

1Nuclear Power Stations Department, Faculty of Engineering, Egyptian-Russian University, Cairo, Egypt. 2Physics Department, Faculty of Science, El-Azhar University, Cairo, Egypt. 3Physics Department, Faculty of Science, Ain Shams University, Cairo, Egypt. 4Steel Technology Department, Central Metallurgical Research and Development Institute, Helwan, Egypt.

E-mail: Noha.physics@yahoo.com.

Abstract. Aluminium, tungsten and aluminium – tungsten ferritic stainless-steel alloys were developed and produced using 30 kg pilot plant induction furnace of medium frequency at the same conditions to be applied in nuclear reactor shielding material. Higher hardness, ultimate strength, and ultimate tensile strength are appeared in the developed alloys. Aluminium stainless-steel elongation had lower values. Total slow neutrons, neutrons > 10 keV, and slow neutrons of aluminium-tungsten based ferritic stainless steel alloys which carried out using 241Am-Be neutron source as well as a wide range up to 1400 keV energies of gamma rays, which emitted from Co-60, Cs-137 and Eu-152, were used by means of sodium iodide (Tl) detector and studied using the XCOM program. Results showed that all studied stainless-steel alloys own a converge values of neutron macroscopic cross sections (Σ, cm⁻¹). Moreover, there is no significant variation of the value of mass attenuation coefficients (σ, cm²/g) for the studied alloys. Good agreement between both experimental and calculated results of mass attenuation coefficients was achieved. A new composition for several nuclear applications such as, nuclear shielding applications were achieved.

1. Introduction

Energy from fusion system own properties of an appealing product with respects to environmental advantages and safety compared with other energy sources [1,2]. Moreover, fusion fuels are obtainable in the nature, opposite to rare fission fuel resources. Then, in the past 40 years many studies concentrated on fusion energy discussion [3].

Fusion reactors have been predictable to work at high temperatures and utilize chemically aggressive coolants such a normal lithium. And therefore, much kinds of materials are needed as covering materials in the fusion reactor. In addition, fusion reactor first walls around the fusion cell must withstand gamma-ray radiation and high energetic strong neutron fluxes, whose are predictable to command to much higher material harm than observed by fission reactors [4,5].

So, chosen of appropriate structural material plays a keys function in designing fusion reactors [6,7]. Stainless steel is such grade of steel that can be applied in severe environmental conditions. In high-temperature medium, such as that of nuclear reactors, suitable radiation resistance materials are needed [8-12]. Stainless steel alloys were considered to be utilized extensively for structural components in more reactor system designs and in different high temperature applications [8]. Due its special mechanical property such, formability and toughness, large surface area, high strength, and excellent thermal and physical properties, stainless steels be proper as nuclear reactor materials [13,14].

Ferritic stainless steel has the lion share in applications that are required for structure stability at high temperature, and corrosion resistance as well [15,16]. Good formability with competitive low-cost ferritic stainless steels, oxidation resistance and excellent corrosion are favorable materials to change austenitic stainless steels, for using in solid oxide fuel cells, automobile exhaust systems,
architecture applications and petroleum refining plants [17-19]. Due to the high resist for corrosion and thermal properties, good mechanical strength and formability, and low cost, ferritic stainless steel alloys are widely used for high temperature applications [14]. Precipitation of chromium carbides, other intermetallic compounds based on chromium and grain growth of ferrite at high temperature are considered the most challenges, facing the application of ferritic stainless steel alloys (FSSs) in nuclear engineering material [16]. By increasing the property of gamma attenuation of ferritic stainless-steel alloys will raise its multifunction using for more nuclear reactor implementation [20].

At the meantime, aluminum has been proved among the most ferrite stabilizer alloying elements, adding to its capability for promoting the generation of equi-axis ferrite structure [21].

Tungsten is recently proposed for inhibiting the affinity of chromium in forming coarse laves, substituting it by more fine intermetallic precipitates. To improve the mechanical properties of steels, tungsten (W) is generally added as strong ferrite former. Increasing the steel yield strength and hardenability, that was accompanied with decreasing charpy impact energy and elongation were observed in many steel alloys due to adding W. Tungsten alloys used for the helium-cooled diverter and the safeguard of the helium-cooled initial wall layer in reactor designing going beyond ITER has been investigated and discussed for several years [22-25].

The studied alloys have a mix of austenite, ferrite and martensitic in their structure. They exhibit characteristics of all phases with higher ductility and strength. Thereby, this work was designed to study the effect of partial modification of the chemical composition of ferritic stainless steel by adding carbon, tungsten, and aluminum to attain the most proper ferritic stainless steel required for serving at the conditions of different nuclear material applications such as, high-temperature segments in primary piping systems, radiation shielding domain and reactor pressure vessels.

Due to the previous purposes, developed study is concentrated on studying Al-W stainless steel. Then, the attenuation properties of the produced stainless steel alloys against neutrons and gamma ray were calculated and compared.

2. Experimental

2.1. Samples preparation

Four heats were melted in 30 kg magnesite crucible induction furnace through melting of ferritic stainless steel scrap. One heat was kept as reference, while the other three heats were modified by adding different amounts of carbon, tungsten, titanium, and aluminum. The chemical composition of the four heats were recorded in Table 1. The molten metal was casted into metal mold with dimensions 70*70*500 mm. Then, the ingots were forged at starting temperature 1050°C, and finished at 950°C to attain 30*30 mm square cross section rods. Samples were cut and prepared for different investigations. Solution treatment was applied on all samples by heating at 1100°C, directed by quick quenching in water.

| Elements | FS3  | FS8  | FS11 | FS12 |
|----------|------|------|------|------|
| C        | 0.053| 0.441| 0.071| 0.084|
| Mn       | 0.633| 0.892| 0.754| 0.744|
| Cr       | 13.800| 12.400| 13.800| 13.900|
| Ni       | 0.079| 0.078| 0.101| 0.113|
2.2. Mechanical testing

Vickers hardness experiments were achieved on high polished surface of stainless steel samples. Zwick-Roel hardness machine with 50 kg working loading is utilized for hardness measurements. The average from many readings was possessed. Tensile test measured for samples at room temperature and yield strength, ultimate, elongation and impact energy were measured. Tensile specimens with dimensions accordingly ASTM-E8 specification. Each of the tensile values was the average of two tensile test data.

2.3. Gamma-rays attenuation measurements

Gamma rays emitted from 3.7μci Eu-152, 9.5 μci Cs-137, and 4.9μci Co-60 radioactive sources were applied as source of gamma ray energies. Eight gamma rays released tops (344.2, 661.6, 778.9, 96, 1112.4, 1173.2, 1332.5 and 1407.2 keV) of the power spectrum were selected to involve a broad range of energies to calculate the attenuation coefficients of the studied alloy barriers. Figure 1 displays the graph of gamma radiation detection technique, where a 3” x 3” sodium iodide (Tl) scintillation detector was applied to calculate the gamma ray intensity for the studied energy lines. The linear attenuation coefficient was evaluated by the Beer-Lambert’s equation, consisting on the gamma-radiation concentration that transmitted during the investigated samples. Specimens were cut in a disc form and smooth to have parallel plates. The total gamma rays and half value layer (HVL) for each sample were obtained by the following equations [26].

\[
\mu = \frac{\ln I_0}{I_x}, \quad HVL = \frac{\ln 2}{\mu}
\]  

(1)

where \( \mu \) (cm\(^{-1}\)) is called the linear attenuation coefficient, \( I_0 \) and \( I_x \) are the concentration of gamma radiation after and before transmissions during the specimen, and \( x \) is called the width of sample. Mass attenuation coefficient (\( \sigma \), cm\(^2\)/g) on the other hand, is a serious nuclear parameter independent of the bulk density of the substance, was evaluated by considering superficial density (\( x \rho \)).

\[
\sigma = \frac{\ln I_0}{I_x x \rho}
\]  

(2)
The calculated values by “WinXCom” program (version 3.1) [27,28] for each sample composition based on the combined rule of the following equation were compared together with the experimental results of the mass attenuation coefficient:

$$\sigma_t = \sum_{l}^{n} W_i \left( \frac{\mu_i}{\rho_i} \right)_m$$  \hspace{1cm} (3)

Where \( \left( \frac{\mu_i}{\rho_i} \right)_m \) is the mass attenuation coefficient for every element in each mixture sample, while \( W_i \) is the partial weight of the elements within each mixture sample.

Figure 1. Diagram of experimental setup for gamma ray detection.

2.4. Neutrons attenuation measurements

The BF₃ neutron detector was used to detect a collimated total slow neutron (main slow neutron emitted from the source and that slowed down by samples), slow neutron, and neutrons with energy higher than 10 keV beam released from ²⁴¹Am-Be neutrons source with activity 3.7 GBq. The neutrons transmitted flow were calculated according to equation (4) [28] to deduce the amounts of macroscopic neutron cross-section. The collimated beam was decelerating with polyethylene block of 7 cm thickness back the sample for slow neutrons calculations, and the neutrons that have energy below 10 keV were cut by a mass of Born carbide B₄C. Scheme of the experiment is shown in Figure 2.

$$I_n = I_0 e^{-\Sigma x}$$  \hspace{1cm} (4)

where \( \Sigma \) is the macroscopic cross section of neutrons, \( I_n \) and \( I_0 \) are the neutron fluxes after and before transmitted through the sample barriers respectively, and \( x \) is the sample thickness.

The maximum experimental errors in attenuation coefficients and half value layers for both gamma-ray and neutron attenuation measurements were evaluated using the following error formulas [29]:

$$\Delta \sigma = \frac{1}{xp} \sqrt{\left( \frac{\Delta I_0}{I_0} \right)^2 + \left( \frac{\Delta I_N}{I_N} \right)^2 + \left( \frac{\Delta \mu}{\mu} \right)^2 \left( \frac{x}{xp} \right)^2}$$  \hspace{1cm} (5)

$$\Delta(HVL)_\gamma = (HVL)_\gamma \sqrt{\left( \frac{\Delta \mu}{\mu} \right)^2 (\ln 2)^2}$$  \hspace{1cm} (6)
3. Results and discussion

3.1. Mechanical properties

The mechanical properties (Vickers hardness, yield strength, ultimate tensile strength, elongation, and impact energy) of the investigated stainless steels were evaluated to calculate the effect of aluminum and tungsten contents on stainless steels. Table 3 and Figure 3 show the different mechanical properties for the four investigated stainless steel alloys.
Figure 3. Mechanical properties of the investigated stainless steel alloys; (a) Vickers hardness, (b) yield strength, (c) ultimate tensile strength, (d) elongation, (e) impact energy.

Table 2. Mechanical properties of the investigated stainless steel alloys; hardness, yield strength, ultimate tensile strength, elongation, and impact energy.

| Steel Code | Mechanical Properties                      |
|------------|--------------------------------------------|
|            | Vickers hardness (MPa) | Yield strength (MPa) | Ultimate tensile strength (MPa) | Elongation (%) | Impact energy (J) |
| FS3        | 146.500                    | 406.500              | 559.500                          | 31.500         | 177.500           |
| FS8        | 187.533                    | 555.500              | 743.000                          | 27.500         | 26.500            |
| FS11       | 135.133                    | 411.000              | 541.000                          | 28.000         | 14.000            |
| FS12       | 164.800                    | 414.000              | 570.000                          | 35.000         | 6.000             |

From the results shown above in Table 2 and represented in Figure 3, it was observed that yield and ultimate strength commonly depicts the structures of the material. Modified ferretic stainless steel alloys containing Al (FS8) exhibit higher hardness, yield strength and ultimate tensile strength than the standard FS3 and the other studied stainless steel alloys. This strengthening is accompanied with decreasing of elongation combined with reduction in impact energy.

As increasing the fine precipitation in the matrix, yield and ultimate strength is strongly enhanced. This refers to the interaction of fine precipitates with dislocations through pile up mechanism [31]. M₇C₃ which can be formed through solution treatment process of FS8 steel, due to its high carbon content. Hence, these precipitates a great impact on promoting the strength of steel. At the meantime, the coarsening of laves based tungsten Fe₂W has not the capability to interact with the dislocation, regarding to its coarse character. At the meantime, the laves in FS11, and FS12 has not a deteriorative effect on the ductility of ferrite matrix, in comparing with the reference steel FS3. As aforementioned, the toughness of the material is mainly depending on the fraction of secondary phases that are precipitated either throughout or along the boundaries. Secondary phase acts as stress concentration location that promote the propagation of the crack along the matrix [32]. Then, it is believed that volume fraction and size of secondary phase are the main parameter in deterioration of toughness. In fact, this concept was strongly confirmed on studying the toughness of investigated steel, as given in Table 2.
3.2. Gamma-ray measurements

A Co-60, Cs-137, and Eu-152 Gamma-ray origins were applied to calculate \( \sigma \) of gamma-radiation with energies (344.2, 661.6, 778.90, 964, 1112.4, 1173.2, 1332.5 and 1407.2 keV). The concentration of \( \gamma \)-radiations transmitted through alloy barriers were given as a function of surface concentrations \((x_\rho, \text{g/cm}^2)\) at various percentage of Al and W to stainless steel alloy. The average values of \((\sigma, \text{cm}^2/\text{g})\) were derive as a slope of those exponential curves. Figure 4 shown measured and calculated results of energy dependence of the calculated and measured values of \((\sigma_{\text{calc}} \& \sigma_{\text{exp}})\) for different stainless-steel alloys. Firstly, these figures display that a perfect agreement between experimental data of mass attenuation coefficients and that calculated by the “WinXcom” computer program (version 3.1). The action of all these curves can be interpreted by the prominent interaction between the studied alloy barriers and gamma rays which are considered a Compton scattering process. Where the total attenuation coefficient decreases quite slowly with rising photon energy \(E\), where \(\sigma\) is inversely proportional to \(E\). The value of \((\sigma, \text{cm}^2/\text{g})\) almost remain unaffected by adding Al or W to stainless steel alloy. This may be assigned to the \(z\)-dependence of the interaction of gamma rays with basically aluminum and tungsten. The comparison of half value layers of various types of investigated stainless steel alloys with and without Al,W for different used gamma ray energies are given in Table 3.

![Graph showing mass attenuation coefficient vs. photon energy for FS8 and FS3 alloys](image-url)
3.3. Neutron measurements

$^{241}$Am–Be neutron source with activity 100 mCi was applied to determine the amounts of the macroscopic cross-section for total slow neutron, $\Sigma_T$, (main slow and go slow in the developed alloys), slow ($\Sigma_s$), and neutrons with energy higher than 10 keV ($\Sigma_{>10keV}$) in developed stainless steel alloys with percentages of Al and W. The values of ($\Sigma$, cm$^{-1}$) were measure as a slope of exponential curves, that the densities of neutrons with various energies transmitted during stainless steel alloy barriers given as a function of thicknesses at various percentages of Al and W stainless steel alloy. Figure 5, shows the variations in values of $\Sigma$ with distinct stainless-steel alloys. The amounts of macroscopic cross-sections of slow neutrons in whole kinds of stainless-steel alloys under investigation were the largest values of the others neutron energies. The behaviour of slow neutrons may be referred to elastic scattering of slow neutron with light elements in all forms of stainless steel alloys. Also, it was noticed that the amounts of macroscopic cross-sections of total slow neutrons slightly increasing than that of neutron with energy higher than 10 keV in all studied alloys. This behavior may
be attributed to the competition between absorption operation and slowdown process which takes place in the case of total slow neutron, while in the case of neutron with energy greater than 10 keV the only slowdown process that appear. (note that, about 23% of neutron energies carried out from \textsuperscript{241}Am-Be neutron source is considered slow neutron). Furthermore, Figure 6 shows the different values of mean free path, MFP, for investigated samples by three various energies of neutrons.

**Figure 5.** Macroscopic cross-sections of studied stainless steel alloys at (a) Total slow neutrons, (b) Slow neutrons, (c) Neutrons with energy > 10 KeV.
4. Conclusion
In the present study, four grades of stainless steel were developed and examined to use as candidate materials for nuclear reactor system.

The effect of Al and W can be assigned to the solution hardening and precipitation strengthening effects of these elements as these elements are strong carbide formers which accelerates the forming of intermetallic compounds and lowers the ductility.

The measured mass attenuation coefficients of gamma radiations are almost the same for all the developed alloys. A comparison of the mass attenuation coefficient with the corresponding theoretical one (based on XCOM) has been done and a good agreement is achieved.

The calculated macroscopic neutron cross-section of total slow, slow neutrons and neutrons with energy > 10 keV for the developed aluminum-tungsten stainless steel has a small variation compared with the standard sample FS3. This change could be assigned to the increase of the aluminum or tungsten contents in the studied alloys.

Achieved results reveal the superiority of the investigated alloys as a blanket structural substance for fusion reactor.
References

[1] International Atomic Energy Agency 1995 Energy from inertial fusion 944.

[2] Holdren, J. P., Berwald, D. H., Budnitz, R. J., Crocker, J. G., Delene, J. G., Endicott, R. D., ... and Schultz, K. R. 1988 Fusion Technology 13(1) 7-56.

[3] Hadaller, O. J., Momently and A. M. 1993 Transportation and Global Climate Change Washington.

[4] Bolt, H., Barabash, V., Krauss, W., Linke, J., Neu, R., Suzuki, S., ... and Team, A. U., 2004 Journal of nuclear materials 329 66-73.

[5] Şahin, S., Übeyli and M. 2008 Journal of fusion energy 27(4) 271-277.

[6] Übeyli, M., Yalçın and Ş. 2006 Journal of Fusion Energy 25(3-4) 197-205.

[7] Ihli, T., Basu, T. K., Giancarli, L. M., Konishi, S., Malang, S., Najmabadi, F., and Wu, Y., 2008 Fusion Engineering and Design 83(7-9) 912-919.

[8] Brnic, J., Turkalj, G., Canadija, M., Lanc, D., and Kscainski S. 2011 Mechanics of time dependent materials 15(4) 341-352.

[9] Hayward, T. M., Svishchev, I. M., Makhija, and R. C. 2003 Supercritical fluids 27(3) 275-281.

[10] Singh, N., Singh, K. J., Singh, K., & Singh, and H., 2004, Interactions with Materials and Atoms 225(3) 305-309.

[11] Singh, V. P., & Badiger, and N. M. 2014 Annals of Nuclear Engineering 64 301-310.

[12] Eissa, M. M., El-Kameesy, S. U., El-Fiki, S. A., Ghali, S. N., El Shazly, R. M., and Saeed A. 2016 Fusion Engineering and Design 112 130-135.

[13] Min, K. D., Hong, S., Kim, D. W., Lee, B. S., Kim, and S. J. 2017 Nuclear Engineering and Technology 49(4) 752-759.

[14] Fuzeau, J., Vasudevan, M., and Maduraimuthu V. 2016 Transactions of the Indian Institute of Metals 69(8) 1493-1499.

[15] Kim, J. K., Kim, Y. H., Lee, J. S., Kim, and K. Y. 2010 Corrosion Science 52(5) 1847-1852.

[16] Liu, H., Wei, L., Ma, M., Zheng, J., Chen, L., Misra, and R. D. K. 2020 Materials research and Technology 9(2) 2127-2135.

[17] Brady, M. P., Yamamoto, Y., Muralidharan, G., Rogers, H., Pint, and B. A. 2013 Oak Ridge TN.

[18] Meetham, G. W., Van de Voorde, and M. H. 2000 Springer Science & Business Media.

[19] Salama, E., Eissa, M. M., Tageldin, and A. S. 2019 Nuclear Engineering and Technology 51(3) 784-791.

[20] Zhang, X., Fan, L., Xu, Y., Li, J., Xiao, X., and Jiang, L. 2015 Materials & Design 65 658-689.

[21] Jang, M. H., Moon, J., Kang, J. Y., Ha, H. Y., Choi, B. G., Lee, T. H., Lee, and C. 2015 Materials Science and Engineering: A 647 163-169.

[22] Klueh, R. L., Maziasz, and P. J. 1989 Metallurgical Transactions A 20(3) 373-382.

[23] Zhao, J., Lee, T., Lee, J. H., Jiang, Z., Lee, and C. S. 2013 Materials and Metallurgical Transactions A 44(8) 3511-3523.

[24] Prifiharni, S., Anwar, M. S., Nikitasari, A., Mabruri, and E. 2018 In AIP Conference Proceedings 1964(1) 20041 AIP Publishing LLC.

[25] Lamarsh, J. R., Baratta, and A. J. 2001 3 783 Upper Saddle River, NJ: Prentice hall.

[26] El Shazly, R. M., and M. M. Sadawy. 2017 International Journal of Scientific Engineering and Research (IJSER) 5: 243-250.

[27] Saeed, A., Elbashar, Y. H., Abou El-azm, A. M., El-Okr, M. M., Comsan, M. N. H., Osman, A. M., El-Sersy, and A. R. 2014 Rad. Phy. and Chem. 102 167-170.

[28] Taylor, and J. 1997 the study of uncertainties in physical measurements .