ISSN 2347-3487

The Attenuation Capability of Selected Steel Alloys for Nuclear Reactor Applications

S. U. El-Khameesy[a],M. M. Eissa[b], S. A. El-Fiki[a], R. M. El Shazly[c], S. N. Ghali[b], AlySaeed[e*]

[a]Physics Department, Faculty of Science, Ain Shams University, Cairo, Egypt.

[b]Steel Technology Department, Central Metallurgical Research and Development Institute (CMRDI), Helwan, Egypt.

[c]Physics Department, Faculty of Science, Al-Azhar University-Cairo, Egypt.

[e]Basic Science Department, Faculty of Engineering, Egyptian-Russian University-Cairo, Egypt

Abstract

Neutronsand gamma ray attenuation of different steel grades (SS304, SS304L, SS316L, SS430, a modified high manganese-nitrogen austenitic stainless steel, and developed cobalt-free Maraging steel) was measured to study their capability to be used as nuclear reactor materials. The hardness and microstructure of the studied steel alloys were carried out using Vickers hardness and optical microscope respectively.Neutron and gamma rays measurements were carried out using a narrow beam transmissions geometry method. Measurements and calculations of gamma ray attenuation coefficients were carried out at energies 238.63, 338.28, 583.19, 911.2, 968.97, 1173.23, 1332.49, and 2614.51 keV. The transmitted gamma rays were detected by the Hyper Pure Germanium detector (HPGe), while, the neutron flux emitted from ^{241}Am-Be neutron source was used to measure the neutron removal cross section for both slow and total neutrons. The transmitted beam of neutrons was measured under a good geometric conditions using ^{3}He counter.A good agreement between experimental data of mass attenuation coefficients and theoretical results calculated by the WinXcom computer program (version 3.1) was obtained.

Keywords

Stainless steel, Removal cross section, Mass attenuation coefficient, Reactor materials

Council for Innovative Research

Peer Review Research Publishing System

Journal: JOURNAL OF ADVANCES IN PHYSICS

Vol. 11, No. 3

www.cirjap.com, japeditor@gmail.com

Introduction

In high-temperature medium, such as this of nuclear reactors, suitable radiation resistance materialsare needed [1-2].In this regard, owing to the superior characteristics of stainless steels (SSs) alloys such as excellent mechanical properties, high radiation resistance, and the corrosion resistance, stainless steel alloys were considered as promising candidate materials for nuclear reactor systems [3-4]. Steels are being utilized extensively for structural components in many Reactor designs and also in other high temperatureapplications [5].The stainless steel alloys are the common structural materials in-core and out-of-core components of nuclear power plants. Their high resistance to degradation by irradiation is particularly important for nuclear applications [6-7].Nickel- free austenitic stainless steels having a large amount of chromium, manganese, nitrogen, and small amount of molybdenum are currently developed to enhance the strength and corrosion resistance of stainless steel. Hence, manganese and nitrogen are employed instead of nickel to obtain austenitic phase, because nitrogen and manganese also stabilize austenitic phase and control mechanical properties of stainless steel as same as nickel[8-9].Commercial cobalt free Maraging steels alloys, with molybdenum, titanium, and aluminum additions, are used in industrial applications that demand high strength steels, such as in aerospace and nucleartechnologies [10-11].

In this work, the neutron and gamma ray shielding properties of SS304, SS304L, SS316L, SS430, a modified high manganese-nitrogen austenitic stainless steel and a developed chromium-titanium containing cobalt-free Maraging steelwerestudied experimentally under good geometry conditions. Neutron and gamma rays attenuation parameters were deduced. Additionally, Vickers hardness and microstructure were carried out.

Experimental measurements and theoretical calculations

Different stainless steel grades including three austenitic stainless steels SS304, SS304L, and SS316L and one ferritic stainless steel SS430were prepared using a pilot plant induction furnace.In addition, modifiedchromium-titanium containing cobalt free Maraging steel(MRG-MoCrTi), and high manganese-nitrogen (3.84%Mn-0.235%N) free-nickelaustenitic stainless steel (SSMn4N) were also prepared. The chemical compositions of the investigated steels are given in Table(1).The different produced steels were hot forged from the cast ingots of diameter 70 mm to bars with final cross section of 30x30 mm^2. Samples from all forged steels, except Maraging steel(MRG-MoCrTi)were initially solution annealed at 1050°C for 30 min, followed by water quenching. WhileMaraging steel(MRG-MoCrTi)was initially solution treated at 820°C for 60 min, and air cooled.For martensite aging, the solution treated maraging steel samples were subjected to age-hardening at 480^{o}C for 120 min and air cooled[12].After etching of SS304, SS304L, SS316L andSS430with a marble reagent, Maraging steel with copper sulphate, and high manganes-nitrogen stainless steel with Picral+Viellathe, microstructure was observed using an optical microscope.

Table 1: Chemical composition and density of investigated steels.

Steel Code	Chemical composition, wt%												Density gm.cm^{-1}
	C	Mn	Si	Cr	Ni	Mo	V	Ti	S	P	N	Fe	
SS304	**0.060**	**1.410**	**0.439**	**18.41**	**8.29**	**0.023**	**0.090**	**0.013**	**0.0002**	**0.0003**	**0.022**	**71.243**	**7.794**
SS304L	**0.017**	**1.490**	**0.453**	**18.48**	**8.08**	**0.166**	**0.077**	**0.004**	**0.0040**	**0.0350**	**0.020**	**71.174**	**7.794**
SS316L	**0.020**	**1.220**	**1.940**	**16.41**	**9.89**	**2.000**	**0.115**	**0.246**	**0.0100**	**0.0100**	**0.030**	**65.19**	**7.782**
SS430	**0.070**	**0.324**	**0.350**	**16.36**	**0.121**	**0.065**	**0.087**	**0.003**	**0.0002**	**0.0003**	**0.018**	**82.602**	**7.719**
SSMn4N	**0.120**	**3.840**	**2.590**	**20.67**	**0.11**	**0.020**	**0.062**	**0.003**	**0.0100**	**0.0090**	**0.235**	**72.331**	**7.542**
MRG-MoCrTi	**0.030**	**0.354**	**0.760**	**05.75**	**12.12**	**5.600**	**0.056**	**0.466**	**0.0130**	**0.0110**	**0.010**	**74.83**	**8.017**

Vickers hardness test was carried out on polished steel samples. The attenuation properties of neutrons and gamma rays were carried out using ^{241}Am-Be neutron source; with activity 5Ci and neutron yield = (1.1-1.4) x 10^7 n/sec,in addition to ^{60}Co and ^{232}Th gamma ray sources. The ^{3}He neutron detector was used to counter the transmitted beam of total and slow neutrons, figure(1).Whilethe Hyper Pure Germanium detector (HPGe) was used to measure the gamma ray intensities for the studied energy lines, figure(2). Neutron and gamma rays attenuation parameters such as removal cross section of both total and slow neutrons, linear and mass attenuation coefficients of gamma rays were deduced from the experimentally attenuation curves. Additionally, theoretical calculations of gamma ray mass attenuation coefficients were carried out using WinXCom computer program (Version 3.1) [13]and compared with the experimental ones.

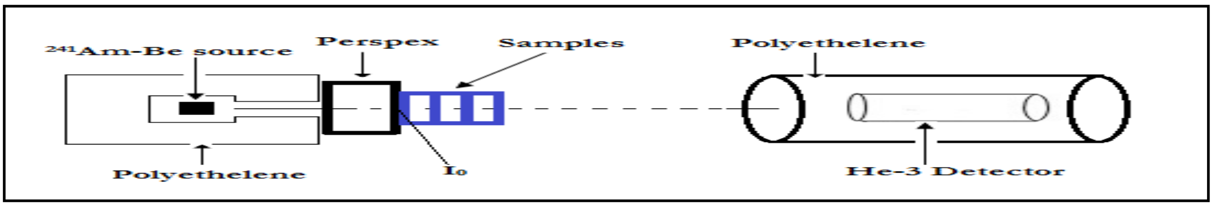


Fig 1:Schematic diagram of neutrons measurements

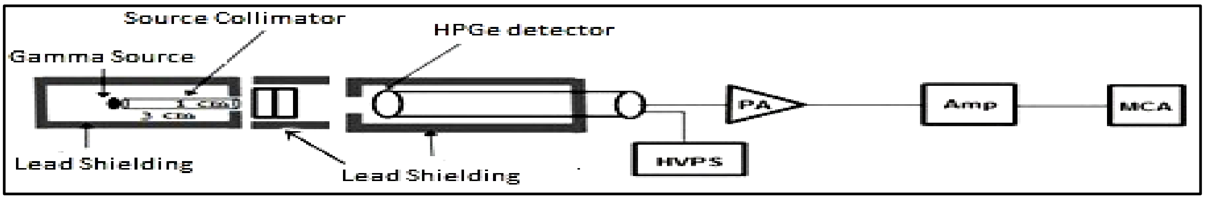


Fig 2:Experimental setup of gamma ray narrow beam transmission method

Results and Discussion

The observed microstructures of the different investigated steels were given in figure (3). The examination of these photos reveals that SS304, SS304L, SS316Land high manganese-nitrogen stainless steels have microstructure composed of mainly austenite. On the other hand, SS430 showed ferritic phase while maraging steel revealed martensite microstructure.

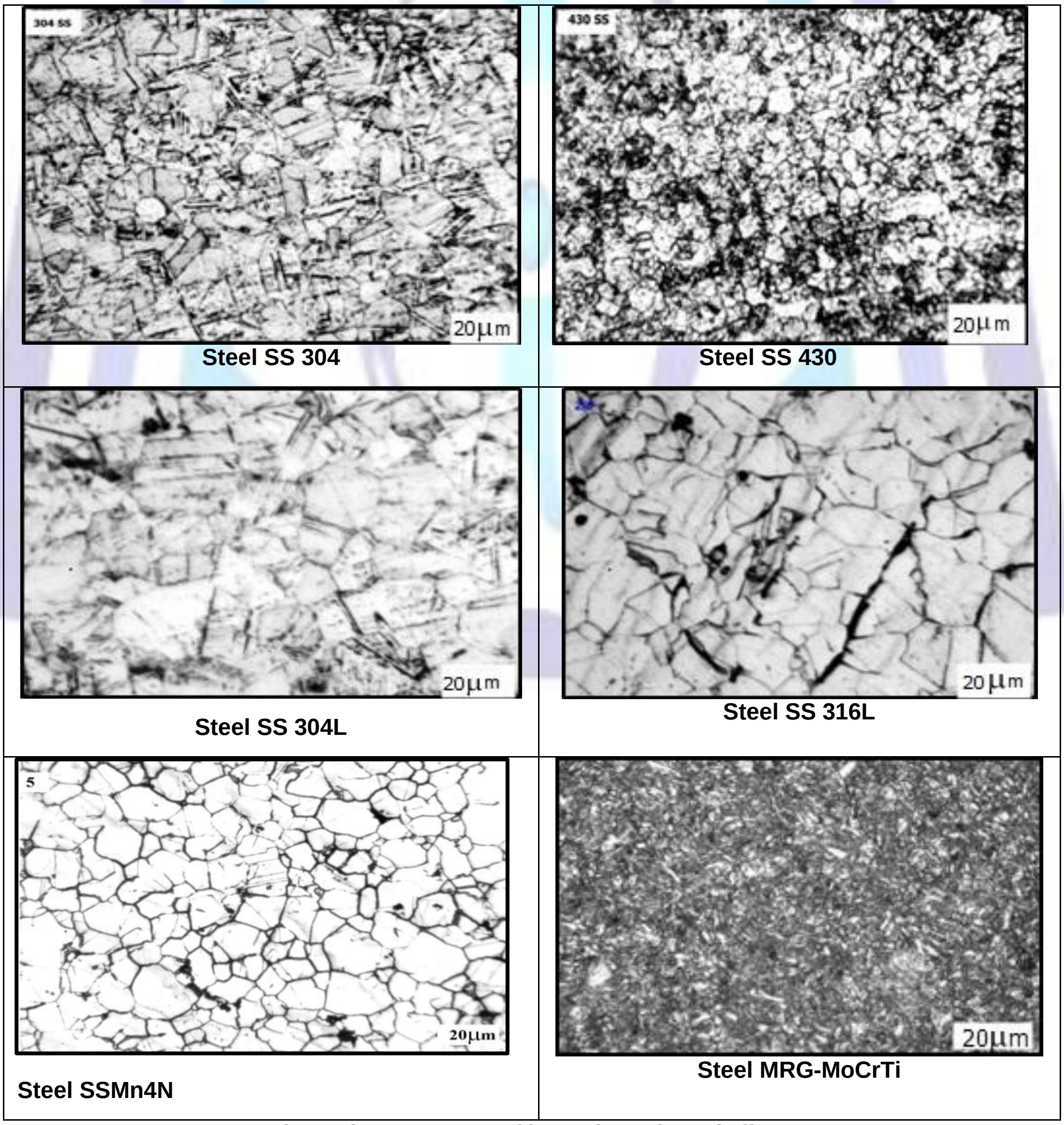


Fig 3:Microstructure of investigated steel alloys

Hardness variation of the investigated steelswas shown in figure (4). A higher Vickers hardness value was observed for thecobalt free Maraging and high manganese-nitrogen steel alloys,respectively.The higher hardness of high manganese-nitrogen free-nickel austenitic stainless steel (SSMn4N) comparing with the other stainless steels SS304, SS304L, SS316L and SS430could be attributed to the its higher manganese and nitrogen contents resulting in higher solid solution hardening.The highest hardness of cobalt-free Maraging steel (MRG-MoCrTi) could be attributed to the martensite microstructure and age hardening[14-17].

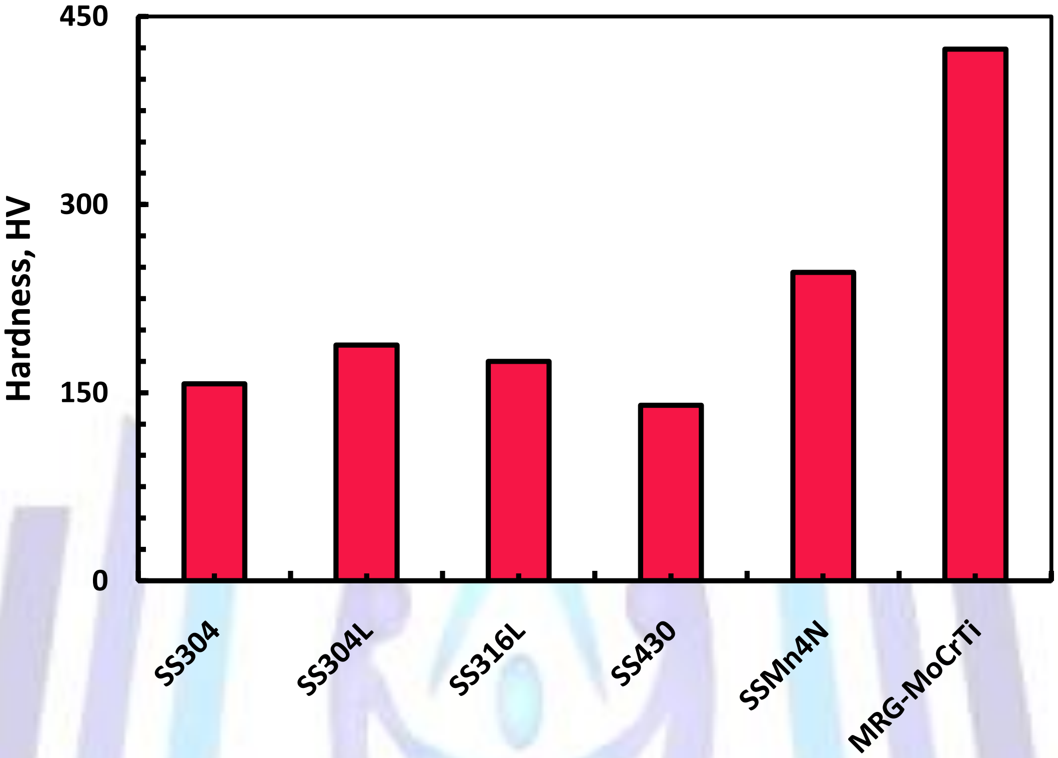


Fig 4:Hardness variation of the investigated steels

Total and slow neutron removal cross section of the studied steelalloyswere carried out and listed in table (2). It is observed that, the highest value of the effective removal cross sections of total neutrons for the high manganese-nitrogen stainless steel (SSMn4N). On the other hand, thehighestvalues of effective removal cross section of slow neutron for cobalt-free Maraging steel.The small values of slow neutron removal cross-section may be attributed to the absence of high slow neutrons cross section element in the studied steel samples.

Table 2: Neutron attenuation parameters for different investigated steels

Steel Code	Total Neutrons		Slow Neutrons	
	Σ_{Total} cm^{-1}	HVLcm	Σ_{Slow} cm^{-1}	HVL cm
SS304	0.1630 ±0.037	4.151	0.0966± 0.007	7.059
SS304L	0.1670± 0.0112	4.151	0.0966± 0.002	7.175
SS316L	0.1620± 0.035	4.276	0.0983± 0.017	7.051
SS430	0.1980± 0.033	3.501	0.0467± 0.002	14.843
SSMn4N	0.2140± 0.021	3.239	0.0890± 0.004	7.762
MRG-MoCrTi	0.2103± 0.013	3.296	0.1150± 0.030	6.048

The linear attenuation coefficients (μ) and half value layer(HVL) of the selected steel alloyswere investigatedand listed in table (3) and (4) respectively. From table (3), it was found that the high manganese- nitrogen stainless steel (SSMn4N) and cobalt free Maraging steel (MRG-MoCrTi) have high linear attenuation coefficient and hence a lower HVL respectively.

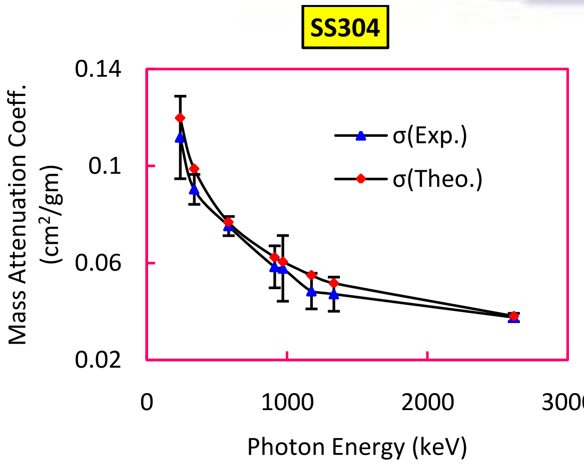
Table 3: Gamma ray attenuation parameters for different investigated steels

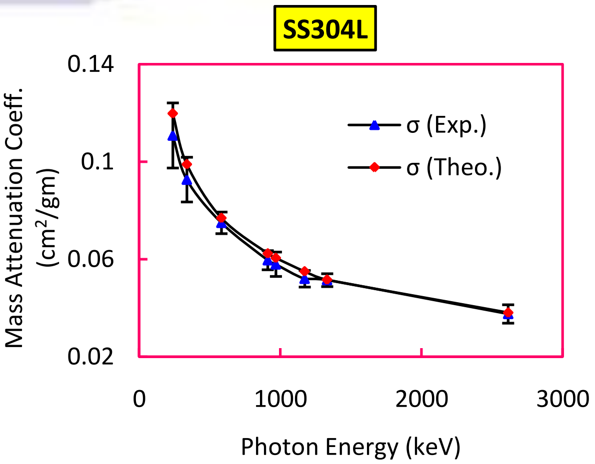
Gamma Energy (keV)	SS304 μ (cm^{-1})	SS304L μ(cm^{-1})	SS316L μ(cm^{-1})	SS430 μ(cm^{-1})	SSMn4N μ(cm^{-1})	MRG-MoCrTiμ(cm^{-1})
238.63	0.871±0.015	0.874±0.005	0.927±0.010	0.819±0.017	1.147±0.009	0.997±0.05
338.28	0.704±0.068	0.731±0.011	0.795±0.022	0.702±0.012	0.973±0.001	0.813±0.013
583.19	0.586±0.053	0.591±0.025	0.565±0.014	0.538±0.005	0.736±0.011	0.626±0.002
911.20	0.455±0.014	0.47±0.017	0.455±0.005	0.465±0.020	0.614±0.030	0.52±0.002
968.97	0.45±0.003	0.457±0.011	0.451±0.011	0.478±0.012	0.564±0.011	0.491±0.010
1173.23	0.377±0.011	0.41±0.010	0.415±0.015	0.375±0.007	0.524±0.005	0.44±0.021
1332.49	0.367±0.009	0.39±0.021	0.401±0.001	0.349±0.002	0.497±0.002	0.412±0.013
2614.51	0.292±0.013	0.296±0.001	0.28±0.003	0.294±0.010	0.369±0.004	0.338±0.007

Table 4: Gamma ray attenuation parameters for different investigated steels

Gamma Energy (keV)	SS304	SS304L	SS316L	SS430	SSMn4N	MRG-MoCrTi
	HVL (cm)	HVL (cm)	HVL (cm)	HVL (cm)	HVL (cm)	HVL (cm)
238.63	0.796	0.793	0.748	0.846	0.604	0.695
338.28	0.985	0.948	0.872	0.987	0.712	0.853
583.19	1.183	1.173	1.227	1.288	0.942	1.107
911.20	1.523	1.475	1.523	1.491	1.129	1.333
968.97	1.540	1.517	1.537	1.450	1.229	1.412
1173.23	1.839	1.691	1.670	1.848	1.323	1.575
1332.49	1.889	1.777	1.729	1.986	1.395	1.682
2614.51	2.374	2.342	2.476	2.358	1.878	2.051

The experimental mass attenuation coefficients(σ_{Exp})and those compute theoretically(σ_{Theo})using WinXCom computer programofthe selected steel alloys wereshown in figure (5). It is shown that the values of mass attenuation coefficient of the alloys arehigh in photo-absorption region, reduces gradually and become lowest in Compton scattering region. These variationscan be explained by photon energy and Z-dependency ofinteraction cross section of the elements. Additionally, a good agreement was observed between both measured and calculated data of mass attenuation coefficients.





ISSN 2347-3487

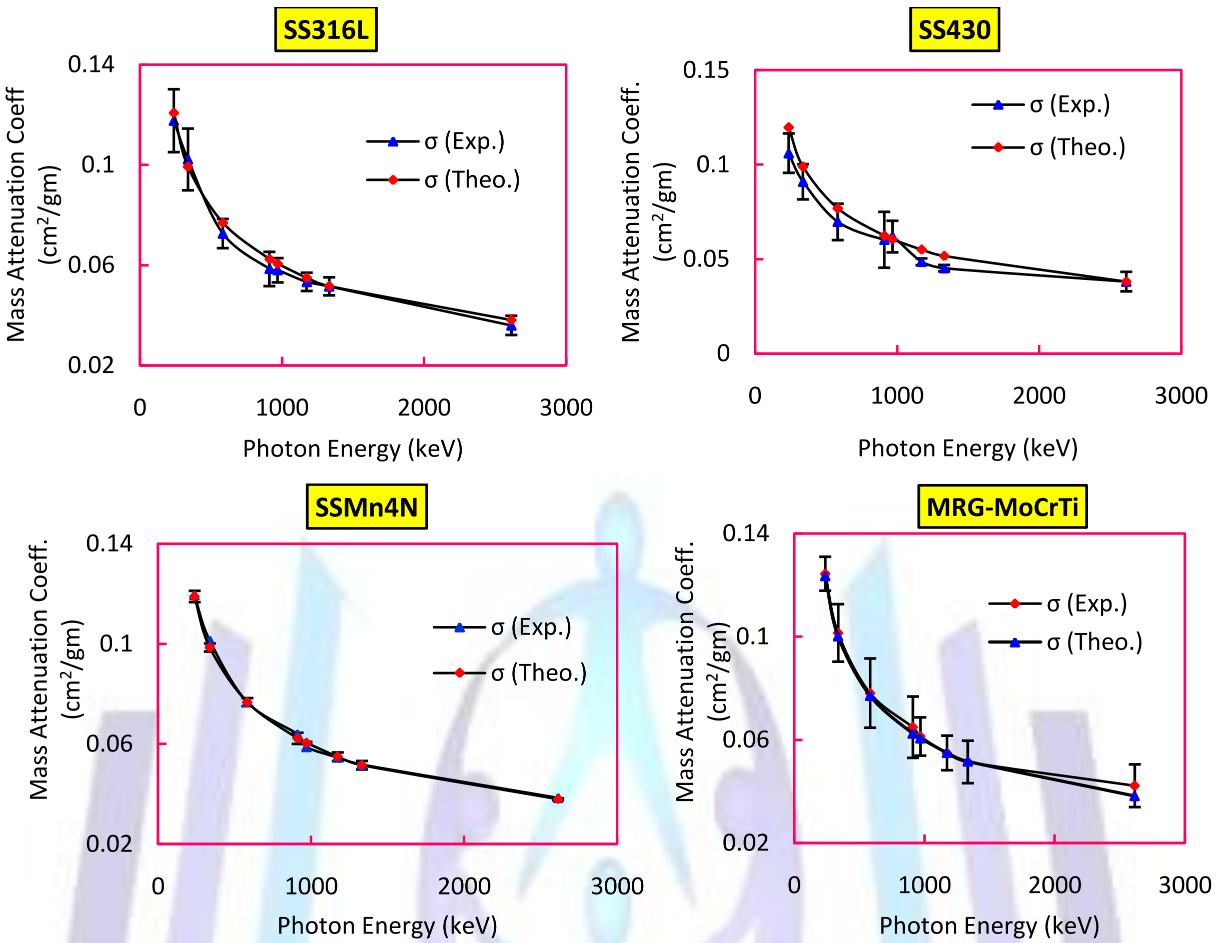


Fig 5:Experimental and theoretical mass attenuation coefficients of the investigated steel alloys as a function of gamma ray energies

Conclusion

From the previous discussions we conclude that,CobaltFree Maraging Steel (MRG-MoCrTi)and Modified High Manganese-Nitrogen austenitic stainless steel (SSMn4N) have a high hardness in comparison with the standard stainless steels SS304, SS304L, SS316L and SS430.The microstructure of the SS304, SS304L, SS316L, SS430 and SSMn4Nshows an austenite phase while the steel (MRG-MoCrTi)has a matensite phase. The highest value of total neutron macroscopic cross-sectionwas found for the high manganese-nitrogen austenitic stainless steel,while,the cobalt free Maraging steel has the highest value of effective removal cross section of slow neutron.The high manganese-nitrogen austenitic stainless steel and cobalt free Maraging steel have high linear attenuation coefficients and hence a lower HVL, respectively.Good agreement was achieved between the experimental data of gamma ray mass attenuation coefficients and the corresponding theoretical prediction.The present study are useful for potential applications of these materials in nuclear reactor design as an effective gamma ray and neutron attenuator materials with high hardness.

References

1. Atsuhiko M. Sukegawa and YoshimasaAnayama, “Flexible Heat-Resistant Neutron and Gamma-Ray Shielding Resins”, Progress in Nuclear Science and Technology, Vol. 4, pp. 627-630, 2014.
2. M. Bastu¨rk, J. Arztmann, W. Jerlich, N. Kardjilov, E. Lehmann, and M. Zawisky, “Analysis of Neutron Attenuation in Boron-alloyed StainlessSteel with Neutron Radiography and JEN-3 Gauge”, Journal of Nuclear Materials, Vol. 341, pp. 189–200, 2005.
3. XinLuo, Rui Tang, Chongsheng Long, Zhi Miao, QianPeng,and Cong Li, “Corrosion Behavior of Austenitic and FerriticSteels in Supercritical Water”, Nuclear Engineering and Technology, Vol.40, No.2, pp. 147-154, 2007.
4. Vishwanath P. Singh and N.M. Badiger, “Gamma Ray and Neutron Shielding Properties of Some Alloy Materials”,Annals of Nuclear Energy, Vol. 64,pp. 301–310, 2014.
5. H. Pous-Romero, I. Lonardelli, D. Cogswell, and H. K. D. H. Bhadeshia,“Austenite Grain Growth in a Nuclear Pressure Vessel Steel”, Materials Science and Engineering A, Vol. 567, pp. 72-79, 2013.

ISSN 2347-3487

6. T. S. Byun, N. Hashimoto, and K. Farrell, “Temperature Dependence of Strain Hardening and PlasticInstability Behaviors in Austenitic Stainless Steels”,ActaMaterialia, Vol. 52 pp. 3889–3899, 2004.

7. IAEA Nuclear Energy Series No. Np-T-3.1, International Atomic Energy Agency, “Integrity of Reactor Pressure Vessels in Nuclear Power Plants: Assessment of Irradiation Embrittlement Effects in Reactor Pressure Vessel Steels, 2011.

8. Dalsuke Kuroda, SchikoHiromoto, Takao Hanawa, and YasuyukiKatada, “Corrosion Behavior of Nickel-Free High Nitrogen Austenitic Stainless Steel in Simulated Biological Environments”, Materials Transactions,Vol. 43, No. 12, pp. 3100-3104, 2002.

9. Linda Mosecker and AlirezaSaeed-Akbari, “Nitrogen in Chromium–Manganese Stainless Steels: A Review on The Evaluation of Stacking Fault Energy by Computational Thermodynamic”, Sci. Technol. Adv. Mater, Vol. 14,pp. 1-14, 2013.

10. K. Sakthipandi, V. Rajendran, and T. Jayakumar, “Aging–induced Microstructural Changes in M250 Maraging Steel using In-situUltrasonic Measurements”, International Journal of ChemTech Research, Vol.7, No. 1, pp. 108-112, 2015.

11. HossamHalfa and A. M. Reda, “Shielding Properties of New Grades of PrecipitationHardening Stainless Steel”, International Journal of Physicsand Research, Vol. 5, No. 2, pp. 7-12, 2015.

12. AymanFathy, Hoda El-Faramawy, TahaMattar, MamdouhEissa and Wolfgang Bleck, “Phase Transformation in New Low Nickel Cobalt Free Maraging Steels”, 13^{th} International Metallurgical& Materials Conference Metal2004, Hardec and Moravici, Czech Republic, 18-20 May 2004, Symposium C article 211, pp. 1-13.

13. L. Gerward, N. Guilbert, K. B. Jensen, and H. Leving, “WinXCom – A Program for Calculating X-Ray Attenuation Coefficients”, Radiation Physics and Chemistry, Vol. 71, pp. 653-654, 2004.

14. AymanFathy, Hoda El-Faramawy, Azza Ahmed, and MamdouhEissa, "Effect of Alloying Elements and Age Hardening on The Peak Hardness Precipitation in Low Nickel Cobalt Free Maraging Steel", Steel Grips, Vol. 2 , No. 6, pp.433-440, 2004.

15. MamdouhEissa, TahaMattar, AymanFathy, Mohamed Kamal, and FaheimNassar, "Effect of Physical Properties and Chemical Composition of ESR on The Cleanlinessand Properties of A New Grade of Maraging Steel", 45^{th} Annual Conference of Metallurgist of CIM, October 1-4, 2006, Montreal, Quebec, Canada, Proceedings of the International Symposium in "Advanced Steels", Edited by J, Szpunar and H. Li, pp. 39-50.

16. TahaMattar, AymanFathy, MamdouhEissa, FahimNassar, and Mohamed Kamal, "Role of Refining Process in Improving The Properties of New Developed Grades of Maraging Steels", Proceedings of 7^{th} International Conference in "Clean Steel", 4-6 June 2007, Balatonfured, Hungary, pp. 498-507.

17. HossamHalfa, AymanFathy, Mohamed Kamal, MamdouhEissa, and Kamal El-Fawahkry, "Enhancement of Mechanical Properties of Developed Ti-Containing Co-Free Low-Ni Maraging Steel by ESR", Steel Grips, Vol.8,pp.278-284, 2010.