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MODIFIED BORON-TITANIUM AUSTENITIC STAINLESS-STEEL ALLOYS FOR POWER REACTORS

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Abstract:

Boron, Titanium and boron – titaniumaustenitic stainless steel alloys were developed to be used as a nuclear reactor shielding material. Three grades of steel alloys with base composition of AISI316 but having either Ti or B or Ti and B (SS316Ti, SS316B and SS316TiB) were designed and produced using 30 kg pilot plant medium frequency induction furnace at the same conditions. Samples of the properly treated steels were subjected to microstructure observation, hardness, tensile and impact testing. The microstructure observation revealed an austenitic phase in all investigated steel alloys. Among the investigated steels, the lowest corrosion rate was found in the modified steel containing B. The macroscopic-cross sections for neutrons > 10 keV, slow, and total slow neutrons were carried out using 241Am-Be neutron source. The developed boron and boron-titanium stainless steel alloys were found to have higher cross sections for neutrons > 10 keV, slow, and total slow neutrons than SS316 while the modified Ti-stainless steel has lower values for slow neutrons and neutrons > 10 keV than the standard stainless steel SS316. Moreover, the associated neutron half value layer (HVL) was calculated for each sample. Additionally, gamma ray shielding properties were performed for several gamma ray energies that emitted from 232Th radioactive source.

Keywords: Nuclear Reactor Materials; B; Ti and Boron-Titanium Stainless Steel; Structural; Mechanical and Attenuation Properties.

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1. Introduction

In recent years, the demand for various absorption materials has been increased in nuclear industry to ensure safety in disposal of spent fuel. Out of various neutron absorption materials, those containing boron (^{10}B) were more preferred in nuclear industry due to their low cost and very high thermal absorption. Austenitic stainless steels with 0.5 – 2 % boron are known as borated stainless steels [1, 2, 3]

Borated stainless steels were used to control neutron flux in reactors, transportation casks and spent fuel pool storage racks over thirty years ago [4]. These materials were characterized as having ductility and impact resistance below what was considered acceptable for structural materials. Thus, they were historically used for their neutron attenuation properties [5].

Borated stainless steel that possesses both neutron attenuation properties as well as adequate ductility and impact resistance is preferred to be used as a structural material that offers obvious advantage and is highly desirable [6].

Titanium was a strong carbide former, lowering the effective carbon content [7]. In austenitic steels with increased carbon content titanium was added to increase the resistance to inter -granular corrosion (stabilized grades), but it also increased mechanical properties at high temperatures. In precipitation hardening steels, titanium was used to form the intermetallic compounds that were used to increase strength [8].

Boron-Titanium stainless steels were candidate materials for structural components of nuclear reactors. B was important element that stabilized the austenite structure. However, an excess amount of B accelerated the production of intermetallic compounds and lowered ductility and corrosion resistance. B-Ti stainless steels were robust materials in this respect because of their good mechanical properties as well as irradiation damage resistance. Their toughness and formability, high strength and good ductility lend them to become suitable as nuclear reactor materials [9].

Accordingly, the aim of the present work was to investigate the structural, mechanical and attenuation properties of the boron, titanium and boron – titanium stainless steels in order to assess their beneficial uses in the nuclear reactor domains.

2. Materials and Methods

2.1. Materials Preparation

To produce titanium, boron and titanium-boronaustenitic stainless steels with base composition of SS316, a series of experiments were carried out. Many attempts were designed to calculate the material balance. Hence, the modified grades of austenitic stainless steels in addition to SS316 were prepared using a 30 Kg pilot plant medium frequency induction furnace. The melting unit based on the induction furnace was lined properly. Iron molds (inner diameter 70 mm) were used to cast the melts. Hereafter, samples of the hot forged steels were solution annealed at 1050 $^{\circ}$C for half an hour, followed by quenching process using water.

X-ray fluorescence (XRF) and spectrographic analysis (SPGA) were used to determine the composition of the produced steel alloys. The obtained results are shown in table 1. ICP-OES Optima 2000 DV Perkin Elmer was used for determination of total boron content in the produced stainless steels.

Table 1: Chemical composition of the investigated stainless steel samples

Steel Code	**Chemical Composition, wt %**														
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**W**	**Cu**	**Ti**	**V**	**Al**	**N**	**B**	**Fe**
SS316	0.05	0.41	0.48	0.018	0.015	16.19	12.92	2.40	0.02	0.12	0.005	0.10	0.040	0.0330	0.0025	66.96
SS316Ti	0.06	0.65	1.15	0.017	0.022	16.44	12.32	2.01	0.02	0.13	0.115	0.11	0.028	0.0343	0.0035	66.64
SS316B	0.08	0.48	0.68	0.017	0.024	16.41	12.21	2.08	0.02	0.13	0.003	0.10	0.022	0.0318	0.1020	67.49
SS316TiB	0.06	0.77	0.94	0.017	0.027	16.51	12.00	2.00	0.03	0.13	0.237	0.12	0.024	0.0340	0.1250	66.81

It was clear from **table 1**that steel SS316 has chemical composition similar to the standard austenitic stainless steel AISI316while steels SS316Ti, SS316B and SS316TiB are modified stainless steel alloys of base composition SS316 containing either Ti or B or Ti and B, respectively.

2.2. Methods Details

Metallography

The samples for metallographic studies were taken and polished using various grades of SIC paper up to 1200 grit followed by cloth polishing by using 1µm diamond paste then these polished samples were etched in an electro -oxalic acid (20%) solution. The microstructures of different areas of these samples were taken with an optical microscope.

Mechanical testing

Vickers hardness test was carried out on stainless steel samples prepared by grinding and polishing. The hardness measurements were carried out using Zwick-Roel hardness tester machine with 150 Kg working load.Round tensile specimens were machined with dimensions according to ASTM-E8 specification. Tensile test (yield strength, ultimate tensile strength, elongation and reduction of area) was carried out for specimens at room temperature. Test was carried out using tensile machine (EZ20-20KN) with a cross head speed of 0.3 mm/min.Charpy V-notch specimens (10mmx10mmx55mm) were prepared and tested by using impact testing machine (150J) with Computer Aided Measurement System (CAMS) with software capable of statistical analysis of data and quality control. Impact test was performed at room temperature (20^{o}C).

Corrosion Resistance Testing

Specimens of the investigated steels were corrosion tested using cyclic anodic polarization technique. Samples were polished to a 1200-grit finish, ultrasonically cleaned and rinsed with ethanol and finally dried. A conventional three-electrode cell in a single compartment-cylindrical glass cell was used with A Pt counter electrode. All the potentials were recorded with respect to a saturated calomel electrode (SCE) reference electrode at 25 ^{o}C. Sodium chloride medium was prepared from analytical grade chemicals and bi-distilled water. The cyclic anodic polarization measurement was carried out. E_{corr} 3 V below in the positive direction (≈ 1 ut starting from -0V above E_{corr}) and then reverse scan direction until E_{corr}. All the aforementioned measurements were repeated two or three times for the sake of having higher degree of precision.

Attenuation Testing

The BF_3 neutron detector was used to detect the slow, neutron with energy > 10 keV, and total slow neutrons energies emitted from ^{241}Am-Be neutron source with activity 100 mCi and neutron yield = (1.1-1.4) $*10^{7}$ n/source to detector distance was kept constant at 7 cm. In case of slow

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neutrons measurements, the collimated beam was slowed down by polyethylene material (6cm x 6cm). Also, the neutrons(energy> 10 keV) was obtained by using boron carbide sheet.

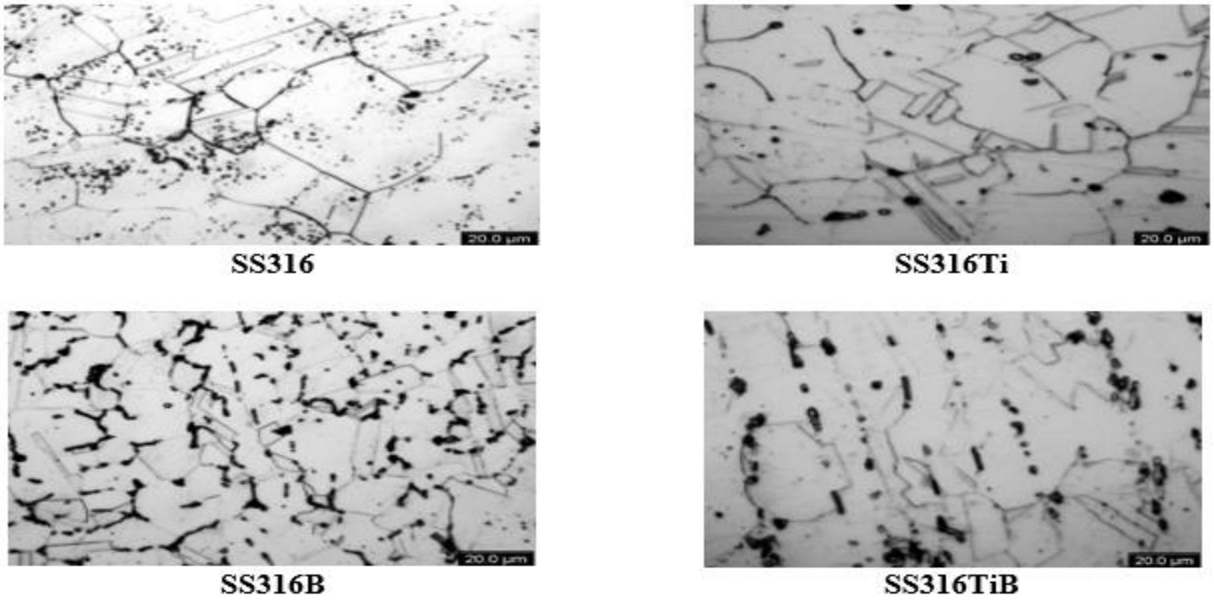
The gamma ray shielding properties of the prepared stainless steel samples were obtained for five gamma energy lines (238.63, 338.28, 583.19, 911.2 and 2614.51 keV) emitted from^{232}Thradioactive source. NaI (Tl) detector was used to measure the gamma ray intensities for the studied energy lines.

The obtained experimental shielding data were compared with the corresponding theoretical results making use of the WinXCom computer program (Version 3.1) [10]at different iron concentrations of the stainless steel samples.

3. Results and Discussions

Microstructure

The optical micrographs of the produced alloys are given in **Fig. 1**Itis illustrated that they are characterized by fully austenite case because of the appearance of a very large number of twins.



SS316 **SS316Ti**

SS316B **SS316TiB**

Figure 1: Microstructure of the investigated stainless steel

Figure 1 shows that there is a dark points formed because of the boride particles ((Fe, Cr)$_2$B) districted in austenitic matrix. It is clear that the boron particles are insoluble in steels at all temperatures, the insolubility is profuse in case of austenitic steels with high boron level which form boride eutectics such as Fe$_2$B and Cr$_2$B in austenitic matrix [11].

Mechanical Properties

The mechanical properties (Vickers hardness, yield strength, ultimate tensile strength, elongation, reduction of area and impact energy) of the investigated stainless steels were evaluated to determine the effect of boron and titanium contentson stainless steels. Table 2 and Figure 2 show the different mechanical properties for the four investigated stainless steel alloys.

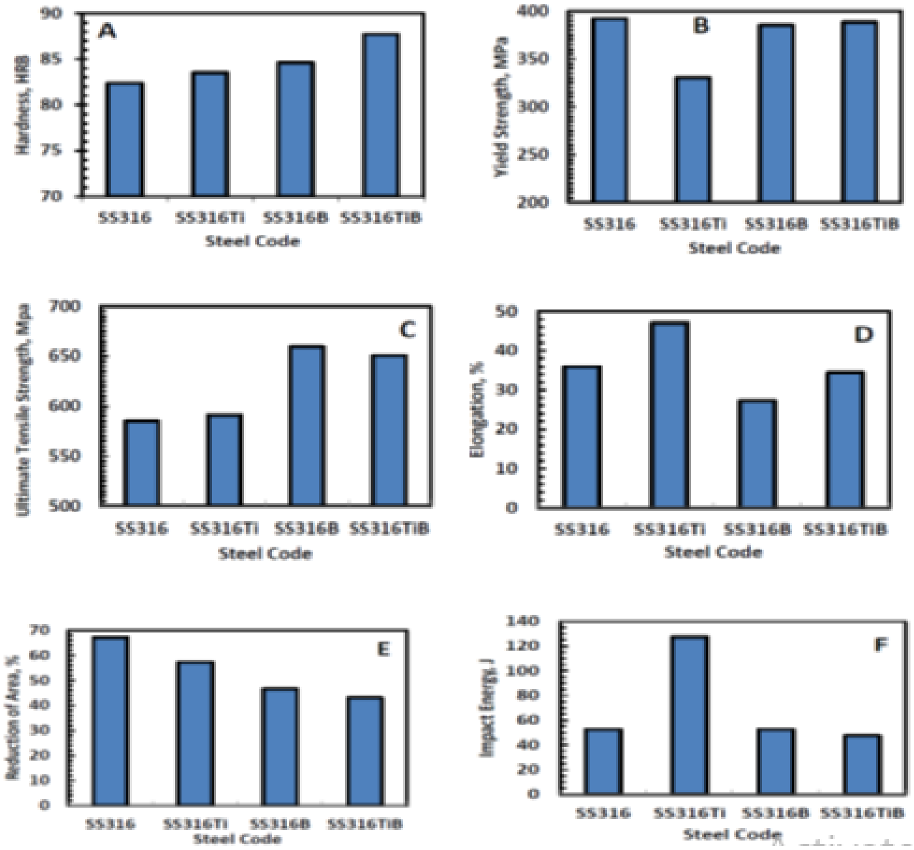


Figure 2: Mechanical properties of the investigated stainless steel alloys; (A) Vickers hardness, (B) yield strength, (C) ultimate tensile strength, (D)elongation, (E) reduction area, (F) impact energy

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

Steel Code	**Mechanical Properties**					
	Hardness (HB)	**Yield Strength (MPa)**	**Ultimate Tensile Strength (MPa)**	**Elongation (%)**	**Reduction Of Area (%)**	**Impact Energy (J)**
SS316	82.4	392	585	35.9	67.2	52.5
SS316Ti	83.5	330	591	47.1	57.3	127.5
SS316B	84.6	385	660	27.3	46.5	52.5
SS316TiB	87.7	388	651	34.5	43.0	47.5

From the results given in Table 2 and represented in Figure 2, it is clear that the modified austenitic stainless steels containing either B or Ti and B (SS316B and SS316TiB) exhibit higher hardness and ultimate tensile strength than the standard SS316 steel, while the yield strength maintains lower value than the standard SS316. This strengthening is accompanied with decreasing of ductility (elongation and reduction of area) combined with slightly reduction in impact energy. The modified steel containing Ti (SS316Ti) has slightly higher hardness and ultimate tensile strength but it also has lower yield strength compared with the standard SS316 steel. This behavior was accompanied with considerably higher ductility (total elongation %) and higher impact energy.

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The strengthening effect of B or Ti and B could be attributed to the solution hardening and precipitation strengthening effects of these elements as these elements are strong carbide or nitride formers. The higher B content accelerates the formation of intermetallic compounds and lowers the ductility.

The higher tensile ductility and impact toughness at room temperature of the modified Ti-containing austenite stainless steel could be attributed to the high work hardening rate. In the present study, SS316Ti exhibited higher work hardening rate reflected in lower yield strength to ultimate tensile strength ratio (0.56) compared with other investigated steels (0.58-0.67) [12].

Corrosion Rate

Table 3 and Figure 3 represent the corrosion rate of the investigated stainless steels alloys. The lowest corrosion rate is shown by the modified steel containing B (SS316B) while the modified steels contained either Ti or Ti and B (SS316Ti and SS316TiB) show lower corrosion rate than the conventional SS316 steel samples. Hence, they can beranked from low to high corrosion rate as follows:
SS316B<SS316TiB<SS316Ti<SS316

Table 3: Corrosion rate of the investigated steels in 3.5w.t% NaCl solution

Steel Code	Corrosion Rate, mm/y
SS316	0.09410
SS316Ti	0.01370
SS316B	0.00103
SS316TiB	0.00876

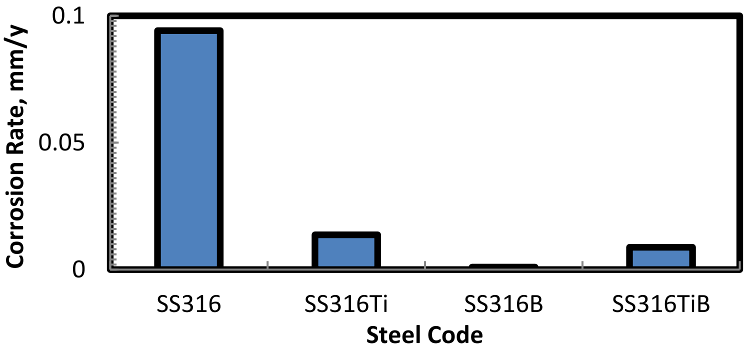

Figure 3: Corrosion rate of the investigated steels in 3.5w.t% NaCl solution

The corrosion rate of borated stainless steels samples is mainly different from the standard austenitic stainless steels because of the presence of the secondary phase. Attack of the areas surrounding the particles has an important role of that reduction [13].

Attenuation Properties

Neutrons Attenuation

Neutrons with energy > 10 keV, slow, and total slow neutrons fluxes emitted from ^{241}Am-Be neutron source were used to study the attenuation properties of neutrons in the modified austenitic stainless steel alloys. The values of the macroscopic cross sections for neutrons with energy > 10 keV, slow, and total slow neutrons were deduced from the attenuation curves and are listed in Table 4.

Table 4: The neutron macroscopic cross sections for the studied alloys

Steel Code	**$\sum_{N>10keV}$ (cm^{-1})**	**$\sum_{t}$ (cm^{-1})**	**$\sum s$ (cm^{-1})**
SS316	0.0280±0.0033	0.0623±0.0070	0.0405±0.0048
SS316Ti	0.0268±0.0046	0.0637±0.0066	0.0376±0.0085
SS316B	0.0345±0.0045	0.0674±0.0025	0.0438±0.0019
SS316TiB	0.0336 ± 0.0050	0.0681 ± 0.0048	0.0436 ± 0.0031

From Table 4, it was observed that, a slight increase in the effective macroscopic cross sections of total slow, neutrons with energy > 10 keV, and slow neutrons for the developed austenitic stainless steels containing either B or Ti and B (SS316B and SS316TiB) compared with the standard SS316 stainless steel. On the other hand, austenitic stainless steel containing Ti has lower cross section values for slow neutrons and neutrons > 10 keV than SS316 steel.

The absorption effects of the boron stainless steels alloys depend on the content of the ^{10}B isotope that has 3838.1 barn absorption cross-sections for thermal neutrons. Because of the high neutron absorption of boron compared to steel, the neutron radiography was a muscular tool for the nondestructive consideration. The most important industrial needs for the shielding materials were the regularity of the absorbing material over the whole volume and maximum thermal neutron absorption ability to perform the required safety purposes [1].

The half-value layer (HVL) was used to determine the thickness of a given material that is necessary to reduce the exposure rate from a source to some level at which the radiation intensity becomes one half that at the surface of the material [13].

The half value layer (HVL) for neutrons >10keV, total slow, and slow neutrons were deduced from the results of removal cross sections and the obtained results are shown in Figure 4.

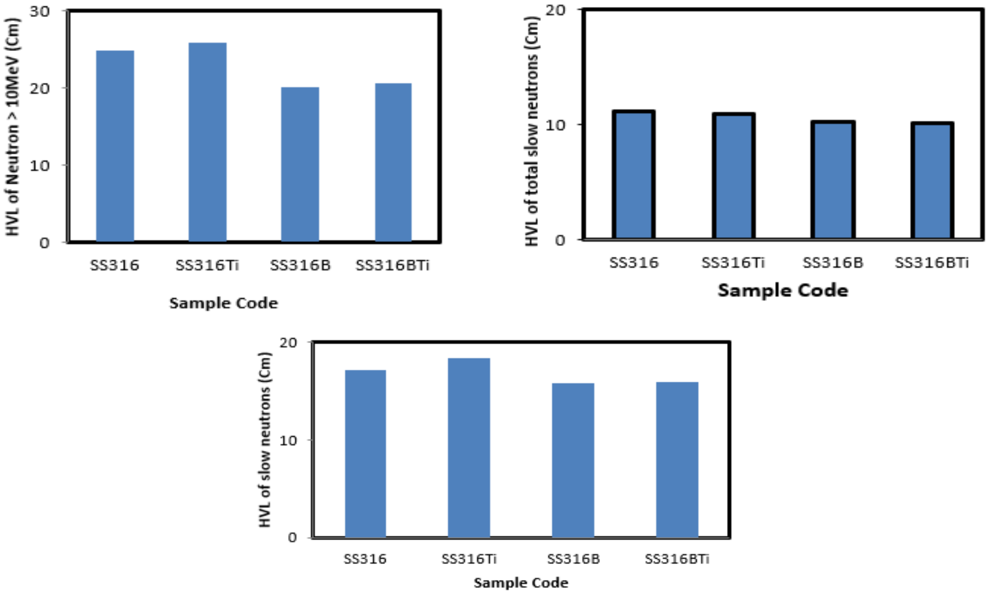

Figure (4): Half value layer of the investigated stainless steel alloys for neutrons

From Figure 4, it is observed that, the austenitic stainless steels containing B (SS304B) is the highest half value layer for neutrons > 10 Kev through the other samples due to the B addition, On the other hand slow and total slow neutrons for the developed austenitic stainless steels containing Ti and B (SS304TiB) compared with the standard SS316 stainless steel., austenitic stainless steel containing Ti has higher half value layer for slow neutrons and than SS316 steel.

Gamma Rays Attenuation

The gamma rays shielding properties of the produced stainless steel alloys were studied at different gamma ray lines having energies fall inthe range 238.63 – 2614.51 keV. The experimental total mass attenuation coefficients (σ_{Exp}) were deduced from the linear attenuation coefficients that were experimentally obtained. The deduced values of (σExp) are shown in Fig. 5compared with the calculated mass attenuation coefficients (σ_{Theo}) that are calculated using Win XCom computer program. An excellent agreement has been obtained between them. The obtained results illustrate that the mass attenuation coefficients have convergent values for all the investigated alloys. This is mainly attributed to the appearance of the small variance in the densities and/or the Z balance of all the studied stainless steel alloys.

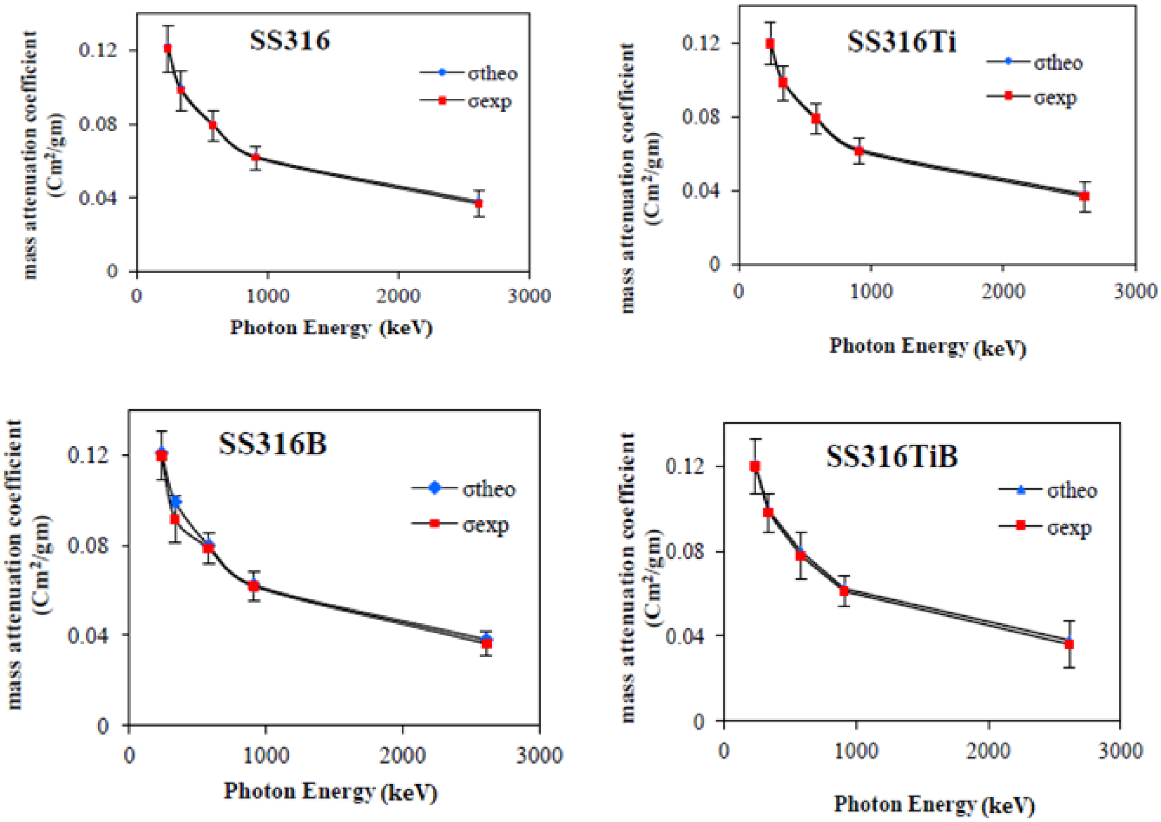

Figure 5: Experimental and theoretical mass attenuation coefficients of the investigated alloys

4. Conclusion and Recommendations

Three grades of steel with base composition of SS316 but having either Ti or B or Ti andB (SS316Ti, SS316B and SS316TiB) were developed, examined and compared with a standardSS316 austenitic stainless steel produced in the same conditions as candidate materials for nuclear reactor system. The developed steels revealed austenitic microstructure. The strengthening effect of B or Ti and B can be attributed to the solution hardening and precipitation strengthening effects of these elements as these elements are strong carbide or nitride formers. The higher B content accelerates the formation of intermetallic compounds and lowers the ductility. Also, the higher tensile ductility and impact toughness at room temperature of the modified Ti-containing austenite stainless steel could be attributed to the high work hardening rate. The corrosion rate of borated stainless steels samples is mainly different from the standard austenitic stainless steels because of the presence of the secondary phase. Attack of the areas surrounding the particles has an important role for reduction of the chromium at these areas. The macroscopic cross sections of total slow, neutrons with energy > 10 keVand slow neutrons for the developed boron-titanium stainless steel were compared with the standard SS316 stainless steel. The mass attenuation coefficients of gamma rays are nearly the same for all the studied alloys. The good mechanical properties as well as attenuation properties of the developed boron-titanium stainless steel alloys made them candidate materials for nuclear reactor systems.

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