Fusion Engineering and Design 112 (2016) 130–135

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Attenuation capability of low activation-modified high manganese austenitic stainless steel for fusion reactor system

M.M. Eissa[a], S.U. El-kameesy[b], S.A. El-Fiki[b], S.N. Ghali[a], R.M. El Shazly[c], Aly Saeed[d,*]

[a] Steel Technology Department, Central Metallurgical Research and Development Institute (CMRDI), Helwan, Egypt
[b] Physics Department, Faculty of Science, Ain Shams University, Cairo, Egypt
[c] Physics Department, Faculty of Science, Al-Azhar University, Cairo, Egypt
[d] Nuclear Power station Department, Faculty of Engineering, Egyptian-Russian University, Cairo, Egypt

HIGHLIGHTS

- Improvement stainless steel alloys to be used in fusion reactors.
- Structural, mechanical, attenuation properties of investigated alloys were studied.
- Good agreement between experimental and calculated results has been achieved.
- The developed alloys could be considered as candidate materials for fusion reactors.

ARTICLE INFO

Article history:
Received 5 February 2016
Received in revised form 3 August 2016
Accepted 4 August 2016

Keywords:
Fusion reactor materials
Manganese stainless steel
Mechanical and structural properties

ABSTRACT

Low nickel-high manganese austenitic stainless steel alloys, SSMn9Ni and SSMn10Ni, were developed to use as a shielding material in fusion reactor system. A standard austenitic stainless steel SS316L was prepared and studied as a reference sample. The microstructure properties of the present stainless steel alloys were investigated using Schaeffler diagram, optical microscopy, and X-ray diffraction pattern. Mainly, an austenite phase was observed for the prepared stainless steel alloys. Additionally, a small ferrite phase was observed in SS316L and SSMn10Ni samples. The mechanical properties of the prepared alloys were studied using Vickers hardness and tensile tests at room temperature. The studied manganese stainless steel alloys showed higher hardness, yield strength, and ultimate tensile strength than SS316L. On the other hand, the manganese stainless steel elongation had relatively lower values than the standard SS316L. The removal cross section for both slow and total slow (primary and those slowed down in sample) neutrons were carried out using ^{241}Am-Be neutron source. Gamma ray attenuation parameters were carried out for different gamma ray energy lines which emitted from ^{60}Co and ^{232}Th radioactive sources. The developed manganese stainless steel alloys had a higher total slow removal cross section than SS316L. While the slow neutron and gamma rays were nearly the same for all studied stainless steel alloys. From the obtained results, the developed manganese stainless steel alloys could be considered as candidate materials for fusion reactor system with low activation based on the short life time of manganese isotopes in a comparison with nickel.

1. Introduction

Recently, generating electricity using fusion reactor systems is considered one of the most attractive long term energy options [1]. A variety of radiation fields (gamma rays and neutrons) are existed in fusion reactors depending upon the fusion process [2]. So, many types of materials are needed as protective materials in the fusion reactor. The materials used in the construction of fusion reactors are the most obstacles in this field. In this regard, considerable efforts were carried out to develop low activation alloys as protective materials in fusion reactor system [3,4]. Radioactivity in fusion reactors could be effectively controlled by materials selection. In this respect, the selection of alloying elements is crucial. Austenitic stainless steels are considered as structural materials in the first wall and blanket structure of magnetic fusion reactors [5]. The approach to reduce long-term radioactivity in austenitic stainless steel alloys could be enhanced by replacing or minimizing the nickel by manganese [6]. Additionally, nitrogen should be

* Corresponding author.
E-mail address: aly_8h@yahoo.com (A. Saeed).

http://dx.doi.org/10.1016/j.fusengdes.2016.08.002
0920-3796/

minimized, while molybdenum and niobium must be avoided [7]. Manganese is an important element to stabilize the austenite structure. Manganese is probably the most important element after carbon that is commonly used to increase hardness and the strength of the steel. Manganese also reduces the solubility of sulphur in austenite and promotes the formation of spherical rather than angular intergranular precipitates [8,9]. Additionally, manganese refines the produced microstructure due to its depression of transformation temperature, besides its ability to decrease the critical cooling rate during hardening [10,11]. However, an excess amount of Mn accelerates the production of intermetallic compounds and reduces ductility as well as corrosion resistance. Therefore, Mn was limited between 15% and 35% in stainless steel structure [12,8,9]. Manganese stainless steels are robust materials for the fusion reactor systems because of their good mechanical properties as well as irradiation damage resistance [13].Their toughness and formability, high strength and good ductility lend them to become suitable as fusion reactor materials [14]. Fe-Cr-Mn stainless steels are candidate materials for structural components of fusion reactors because of their low induced long-term radioactivity compared to that of typical Fe-Cr-Ni austenitic stainless steels [15].

For the aforementioned reasons, the present study is focused on developing of a low activation austenitic stainless steel Mn-Cr-Fe with low nickel content. Then, the structural, mechanical and attenuation properties of the prepared stainless steel alloys were studied and discussed.

2. Samples preparation

With the objective of partially replacement of nickel by manganese in austenitic stainless steels, a series of many experiments was carried out. Many attempts were designed to calculate the materials balance and manganese required for producing the desired stainless steels with different combinations of manganese and nickel contents. Hence, modified grades of high manganese-low nickel austenitic stainless steels were prepared using a 30 kg pilot plant medium frequency induction furnace. The induction furnace melting unit was lined with basic lining. All melts were cast in iron moulds of inner diameter 70 mm. The produced ingots were hot forged to steel bars with cross section $30 \times 30\,mm^2$. Samples from the forged steels were initially solution annealed at 1050 °C for 30 min and followed by water quenching.

3. Experimental measurements

The chemical compositions of the obtained stainless steel alloys were analyzed using X-ray fluorescence (XRF) and spectrographic analysis (SPGA). Kjeldahl method [16] was used for determination of total nitrogen content in the produced steels. Samples of the investigated stainless steels were prepared for microscopic examination. After etching with a 5CCHCl+29 picric acid+100 CC Ethyl alcohols, the microstructure was observed using an optical microscope. X-ray diffraction (X'PERT PRO PANLYTICAL device using of CuKα target with secondary monochromator 45 kV, 40 mA) was employed for identification of the constituent phases in the studied stainless steel alloys. Vickers hardness tests were carried out on high polished stainless steel samples. The hardness measurements were carried out using Zwick-Roel hardness tester machine with 50 kg working load. An average of five readings was taken. Tensile test was carried out for specimens at room temperature and yield strength, ultimate tensile strength and elongation were determined. Round tensile specimens were machined with dimensions according to ASTM-E8 specification [17]. Tensile test was carried out using EZ20 20 KN with a cross head speed of 0.3 mm/min. Each of the tensile values was the average of two tensile test data.

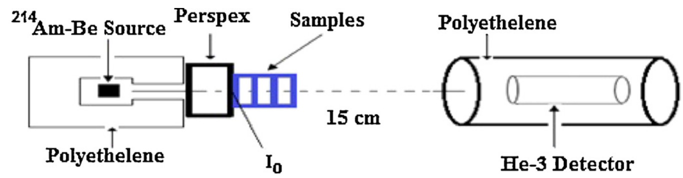

Fig. 1. Schematic diagram of neutrons measurements.

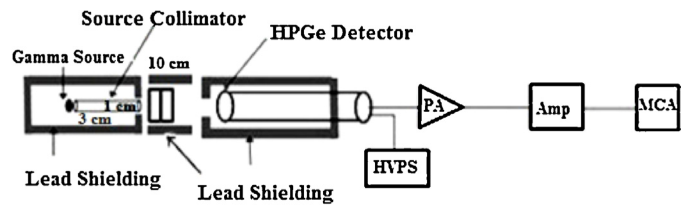

Fig. 2. Experimental setup of gamma ray narrow beam transmission method.

The density of the prepared stainless steel was measured using the standard Archimedes principle [18]. The slow and total slow neutron fluxes, emitted from ^{241}Am-Be neutron source with activity 5Ci and neutron yield = $(1.1–1.4) \times 10^7$ n/sec, were measured by ^{3}He detector. In the case of slow neutrons measurements the collimated beam was slowed down by Perspex material behind the sample. The scheme of the experiment was shown in Fig. 1.

The gamma ray attenuation coefficients of the prepared stainless steel samples were obtained for eight gamma energy lines (238.63, 338.28, 583.19, 911.2, 968.97, 1173.23, 1332.49, and 2614.51 keV) emitted from ^{60}Co and ^{232}Th radioactive sources. Hyper Pure Germanium detector (HPGe) (with relative efficiency ≈30% relative to a $3'' \times 3''$ NaI (Tl) detector, active volume 62.3 cm^3, and resolution 1.8 keV at 1.33 MeV γ-lines) was used to measure the gamma ray intensities for the studied energy lines. Fig. 2 shows the experimental setup. All measurements were carried out at room temperature. To compare the obtained experimental and theoretical data, the WinXCom computer program (version 3.1) [19] was used to calculate the mass attenuation coefficients of γ-rays for such used energies for the studied stainless steel samples.

4. Results and discussions

The chemical compositions of the investigated steels were shown in Table 1. Which should that the developed stainless steel includes two grades of steel with manganese content, 8.85 and 9.91 wt.% and standard SS316L stainless steel. It is cleared that steel SS316L has chemical composition conforms to the standard austenitic stainless steel AISI 316L. In steels: SSMn9Ni and SSMn10Ni, the nickel content was partially replaced by manganese. The molybdenum was totally eliminated and nickel was much minimized in the prepared manganese stainless steel alloys because of the considerations mentioned in the introduction.

Three different tools one theoretical (Schaeffler diagram) and two experimental (X-ray diffraction and optical microscopy) were used to study the structural properties of the investigated stainless steels.

The Schaeffler diagram is considered one of the ways to determine the stability of austenite and other phases in the matrix of stainless steels. For the Schaeffler diagram of the present stainless steel alloys, nickel and chromium equivalents were calculated using the following expressions [20] and listed in Table 2.

$$Ni_{Equi} = Ni + 0.5Mn + 30C + 30N \quad (1)$$

$$Cr_{Equi} = Cr + 2Si + 1.5Mo + 5V + 1.5Ti \quad (2)$$

with all concentrations being expressed in weight percentages.