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# Investigation of mechanical properties and proton irradiation behaviors of SA-738 Gr.B steel used as reactor containment

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ABSTRACT

The proton irradiation behaviors of two kinds of SA-738Gr.B steels prepared by different heat treatment used as AP1000 reactor containment were investigated by transmission electron microscopy and positron annihilation lifetime spectrum (PAS). The mechanical properties of as-received steels were also measured. In the unirradiated conditions, the SA-738Gr.B steels had high tensile strength and excellent impact fracture toughness, which met the performance requirements of ASME codes. Both kinds of SA-738Gr.B steels were irradiated by 400 keV proton from $1.07 \times 10^{17}$ $H^+/cm^2$ to $5.37 \times 10^{17}$ $H^+/cm^2$ fluence at 150 °C. Some voids and dislocation loops with several nanometers were observed in the cross-section irradiated samples prepared by electroplating and then twin-jet electropolishing technology. The number of irradiation defects increased with increasing of displacement damage, as well as for the mean positron lifetimes. The stress-relief annealing treatment improved irradiation resistance based on open volume defect analysis from proton irradiation. SA-738Gr.B (SR) steel had higher proton irradiation resistance ability than that of SA-738Gr.B (QT) steel. The mechanism of irradiation behaviors were also analyzed and discussed.



## 1. Introduction

In order to enhance nuclear energy safety and improve economic efficiency, Generation III nuclear power plants with more safe and efficient are constructing in various countries such as China. The typical representative is AP1000 advanced passive nuclear power designed by Westinghouse Corporation that adopts gravity and natural circulation of water [1]. The passive containment cooling system of AP1000 is a double-layer structure that consists of steel-made containment and reinforced concrete shield building, which is difference with traditional pre-stressed concrete containment [2]. The unconventional design of AP1000 nuclear containment brings the high-level requirements of the welding performance, tensile strength and low temperature toughness. The design pressure and temperature of AP1000 reactor containment is 0.407 MPa and 300 °F (about 150 °C), respectively [1,3]. AP1000 reactor containment manufactured using SA-738Gr.B steel has extremely large size, which involves many welding assemblies and will be subjected to a complex service environment. So, it needs the SA-738Gr.B steel to have high comprehensive performance in order to ensure nuclear power safety. However, it has less done research on properties and performance of SA-738Gr.B steel, such as weld ability, corrosion properties and irradiation behaviors. L. Z. Ding [4] just reported the weld ability of SA-738Gr.B steel.

In fact, as a reactor containment, SA-738Gr.B steel hardly suffers neutron irradiation under safe operation condition because the maximum neutron dose of nuclear pressure vessel in 60 year service is just about 0.05 dpa (displacement per atom, dpa) [5]. However, the irradiation properties should be considered in case of nuclear accident, which decides the accident tolerance ability of reactor containment. Actually, less literatures reported its irradiation behaviors. In the present work, the irradiation properties of two kinds of SA-738Gr.B steels irradiated with different proton fluence were investigated by transmission electron microscopy and positron annihilation lifetime spectrum (PAS). Proton irradiation has been demonstrated as a superior method for simulating neutron irradiation in studying the irradiation behavior of stainless steels [6]. In addition, PAS can reveal more details of irradiation-induced defects at a low irradiation dose [7].

## 2. Experiment

The samples used in this study were two kinds of SA-738Gr.B steels provided by Wuhan Iron & Steel (Group) Corporation in China. The heat treatment for one kind of steel was quenching and tempering, and for another kind of steel was quenching, tempering

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**Table 1**
The chemical composition of SA-738Gr.B steel (mass fraction, %).

| C | Si | Mn | P | S | Ni | Cr | Mo | Nb+V+Ti | CE | Fe |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.09 | 0.28 | 1.42 | ≤ 0.015 | ≤ 0.005 | 0.41 | 0.04 | 0.22 | ≤ 0.10 | 0.42 | Bal. |

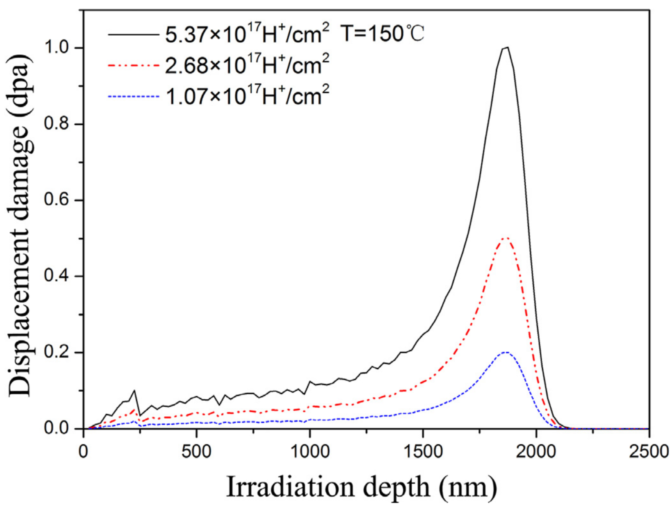


**Fig. 1.** Depth profile of displacement damage in SA-738Gr.B steel irradiated by 400 keV $H^+$ with different ion fluence calculated by SRIM 2008.

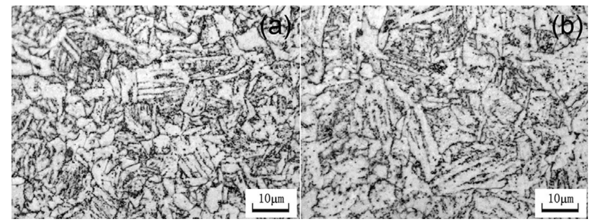


**Fig. 2.** Metallographic images of as-received SA-738Gr.B steel (QT) steel (a) and SA-738Gr.B (SR) steel (b).

and then stress-relief annealing (SR), which were represented using SA-738Gr.B (QT) steel and SA-738Gr.B (SR) steel, respectively. The stress-relief annealing treatment was carried out at 600ºC for 10 h. The speeds of both rising temperature and decreasing temperature were controlled below 80ºC/h. The chemical composition of SA-738Gr.B steel was listed in Table 1, which perfectly met the requirement of ASME standard [8].

The samples with about 10 mm × 10 mm × 3 mm used for metallographic analysis and ion irradiation were firstly cut from as-received steel plates by using a precision diamond knife cutting machine and then grinded by SiC sandpapers from 180 to 5000 grid, polished using 3~0.05 µm diamond suspensions. After that, some samples were finally chemical etched using a 4% nitric acid alcohol solution for metallographic observation, and others were electrochemical polished using a 5% $HClO_4$ ethanol solution for ion irradiation experiment. Both sides of each sample 3 mm in diameter from as-received steels were firstly ground using SiC sandpaper from 240 to 1200 grid and then polished using 1 µm diamond paste. Finally, samples were twin-jet electropolished using a 10% $HClO_4$ ethanol solution to perforation for TEM observations.

Irradiation was conducted at 150ºC with 400 keV $H^+$ using a NEC 400KV ion implanter in our research group. The ion flux was kept at $2\times10^{13}$ ions/cm$^2$.s to prevent temperature ramping from excessive beam heating. The depth distribution of displacement damage was simulated by Monte Carlo calculations using the Stopping and Range of Ions in Matter (SRIM) 2008 as shown in Fig. 1. The displacement energy of all elements in the SA-738Gr.B steel was assumed to be 40 eV [9]. The $H^+$ ion implantations resulting in peak displacement damage was 1.0dpa, 0.5dpa and 0.2dpa after irradiation with $5.37\times10^{17}$ $H^+$/cm$^2$, $2.68\times10^{17}$ $H^+$/cm$^2$ and $1.07\times10^{17}$ $H^+$/cm$^2$, respectively [10]. The depth of peak displacement damage was about 1850 nm as shown in Fig. 1.

Because of low irradiation depth, the cross-section TEM samples were prepared by electroplating and then twin-jet electropolishing technology [11]. The irradiated bulk surface was firstly deposited a nickel coating with about 2 mm thickness by an electroplating technique in modified Wood nickel solution and then cut into thin slices along the ion incident direction by using a precision diamond knife cutting machine. The samples with 3 mm in diameter were cut from the cross-section thin slices using a hole punch. In order to obtain a perfect TEM samples, it needed to make sure the boundary between irradiated area and nickel coating located in the middle of $\varphi$3mm. The cross-section samples were further thinned by a dimple grinder, and then were twin-jet electropolished using a 10% $HClO_4$ ethanol solution to perforation for TEM observations. The microstructure of the as-received TEM samples and the cross-section irradiated TEM samples were analyzed by using a JEOL 2100 transmission electron microscope.

Positron annihilation lifetime spectrum performed at room temperature and tested by means of a conventional fast-fast coincidence positron lifetime spectrometer using $^{22}$Na positron source which consist of a pair of $BaF_2$ detectors providing the time resolution of 170 ps full-width at the half-maximum. Measured spectra was transformed into two exponential components by LT9.0 program after subtracted background value [12]. Each spectra accumulated two million counts during the test process.

The mechanical properties including tensile properties and impact fracture toughness of as-received steels were also measured. The tensile samples were machined according to ASTM E8M. Tensile test was carried out on an Instron1341 servo-hydraulic testing machine with cylindrical samples at room temperature using a strain rate of 0.008 s$^{-1}$. An extensometer was used to measure yield strength (0.2% strain), ultimate tensile strength (UTS) and elongation ($\delta$). The impact fracture toughness was also test using charpy V-notch samples at room temperature, 0 ºC, −20 ºC and −40 ºC.

## 3. Results and discussions

Fig. 2 is metallographic images of the unirradiated SA-738Gr.B(QT) steel and SA-738Gr.B(SR) steels. It is observed that the morphology of SA-738Gr.B steel is a mixture of lath-shaped and equiaxial bainite with a small amount of medium temperature ferrites. The length and width of lath-shaped bainites are tens of microns and several hundred nanometers, respectively. A large number of carbide precipitates distribute at the boundaries of bainite grain, which shows as dark microstructure in the metallographic images. According to the metallographic analysis, it can be concluded that the stress-relief annealing treatment dose not obviously change the morphology of SA-738Gr.B steel. Only the dispersive degree of carbide precipitates in SA-738Gr.B(SR) steel is a little larger than that in SA-738Gr.B (QT) steel from metallographic images.