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Changes in Mechanical Properties of SA508 Gr.4N Model Alloys with Neutron Irradiation

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1. Introduction

The SA508 Gr.4N specifications in the ASME code provides better properties with a higher strength and higher toughness than SA508 Gr.3 low alloy steel by a change in chemistry with increased Ni and Cr contents. For the application of SA508 Gr.4N low alloy steels to the pressure vessel, particular for reactor pressure vessels (RPV), we have carried out comprehensive and systematic researches on SA508 Gr.4N in recent years [1-4]. To use SA508 Gr.4N low alloy steel as a material for RPV, the embrittlement behavior by neutron irradiation should be clarified because of its higher Ni content. It is generally known that the presence of Ni in RPV steel increases the sensitivity to irradiation embrittlement. In this study, the irradiation embrittlement behavior of SA508 Gr.4N Ni-Cr-Mo low alloy steel were characterized using model alloys. Several sets of irradiation tests were carried out in a research reactor to evaluate the irradiation embrittlement behavior of SA508 Gr.4N low alloy steel.

2. Experimental Procedure

Several different heats of SA508 Gr.4N model alloy were used in this study. Table 1 summarizes the chemical compositions of model alloys along with the specifications of the chemical compositions in ASME [5]. SA508 Gr.4N low alloy steel has higher Ni and Cr content and lower Mn content compared to Gr.3 low alloy steel. The model alloys were fabricated using vacuum induction melting based on the chemical composition range of the ASME specifications. After the forging process, the model alloys were heat-treated by austenitizing at 880^{o}C for 2 hours after homogenization at 1200^{o}C for 10 hours, and were then tempered at 660^{o}C for 10 hours, which are the typical heat treatments for SA508 Gr.3 RPV steels. The controlled cooling rate was applied after austenitization to simulate the microstructure of the 1/4t location in a thick, heavy section RPV.

Table 1 Chemical compositions of tested materials (wt%, Fe=bal.)

ID	C	Ni	Cr	Mo	Mn
KL4	0.19	3.58	1.80	0.50	0.30
OP3	0.21	3.60	1.78	0.49	0.20
OP4	0.20	2.89	1.88	0.49	0.21
KM4	0.18	3.44	1.80	0.49	0.33

Standard Charpy V-notch specimens and pre-cracked Charpy V-notch (PCVN) specimens (10mm x 10mm x 55mm) were fabricated for impact toughness and fracture toughness tests. Sub-sized PCVN (5mm x 5mm x 27.5mm) specimens were also used for the irradiation test. Two types of small plate specimens were used for the tensile test. Tensile tests were carried out at room temperature at a strain rate of 1.1 x10^{-3}/s according to ASTM E8M. Charpy impact tests were conducted within a temperature range of -196 to 130^{o}C following the ASTM E23 procedure. Fracture toughness tests were conducted in 3-point bending based on the ASTM E1921 procedure.

Four irradiation capsules were irradiated in research reactors ‘Hanaro’ in Korea and the Halden Boiling Water Reactor (HBWR) in Norway. Each capsule contained several types of specimens, such as tensile, Charpy impact, pre-cracked Charpy V-notched (PCVN) and sub-sized PCVN specimens. The specimens were irradiated up to 1.5x10^{20}n/cm^2 (E>1MeV), and the target irradiation temperature was 290 ± 10^{o}C. The mechanical tests of the irradiated specimens were carried out at the Irradiated Material Examinations Facility (IMEF) at the Korea Atomic Energy Research Institute (KAERI).

3. Result

3.1. Tensile properties at room temperature

Tensile test results of SA508 Gr.4N model alloys at room temperature under the irradiated conditions are presented in Table 2. The yield strength was increased with an increase in the neutron fluence level, and the amount of strength increase was comparable to commercial SA508 Gr.3 low alloy steel. The yield strength of model alloy KL increased by 81MPa from 564MPa after irradiation to a fluence level of 8.2 x 10^{19}n/cm^2. Even after severe irradiation up to a fluence level of 1.53 x 10^{20}n/cm^2, the yield strength of KM4 was 671MPa which was increased by 136MPa.

Table 2 Yield strengths of SA508 Gr.4N model alloys with various neutron fluence levels

	Fluence (n/cm^2, E>1MeV)	YS $_{Un-irr}$ (MPa)	YS $_{Irr}$ (MPa)
KL4	8.20E+19	564	645
	3.87E+19		611
	1.73E+19		609
KM4	1.53E+20	535	671

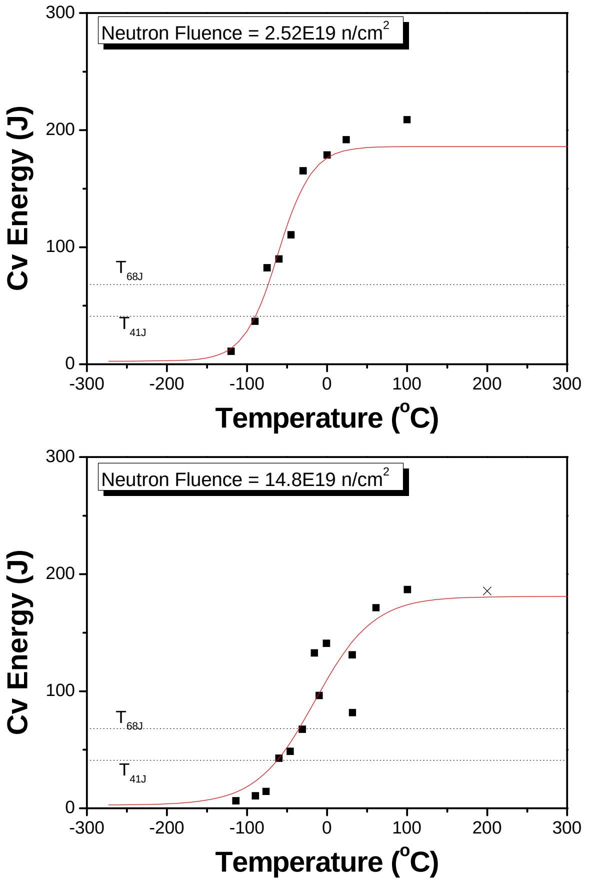

Fig. 1. Charpy impact energy transition curves of SA508 model alloys with different neutron fluence level

3.2. Transition behavior

Fig. 1 shows the results of the Charpy impact tests for SA508 Gr.4N model alloys after neutron irradiation. The determined values of the index temperature, T_{41J}, were -90°C, and -63°C at a fluence level of 2.5x10^{19} n/cm^2, and 14.8x10^{19} n/cm^2 (E>1.0MeV), respectively. The irradiation temperature was ranged from 285°C to 300 °C. As the neutron fluence level increased, the transition region of the model alloy was moved toward the higher temperature region. The fracture toughness test using a standard PCVN specimen was carried out and the irradiation effects on fracture toughness was evaluated. Similar to the Charpy impact test results, the reference temperature, T_0, was increased with an increase in the neutron fluence level. However, there is no drastic increase in the reference temperature, T_0. It is noticeable that the value of T_0 after severe neutron irradiation of up to 11.1 x10^{19} n/cm^2 was -77°C, which is almost equivalent to that of un-irradiated commercial SA508 Gr.3 low alloy steel. The T_0 values for un-irradiated commercial SA508 Gr.3 low alloy steel ranged from -80°C to -60°C.

4. Summary

The mechanical properties and irradiation embrittlement behavior of SA508 Gr.4N low alloy steel were evaluated. The yield strength and tensile strength were increased with an increase in fluence level, but there is no drastic increase in strength. A significant increase in the transition temperature shifts from the Charpy impact test and fracture toughness test was not observed in SA508 Gr.4N model alloy. The overall irradiation embrittlement behavior of SA508 Gr.4N low alloy steel is almost similar to that of SA508 Gr.3 low alloy steel, and an increase in Ni content by a few percentage points in SA508 Gr.4N model alloys compared to SA508 Gr.3 low alloy steel did not result in an increased embrittlement of these alloys.

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