Neutron irradiation effects on mechanical properties in SA508 Gr4N high strength low alloy steel

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1. Introduction

The Reactor Pressure Vessel (RPV) is the key component in determining the lifetime of nuclear power plants because it is subject to the significant aging degradation by irradiation and thermal aging, and there is no practical method for replacing that component. Advanced reactors with much larger capacity than current reactor require the usage of higher strength materials inevitably [1]. The SA508 Gr.4N Ni-Cr-Mo low alloy steel, in which Ni and Cr contents are larger than in conventional RPV steels, could be a promising RPV material offering improved strength and toughness from its tempered martensitic microstructure [2-5].

For a structural integrity of RPV, the effect of neutron irradiation on the material property is one of the key issues. The RPV materials suffer from the significant degradation of transition properties by the irradiation embrittlemet when its strength is increased by a hardening mechanism. Therefore, the potential for application of SA508 Gr.4N steel as the structural components for nuclear power reactors depends on its ability to maintain adequate transition properties against the operating neutron does [6]. However, it is not easy to fine the data on the irradiation effect on the mechanical properties of SA508 Gr.4N steel.

In this study, the irradiation embrittlement of SA508 Gr.4N Ni-Cr-Mo low alloy steel was evaluated by using specimens irradiated in research reactor. For comparison, the variations of mechanical properties by neutron irradiation for commercial SA508 Gr.3 Mn-Mo-Ni low alloy steel were also evaluated.

2. Experimental Procedure

Experiments have been carried out using the commercial SA508 Gr.3 RPV steel and SA508 Gr.4N model alloys. The H2 alloy is a representative of the commercial RPV steel forging SA508 Gr. 3 and the KL4-Ref model alloy is a SA508 Gr.4N model alloy produced as 50kg ingots by vacuum induction melting based on the chemical composition range of the ASME spec. [2]. The chemical compositions of the tested materials are given in Table 1. The KL4-Ref model alloy were heat-treated by austenitizing at 880°C followed by air quenching, and were then tempered at 660°C, which are the typical heat treatments for RPV steels, including SA508 Gr.3.

The standard Charpy V-notch specimens and the pre-cracked Charpy V-notch (PCVN) specimens with dimensions of W: 10mm, T: 10mm, and L: 27.5mm were fabricated for testing impact toughness and fracture toughness. The tensile specimens of small plate type with a gage length of 6mm and a thickness of 0.5mm were also fabricated for tensile test. The specimens were irradiated up to 8.2 x 10^{19}n/cm^2 (E>1MeV) at 290 ± 10°C in the instrumented capsules at the Korean research reactor, HANARO.

Table 1. Chemical compositions of tested materials (wt%)

	C	Ni	Cr	Mn	Fe
H2	0.19	0.82	0.17	1.35	Bal.
KL4-Ref	0.19	3.60	1.80	0.30	Bal.

Tensile tests were carried out at room temperature at a strain rate of 1.1 x10^{-3}/s according to ASTM E8M-08. The yield strength was determined by a 0.2% strain offset stress. Charpy impact tests were performed in the temperature range of -196 to 130°C following ASTM E23-07a procedure. Hyperbolic tangent curve fitting was done for the absorbed impact energy data to obtain the characteristic temperatures. Fracture toughness tests were conducted in 3-point bending based on ASTM E1921-09c procedure. The test temperature was controlled within ± 1°C by using liquid nitrogen in an isopentane fluid bath and an insulated chamber.

3. Results and Discussion

Tensile test results of KL4-Ref alloy in the unirradiated and irradiated conditions at room temperature are presented in Fig. 1. Yield strength and tensile strength were increased with the increase of fluence level, but there is no significant increase in strengths compared with commercial SA508 Gr.3 RPV steel

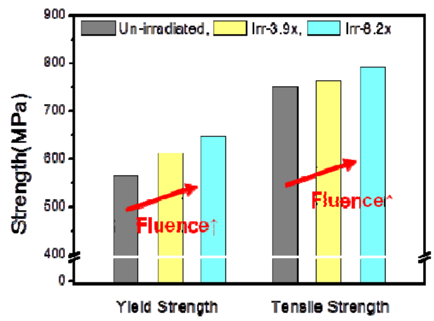

Fig. 1. Changes in tensile properties of KL4-Ref with neutron fluence level.

Yield strength of KL4-Ref increased by 80MPa from 561MPa in the unirradiated condition after irradiation to the fluence of 8.2 x 10^{19}n/cm^2 while that of H2 increased by 43MPa after irradiation. Under typical irradiation conditions for pressurized water reactor (PWR) operation, it is well known that the increase of yield strength for RPV steels is usually less than 50% of yield strength at room temperature for unirradiated steels. From the viewpoint of rate of increase, the variations of tensile strength and elongation are similar level in both steels.

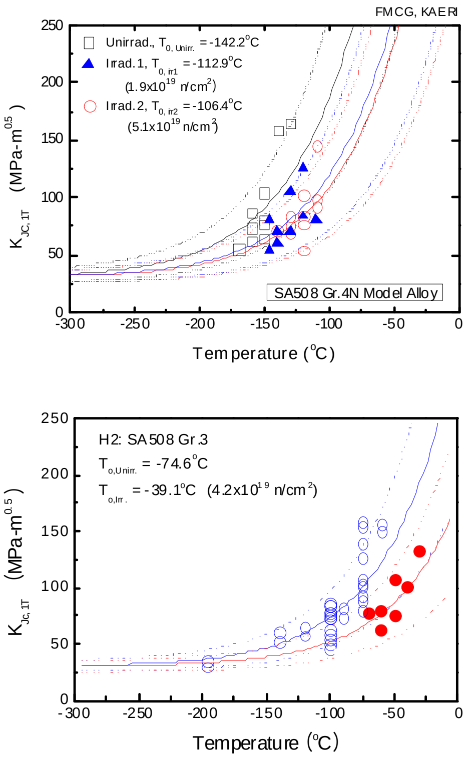

Fig. 2. Changes in transition behavior of H2 and KL4-Ref after neutron irradiation

Fig. 2 shows the standard master curves of H2 and KL4-Ref with irradiation conditions. Reference temperature (T_0) of KL4-Ref was shifted toward higher temperature with an increase of the neutron fluence level. Although it is difficult to compare the transition temperature shift (TTS) quantitatively because of different neutron fluence level, ΔT_0 of KL4-Ref was not significantly increased even in higher fluence level. Furthermore, highly irradiated KL4-Ref showed much better transition properties than un-irradiated commercial SA508 Gr.3 steel, even though it has higher Ni contents than H2 steel. Increased Ni content in SA508 Gr.4N model alloy didn't show significant effects on the irradiation embrittlement behavior. Even in severe irradiation condition, irradiated KL4-Ref showed better mechanical properties than unirradiated commercial SA508 Gr.3 steel.

3. Summary

The irradiation embrittlement behavior of SA508 Gr.4N Ni-Cr-Mo low alloy steel was evaluated by using specimens irradiated in research reactor and compared with results of commercial SA508 Gr.3 low alloy steel. Yield strength and tensile strength were increased with the increase of fluence level, but there is no significant increase in strengths compared with commercial SA508 Gr.3 RPV steel. Transition temperature shifts by fracture toughness (ΔT_0) tests was not significantly larger than commercial SA508 Gr.3 steel in spite of its high fluence level. It is noticeable that highly irradiated KL4-Ref showed much better mechanical properties than un-irradiated commercial SA508 Gr.3 steel, even though it has higher Ni content than commercial SA508 Gr.3 steel. It seems that the increased Ni content in the SA508 Gr.4N model alloy did not show significant effects on the irradiation embrittlement behavior.

Acknowledgement

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