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Comparison on Mechanical Properties of SA508 Gr.3 Cl.1, Cl.2, and Gr.4N Low Alloy Steels for Pressure Vessels

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1. Introduction

Low alloy steels used as nuclear reactor pressure vessel (RPV), steam generator (SG) and piping occupy a large portion of structural materials for nuclear power plants. In this study, microstructure and mechanical properties of SA508 Gr.3 Cl. 1, Cl.2, and Gr.4N low alloy steels are characterized to compare their properties. To evaluate the fracture toughness in the transition region, the master curve method according to ASTM E1921 was adopted in the cleavage transition region. Tensile tests and Charpy impact tests were also performed to evaluate the mechanical properties, and a microstructural investigation was carried out.

2. Experimental Procedures

The chemical compositions of the steels used in this study are given in Table 1. SA508 Gr.3 Cl.1 and Cl.2 steels are commercial low alloy steels for pressure vessels, and SA508 Gr.4N steel is a model alloy with a typical composition within the ASME specified composition. SA508 Gr.4N model alloy was fabricated as 1 ton ingot by vacuum induction melting followed by forging and heat treatment process of quenching and tempering.

Table 1 Chemical compositions of the SA508 steels

	C	Mn	Ni	Cr	Mo
SA508 Gr.3 Cl.1	0.21	1.36	0.92	0.21	0.49
SA508 Gr.3 Cl.2	0.24	1.39	0.86	0.22	0.53
SA508 Gr.4N Model alloy	0.20	0.23	3.41	1.83	0.51

The microstructures were investigated by an optical microscope and scanning electron microscope (SEM). Tensile specimens were tested at the temperature range of room temperature to 371°C. The yield strength was determined by a 0.2% strain offset stress. Charpy impact tests were performed with standard Charpy V-notch specimens (10x10x55 mm) in the temperature range of −196 to 100 °C according to the ASTM E23 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-points bending according to ASTM E1921 over the temperature range of -196 to -40°C with pre-cracked Charpy V-notch (PCVN) specimens (10x10x55mm), in which the initial fatigue crack was about half the specimen width.

2. Results and Discussions

SEM images of the microstructure of the tested materials are shown in Figs. 1(a) through 1(f). SA508 Gr.3 Cl.1 and Cl.2 steels show a typical tempered upper bainitic structure, which is a lath structure within the prior-austenite grain. Cementite particles of a long rod shape are distributed along the bainitic ferrite lath boundaries, and spherical type cementite and fine M_2C type carbides are dispersed inside the laths. It seems that SA508 Gr.3 Cl.2 steel has a small prior-austenite grain and fine cementites compared to Cl.1 steel. The predominant microstructure of the SA508 Gr.4N model alloy is tempered martensite, though a mixture of martensite and bainite was observed in the optical micrographs. The size of the martensite packet including a lath structure is much smaller than that of the bainite packet or sheaf. The SA508 Gr.4N model alloy has finer precipitates than A508 Gr.3 steels and most of the

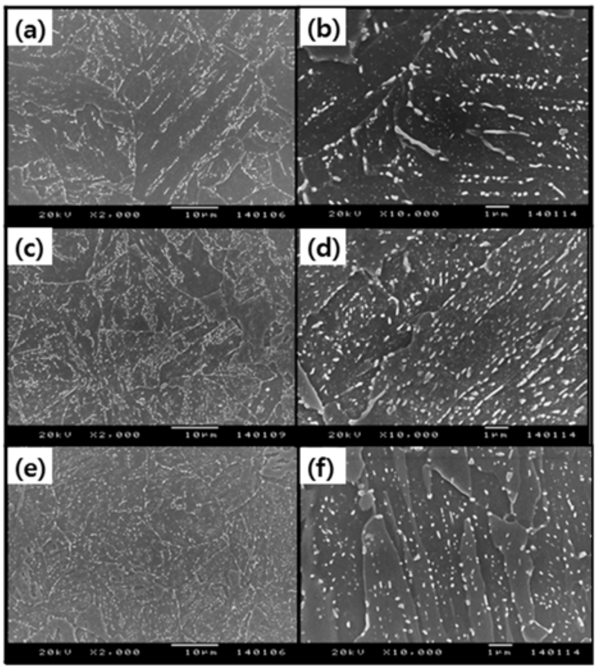

Figure 1 Microstructure of SA508 low alloy steels: (a), (b) Gr.3 Cl.1, (c), (d) Gr.3 Cl.2, and (e), (f) Gr.4N

precipitates are Cr-rich carbides such as M_7C or $M_{23}C_6$ type.

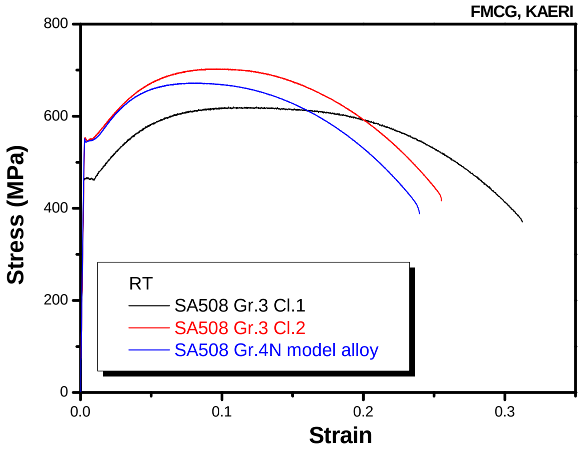

Figure 2 Stress-strain curves of SA508 steels at room temperature

Table 2 Charpy impact test results of SA508 low alloy steels

Material	USE(J)	T_{41J} (°C):
SA508 Gr.3 Cl.1	256	-41
SA508 Gr.3 Cl.2	196	-49
SA508 Gr.4N model alloy	240	-132

Fig. 2 shows the tensile results of three SA508 low alloy steels at room temperature. The SA508 Gr.4N model alloy shows the best tensile properties. The yield strengths at room temperature were 445 MPa (SA508 Gr.3 Cl.1), 500 MPa (SA508 Gr.3 Cl.2) and 540 MPa (SA508 Gr.4N) and met the minimum requirements of yield strength in the SA508 spec. of the ASME code. The minimum required yield strengths of SA508 Gr.3 low alloy steels are 345 MPa (SA508 Gr.3 Cl.1), and those of SA508 Gr.4N steels are from 480 MPa (Cl.3) to 585 MPa (Cl.1).

Charpy V-notch impact tests were carried out in accordance to ASTM E23 and the results are summarized in Table 2. The impact toughness of SA508 Gr.4N model alloy is drastically improved. The index temperature, T_{41J}, of SA508 Gr.4N model alloy was -132 °C, which was improved more than 80 °C compared to Gr.3 steel. The upper shelf energy (USE) of SA508 Gr.3 Cl.2 steel is lowered by about 23 % from 256 J in Cl.1 to 196 J in Cl.2, though it shows a similar transition temperature with SA508 Gr.3 Cl.1.

Fracture toughness tests were carried out using pre-cracked Charpy specimens. The reference temperature of the cleavage fracture in the transition temperature range, T_0, was determined in accordance with the ASTM standard E1921 Master curve method. The fracture toughness reference temperature, T_0 of SA508 Gr.3 Cl.1, SA508 Gr.3 Cl.2 and SA508 Gr.4N were -106.8 °C, -96.1 °C and -146.8 °C, respectively.

3. Conclusions

The microstructure and mechanical properties of SA508 Gr.3 Cl.1, Cl2 and Gr.4N low alloy steels were characterized. The predominant microstructure of SA508 Gr.4N model alloy is tempered martensite, while SA508 Gr.3 Cl.1 and Cl.2 steels show a typical tempered upper bainitic structure. SA508 Gr. 4N model alloy shows the best strength and transition behavior among the three SA508 steels. SA508 Gr.3 Cl.2 steel also has quite good strength, but there is a loss of toughness. From the viewpoint of mechanical properties, SA508 Gr.4N steel is a fascinating material for the pressure vessel application, which has both high strength and high fracture toughness.

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