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Effects of PWHT on Fracture Toughness of EB Welds in SA508 Gr.3 Low Alloy Steel

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1. Introduction

In the fabrication of domestic Reactor Pressure Vessels (RPVs), Submerged Arc Welding (SAW) has been widely used; however, its multi-pass welding process requires a long manufacturing time. With the development of Small Modular Reactors (SMRs), Electron Beam Welding (EBW), which can significantly reduce manufacturing time, is considered as an alternative. EBW enables single-pass welding, reducing fabrication time by more than 90% compared to conventional SAW [1]. Nevertheless, due to the high residual stress generated during EBW, Post-Weld Heat Treatment (PWHT) is essential [2]. However, studies on PWHT for EBW welds remain insufficient.

In this study, EBW was applied to SA508 Gr.3 low alloy steel, followed by PWHT at 610°C and 630°C for 30 hours, and additional Quality Heat Treatment (QHT). Additionally, the effects of various PWHT conditions on microstructure and fracture toughness were analyzed.

2. Methods and Results

2.1 Materials and Post-Weld Heat Treatment Conditions

SA508 Gr.3 Cl.1 low alloy steel, which is used for commercial RPVs, was employed to simulate the welded joint. The PWHT was conducted under the conventional SAW process condition of 610°C for 30 hours, and an additional PWHT at 630°C for 30 hours was performed to evaluate the effect of temperature variation. Furthermore, the effect of applying the QHT condition for RPV steels (880°C for 2 hours followed by 660°C for 7 hours) was also analyzed. The specimens were designated as “A” for the as-welded condition, “H1” for 610°C/30 hr PWHT, “H2” for 630°C/30 hr PWHT, and “Q” for the QHT.

2.2 Microstructure

The microstructures of each heat-treated specimen were analyzed using an optical microscope (OM; Nikon Eclipse-MA200, Japan) and a thermal field-emission scanning electron microscope (FE-SEM; Thermo Scientific Scios 2, USA). For microstructural analysis, the specimens were polished and etched with a 3% nital solution.

The base metal consisted mainly of upper bainite with a bainitic lath structure. The EBW weld and heat-affected zones (HAZ) were narrower than those of the SAW weld. The weld zone showed coarse columnar structure consisting of Widmanstätten ferrite and bainite, and the HAZ contained martensite and lower bainite. After PWHT, elongated precipitates formed along lath boundaries, with more coarse precipitates at higher temperatures. The PWQHT specimen showed a base metal-like microstructure observed, but coarse grains and precipitate bands remained in the weld zone.

2.3 Mechanical testing

Tensile tests were conducted in accordance with ASTM E8/E8M [3] using miniature plate-type specimens (2 mm wide, 1 mm thick) taken longitudinally from the weld. Tests were performed at 288°C, using an MTS universal testing machine with a strain rate of 4.6×10^{-4}/s. Yield strength was determined by the 0.2% offset method, and tensile strength from the maximum load. The engineering stress-strain curve at 288°C is shown in Fig. 1. The A weld showed the highest yield and tensile strengths (708 MPa and 945 MPa). Strength decreased by over 20% in H1 and over 30% in H2 compared to A. The Q specimen, subjected to QHT, exhibited tensile properties similar to the base metal (404 MPa yield strength, 601 MPa tensile strength), but total elongation was slightly lower at 22%.

Charpy impact tests were conducted using a DTI-603D impact tester (500 J capacity, Daekyung Tech) following ASTM E23 [4], over a temperature range of −120°C to 120°C. Transition behavior was evaluated using T_{41J} and T_{68J}, corresponding to absorbed energies of 41 J and 68 J from the impact transition curves (Fig. 2). The as-welded specimen showed the lowest toughness, while PWHT increased upper shelf energy (USE) and reduced transition temperature. The QHT-treated specimen (Q) exhibited the best impact toughness. The as-welded HAZ showed higher toughness than the base metal, and H1 treatment further improved it by lowering the transition temperature. However, H2 slightly reduced toughness. The Q specimen showed lower toughness than as-welded HAZ but remained superior to the base metal.

Pre-cracked Charpy V-notch (PCVN) tests were conducted using standard specimens (10 × 10 × 55 mm, T-L orientation) following ASTM E1921[5] to evaluate fracture toughness in the transition region. The as-welded specimen showed a T_0 of −77°C, which slightly decreased after PWHT at 610°C, indicating minor toughness improvement. However, PWHT at 630°C raised the T_0, significantly reducing fracture toughness. Similar trends were observed in HAZ specimens, which generally showed higher toughness than the weld. Notably, in the HAZ, PWHT at 610°C significantly reduced T_0 compared to condition A, showing greater toughness improvement than in the weld. QHT resulted in similar T_0 values for both weld and HAZ specimens.

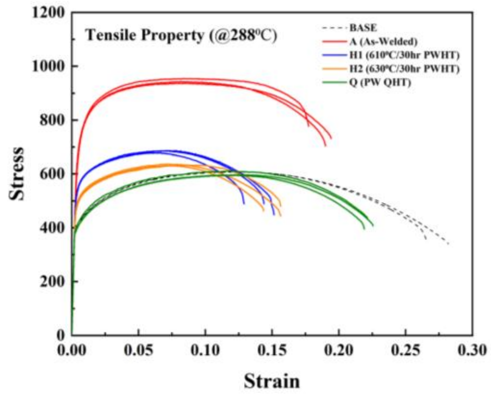

Fig. 1. Engineering stress-strain curves

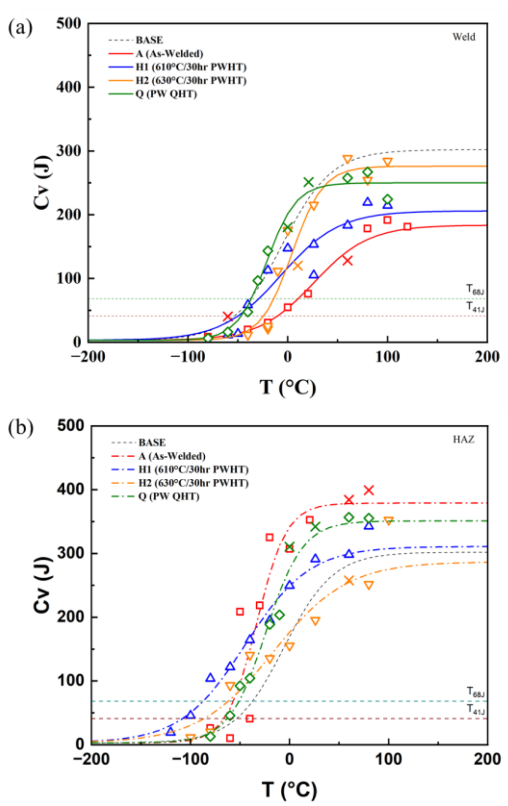

Fig. 2. Charpy ductile-brittle transition curves : (a) Weld, (b) HAZ

3. Conclusions

1. The EBW weld zone exhibited coarse Widmanstätten ferrite and bainite with a columnar structure, while the HAZ showed finer martensite and lower bainite.
2. PWHT at 610°C reduced strength but improved impact toughness due to matrix softening and residual stress relaxation. At 630°C, these effects were more pronounced, though fracture toughness decreased due to precipitate coarsening.
3. After PWQHT, HAZ showed microstructure and mechanical properties similar to the base metal. However, the weld zone retained coarse grains and precipitate bands, leading to lower fracture toughness.

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