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Effects of Electron Beam Power on the Mechanical Properties of Welds in SA508 Low Alloy Steel

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1. Introduction

Small Modular Reactors (SMRs) are constructed through factory fabrication and transportation of major components, requiring weight reduction of large structures such as reactor pressure vessels (RPVs) [1]. Accordingly, high-strength materials are required. Commercial RPVs are currently fabricated using SA508 Gr.3 low-alloy steel, whereas SA508 Gr.4N steel exhibits superior strength and toughness compared to Gr.3 and may be considered as a candidate material for RPV applications [2]. In addition, Electron Beam Welding (EBW) is considered an alternative to conventional Submerged Arc Welding (SAW) to reduce the manufacturing time of SMRs. EBW involves low heat input, resulting in a high cooling rate and promoting the formation of low-temperature transformation products. Since SA508 Gr.3 and Gr.4N exhibit different phase transformation behaviors depending on their alloy systems, evaluation of the microstructures and mechanical properties of EB welds is required.

In this study, EBW was applied to SA508 Gr.3 and Gr.4N low-alloy steels, followed by identical Post-Weld Heat Treatment (PWHT). The welding current was varied to change the heat input, and the resulting weld microstructures, room-temperature tensile properties, and Charpy impact toughness were evaluated.

2. Methods and Results

2.1 Materials and Welding Conditions

SA508 Gr.3 low alloy steel, which is currently used for commercial RPVs, and SA508 Gr.4N low alloy steel as a comparative material were used to simulate the EB weld joints. The heat input was controlled by setting the welding current to 200 mA and 170 mA to control the cooling rate. The PWHT was performed for both materials at 610°C for 30 h under the conventional SAW process condition. The specimens were designated according to steel grade, welding current, and heat treatment condition. The as-welded specimens of SA508 Gr.3 at 170 mA and 200 mA were designated as “3A1” and “3A2”, respectively, and those after PWHT were designated as “3P1” and “3P2.” For SA508 Gr.4N steel, the as-welded specimen at 200 mA was designated as “4A2” and the PWHT specimens at 170 mA and 200 mA were designated as “4P1” and “4P2”, respectively.

2.2 Microstructure

The cross-sections of the welded joints were examined to compare the weld bead width and microstructures under different welding current conditions. Each specimen was polished and etched with a 3% nital solution, and the microstructures were analyzed using an optical microscope (OM; Nikon Eclipse MA200, Japan) and a field-emission scanning electron microscope (FE-SEM; Thermo Scientific Scios 2, USA).

The base metal of SA508 Gr.3 exhibited upper bainite with a bainitic lath structure, whereas SA508 Gr.4N showed martensite due to differences in alloy systems. As the welding current decreased from 200 mA to 170 mA, the weld bead width decreased in both steels. In the as-welded condition, SA508 Gr.3 exhibited a coarse columnar structure composed of Widmanstätten ferrite and bainite at 200 mA, while martensite was observed at 170 mA. In contrast, SA508 Gr.4N exhibited dendritic structures in the weld zone, which became finer and narrower at the lower welding current. These microstructural variations are considered to changes in cooling rate associated with different welding currents.

2.3 Mechanical testing

Tensile tests were performed on miniature plate-type specimens extracted longitudinally from the weld. The tests were conducted at room temperature using an MTS universal testing machine at a strain rate of 4.6×10^{-4} s^{-1} in accordance with ASTM A370 [3]. Yield strength was determined by the 0.2% offset method, and tensile strength was defined as the maximum load. The room-temperature engineering stress–strain curves of SA508 Gr.3 and Gr.4N welds at different welding currents are shown in Fig. 1. At 200 mA in the as-welded condition, SA508 Gr.4N exhibited approximately 30% higher yield and tensile strengths than SA508 Gr.3. This difference is considered to be related to the formation of martensite in Gr.4N. For SA508 Gr.3, decreasing the welding current from 200 mA to 170 mA increased the yield and tensile strengths by approximately 18–25% in the as-welded condition and by 5–9% after PWHT. In contrast, SA508 Gr.4N showed only marginal changes after PWHT with reduced welding current.

Charpy impact tests were performed using standard Charpy V-notch specimens in the transverse–longitudinal direction in accordance with ASTM E23 [4]. The tests were conducted using a DTI-603D impact tester (500 J capacity, Daekyung Tech) over a temperature range of −120°C to 120°C. Hyperbolic tangent curve fitting was applied to the absorbed impact energy data [5]. At 200 mA in the as-welded condition, the room-temperature absorbed impact energy of SA508 Gr.3 was approximately 80 J, whereas SA508 Gr.4N exhibited about 120 J. After PWHT, reducing the welding current from 200 mA to 170 mA significantly increased the absorbed energy of SA508 Gr.3 (from approximately 150 J to 450 J), while SA508 Gr.4N exhibited similar absorbed energy values (160 J and 155 J) under the same conditions.

Therefore, under identical PWHT conditions, the effect of welding current on both strength and toughness was more pronounced in SA508 Gr.3 steel than in SA508 Gr.4N. This difference is considered to be related to the initial weld microstructures, where Gr.4N exhibited martensite, whereas Gr.3 formed bainite at 200 mA and martensite at 170 mA.

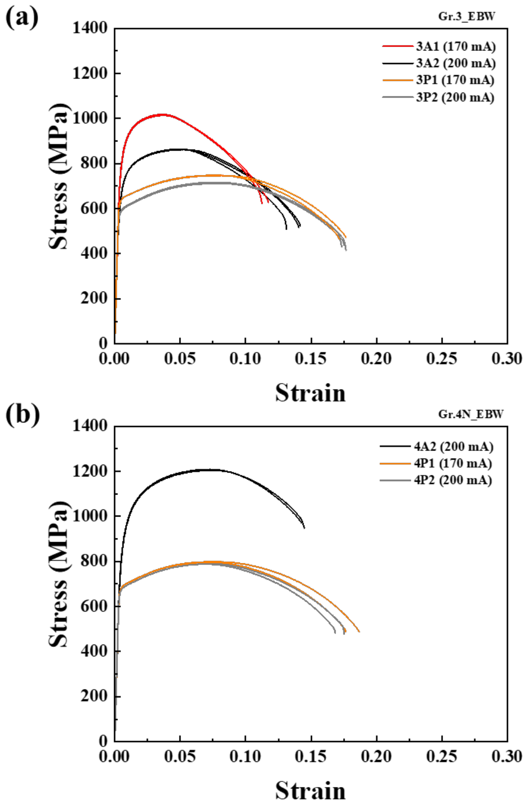

Fig. 1. Engineering stress-strain curves of (a) SA508 Gr.3 welds and SA508 Gr.4N welds at different welding currents.

3. Conclusions

1. In the as-welded condition, the weld zone of SA508 Gr.3 exhibited a coarse columnar microstructure composed of Widmanstätten ferrite and bainite, whereas SA508 Gr.4N formed martensite within a dendritic structure. These microstructural differences resulted in approximately 30% higher strength and about 50% higher room-temperature Charpy impact energy in SA508 Gr.4N compared to SA508 Gr.3.

2. As the welding current decreased from 200 mA to 170 mA, martensite formed in SA508 Gr.3, whereas no significant microstructural change was observed in SA508 Gr.4N. Accordingly, the tensile properties and toughness of SA508 Gr.3 showed pronounced changes with welding current, while only marginal differences were observed in SA508 Gr.4N.

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