

Manufacturing and Reliability Assessment of Submerged-Arc-Welded Steel Pipes below 14 Inches in Diameter as Alternatives to Seamless Pipes for Nuclear Power Applications

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1. Introduction

Austenitic stainless steel pipes, which provide the corrosion resistance and high-temperature properties required for the secondary auxiliary steam system of nuclear power plants, are used in these applications. Piping larger than 14 inches in diameter is fabricated with submerged-arc-welded (SAW) pipes, whereas piping of 14 in or smaller in diameter has relied on seamless pipes owing to a lack of domestic manufacturing technology. Small-diameter seamless pipes are less economical in terms of production cost and process time, and they are prone to material waste and wall-thickness variation. Applying SAW to heavy-wall pipes of 14 in or smaller in diameter requires overcoming manufacturing constraints in small-diameter forming and in internal welding within a confined space. Previous studies have focused mainly on large-diameter industrial piping, covering the solidification cracking behavior of weld metal, the weldability and joint performance of heavy plate, and the prediction of residual stress in SAW pipes by finite element analysis [1-3].

However, few studies have addressed the manufacturing process and reliability of small-diameter nuclear piping in an integrated manner. Accordingly, this study establishes the manufacturing process for small-diameter, heavy-wall SAW pipes of 8, 10, and 12 in, examines the changes in microstructure and mechanical properties with post-weld heat treatment (PWHT) conditions, and evaluates their reliability relative to seamless pipes through nondestructive examination and corrosion testing.

2. Methods and Results

2.1 Pipe Manufacturing and Experimental Procedure

In this study, SAW pipes with nominal outer diameters of 8, 10, and 12 in and wall thicknesses of 10–19 mm were fabricated using STS 304 and STS 304L. Because securing the required curvature during press bending becomes more difficult as the pipe diameter decreases, the lower liner height in the three-point press bending was increased in 5 mm

increments to obtain the target curvature. The 8 in pipe reached its target curvature at a liner height of 105 mm.

Since the existing internal welding equipment could not be applied to pipes of 12 in or smaller because of the confined internal space, the Boom, Curve Torch, wire feeder, and flux supply and recovery units were miniaturized, and the equipment was modified so that the welding head travels inside the pipe. This enabled internal SAW to be applied to pipes down to 8 inch in outer diameter and 19 mm in wall thickness. Microstructural and mechanical property evaluations were conducted on the 8 in, 10 mm-thick pipe as the representative specimen, since its smallest diameter imposes the greatest constraints on both forming and welding. The material properties were compared between the as-welded condition and specimens held at 1,000–1,150°C for 2 h followed by water cooling.

2.2 Microstructure

Fig. 1 shows the optical micrographs of the 8 in SAW weld metal at different PWHT temperatures; in the as-welded condition, a dendritic structure formed during solidification and vermicular δ -ferrite are observed. As the PWHT temperature increased, the δ -ferrite transformed into a globular morphology and decreased in amount. Its content decreased progressively from 7.15% in the as-welded condition to 1.738% at 1,000°C, 0.864% at 1,050°C, 0.146% at 1,100°C, and 0.125% at 1,150°C.

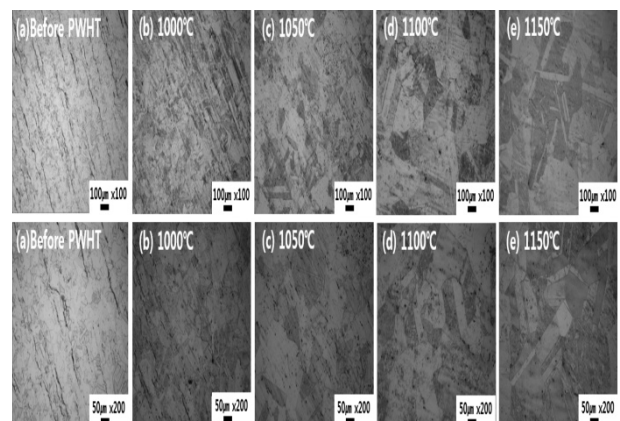


Fig. 1. Optical microstructures of 8 in SAW weld metal at different PWHT temperatures.

XRD analysis likewise showed that the ferrite peak weakened with increasing PWHT temperature, consistent with the ferritescope measurements. This is attributed to sufficient diffusion time being secured for the δ -ferrite to transform into thermodynamically stable austenite in the austenitic stainless steel [4].

2.3 Mechanical Properties

The tensile strength of the base metal ranged from 596 to 637 MPa and the elongation from 81 to 90%, showing little variation with temperature; this trend can be seen in Fig. 2. For the weld metal, the tensile strength decreased from about 520 MPa in the as-welded condition to 436–460 MPa after PWHT, whereas the elongation improved from about 60% to 69–72%. The hardness tended to decrease with increasing PWHT temperature, dropping from 202 Hv to 148 Hv in the base metal and from 188 Hv to 147 Hv in the weld metal. The room-temperature Charpy absorbed energy of the weld metal was found to improve from about 55 J in the as-welded condition to more than 85 J after PWHT. The mechanical properties were most stable at 1,100°C and 1,150°C, but grain coarsening progressed at 1,150°C. Considering the manufacturing efficiency, holding at 1,100°C for 2 h followed by water cooling was confirmed to be the optimal PWHT condition.

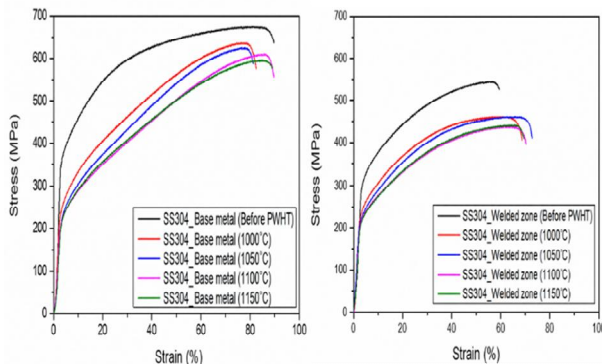


Fig. 2. Tensile behavior of the base metal (left) and weld metal (right).

2.4 Nondestructive Examination and Corrosion Properties

In the radiographic testing and full-body ultrasonic testing, no internal defects exceeding 0.5 mm were detected. In the hydrostatic test of the 8 in, 10 mm-thick prototype, pressure integrity was maintained up to 15 MPa without leakage or failure, exceeding the target pressure of 14.2 MPa. In the ASTM A262 [5] Pr.A, Pr.E, and DL-EPR tests, all specimens satisfied the intergranular corrosion acceptance criteria; in the Pr.C Huey test, the corrosion rate of the weld metal after

PWHT decreased from 0.240 mm/yr to 0.170–0.199 mm/yr, narrowing the gap with the 0.117 mm/yr of the seamless pipe. The stress corrosion cracking tests were conducted in a 0.01 M $\text{Na}_2\text{S}_4\text{O}_6$ solution at 340°C and 150 bar and in a 40% NaOH environment at 290°C and 50 bar, and no cracking was observed in the developed pipe even after long-term exposure.

2.5 Performance Comparison with Seamless Pipe

Table I compares the performance of the developed SAW pipe with that of the seamless pipe. The yield strength reached 272 MPa or higher in the base metal and 251 MPa or higher in the weld metal, exceeding the seamless pipe's 205 MPa and the target of 210 MPa or higher. The tensile strength reached 662 MPa or higher in the base metal and 579 MPa or higher in the weld metal, exceeding the seamless pipe's 515 MPa and the target of 525 MPa or higher. Elongation and Charpy absorbed energy also exceeded the target and the seamless pipe, with the base metal showing somewhat higher values than the weld metal. This is attributed to improved weld metal ductility and toughness as δ -ferrite transformed into austenite during PWHT. Hardness remained below the target upper limit of 280 Hv.

The developed pipe also met the target level in nondestructive examination and corrosion resistance. Radiographic and ultrasonic testing detected no flaw exceeding the 0.5 mm target. The intergranular corrosion and stress corrosion cracking tests likewise showed no cracking, with the pipe remaining crack-free for 1,000 h against the 500 h target. Overall, the developed 8–12 in SAW pipe met the target level across all categories, performing equal to or better than the seamless pipe.

Table I: Performance comparison between the seamless pipe and the developed SAW pipe

Item	Unit	Target	Seamless	SAW (Base/Weld)	Result
Yield strength (MPa)	MPa	>210	205	B>272 / W>251	PASS
Tensile strength (MPa)	MPa	>525	515	B>662 / W>579	PASS
Elongation (%)	%	>40	40	B>59 / W>45	PASS
Charpy -46°C (J)	J	>30	27	B>136 / W>68	PASS
Hardness (Hv)	Hv	<280	<290	B<164 / W<151	PASS
Min. flaw (mm)	mm	≤0.5	1(X-ray/UT)	No flaw	PASS
Intergranular corrosion	-	No fissures	No fissures	No fissures	PASS
SCC (simulated)	-	No crack/500h	No crack/500h	No crack/1000h	PASS
Hydrostatic test (MPa)	MPa	>14.2	>8.1	15	PASS

3. Conclusions

This study established the manufacturing technology for small-diameter, heavy-wall SAW welded pipes of 14 in or smaller in diameter as alternatives to seamless pipes for nuclear power applications, and evaluated their reliability. By improving the press-bending liner and the internal welding equipment, internal SAW was realized for pipes down to 8 inch in outer diameter and 19 mm in wall thickness. As the PWHT temperature increased, the δ -ferrite in the weld metal transformed into austenite and decreased, and the tensile, hardness, and impact properties were most stable under the condition of holding at 1,100°C for 2 h followed by water cooling. Weld integrity was confirmed by nondestructive examination and hydrostatic testing, and corrosion reliability by ASTM A262 and SCC testing. Within the scope of this test program, the developed SAW welded pipes exhibited mechanical properties, weld integrity, and corrosion resistance comparable to or better than those of the reference seamless pipe, demonstrating their potential as domestically manufactured alternatives for small-diameter nuclear power piping.

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