Research Article

The Effect of Welding Residual Stress for Making Artificial Stress Corrosion Crack in the STS 304 Pipe

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The stress corrosion crack is one of the fracture phenomena for the major structure components in nuclear power plant. During the operation of a power plant, stress corrosion cracks are initiated and grown especially in dissimilar weldment of primary loop components. In particular, stress corrosion crack usually occurs when the following three factors exist at the same time: susceptible material, corrosive environment, and tensile stress (residual stress included). Thus, residual stress becomes a critical factor for stress corrosion crack when it is difficult to improve the material corrosivity of the components and their environment under operating conditions. In this study, stress corrosion cracks were artificially produced on STS 304 pipe itself by control of welding residual stress. We used the instrumented indentation technique and 3D FEM analysis (using ANSYS 12) to evaluate the residual stress values in the GTAW area. We used the custom-made device for fabricating the stress corrosion crack in the inner STS 304 pipe wall. As the result of both FEM analysis and experiment, the stress corrosion crack was quickly generated and could be reproduced, and it could be controlled by welding residual stress.

1. Introduction

Environmentally assisted crack, such as stress corrosion crack (SCC) of the NPP structural materials, has been one of the causes for the shutdown of the power plant resulting in a significant loss, incapacitating the production electric power. The resultant repair and replacement of components in light water reactors (LWR) remains as one of the limiting factors for the safe and economic operation of LWRs, especially in the plant life extension period. Stress corrosion cracking usually occurs when the following three factors exist at the same time: susceptible material, corrosive environment, and tensile stress (including residual stress). Among these factors, the residual stress becomes critical problem for stress corrosion cracking when it is difficult to improve the material corrosivity of the components and their environment under operating conditions [1, 2]. Generally, the residual stresses are induced by welding process. The welding is mostly used for manufacturing of structure materials such as nuclear power plant and vehicle. Horikawa et al. reported that the crack propagation rate increased at the tungsten inert gas- (TIG-) welded joint. Tani et al. reported that chloride induced SCC of the austenitic stainless steel occurred independently of the tensile residual stress value. They have performed the SCC test on the austenitic SS using loading device and showed that the specimen of type 304L SS was fractured even when the applied stress was below 200 MPa which was less than 0.2% proof stress of type 304L SS [3]. Most of the studies have used the slow-strain-rate test (SSRT), which is not useful for studying the effect of stress level [4]. Since the research of Mazille and Rothea, [5, 6] it is well known that Ni-based alloy and stainless steel are susceptible to stress corrosion cracking (SCC) in deaerated pure water at high temperature, but the test was performed in autoclave which is possible to contain a specimen. The conventional method of manufacturing artificial stress corrosion cracks is difficult to imitate environmental conditions of the NPP because the resulting cracks are not obtained by using a pipe actually used for equipment of nuclear power plants but by using a simulation specimen.
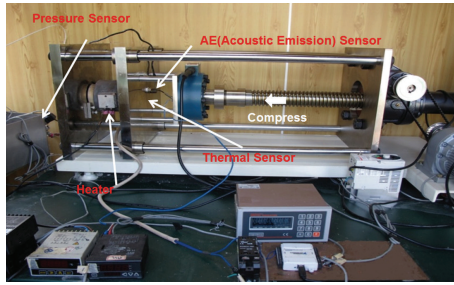
Figure 1: The stress corrosion crack forming equipment.

Figure 2: The semiautomatic GTA welding system for giving the residual stress.

Figure 3: BOP bead inner STS 304 pipe.

In this study, the stress corrosion crack was artificially produced on the materials of the nuclear power plant by using the custom-made device. The device provided real environment of nuclear power plant and the semiautomatic GTAW process was used for giving the residual stress in the inner of the pipe. The fracture time, which is defined by pressure drop in a SCC test, of the STS 304 pipe was used to confirm the residual stress effect by welding heat input. Also, 3D FEM (Finite Element Method) analysis model is designed about STS 304 pipe and performed heat transfer analysis and residual stress analysis.

2. Experimental Methods

2.1. Forming the Stress Corrosion Crack. The test material was austenitic STS 304, which is used as pipelines in the Reactor Coolant System of nuclear power plants (O.D. = 89 mm, t = 7.7 mm). The stress corrosion crack forming equipment is shown in Figure 1. The equipment for forming stress corrosion cracks consisted of heater, pressure sensor, AE (acoustic emission) sensor, load cell, and DAQ (data acquisition) system, and so forth. Generally, an autoclave was used to make an environment condition of high pressure and high temperature for making a SCC. But, in this study, the autoclave was not used. The heating coils were directly imposed on the surface of pipe to generate high steam pressure and temperature of inner pipe, and the inside of pipe specimen was filled with corrosive solutions. The test was performed using the stainless steel 304 pipe in 2 M Na_2SO_4 and 1 M NaOH solutions. The length of specimen is 150 mm. Table 1 shows mechanical properties of the STS 304. The yield stress of the STS 304 material is 139 MPa and vapor pressure of the specimen according to ideal gas equation is 165 bar at 350°C. In this case, hoop stress was 124 MPa caused by vapor pressure.

The GTAW process was used for the combined action of the chemical environment and the residual stresses in the custom-made system. Figure 2 shows the semiautomatic GTA welding system for giving the residual stress. And Table 2 is the welding conditions for GTAW.

2.2. For Inducing Residual Stress Inner Pipe. Table 3 shows experimental conditions for welding. We welded an inner pipe using the same condition on the same line. Figure 3 shows BOP (Bead on Plate) bead inner of the pipe using the GTAW process.
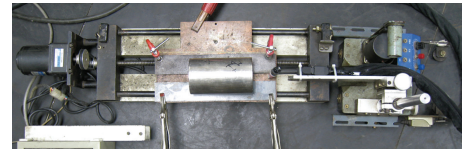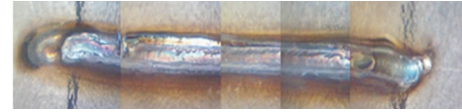
2.3. 3-D FEM Analysis. For the heat transfer analysis, we had divided a step of heating and cooling analysis for each pass by using the thermal physical properties of STS 304 according to temperature and typically melting point of steel. Table 4 shows thermal physical properties of STS 304 according to temperature. For the FEM stress analysis, we predicted a variation of the welding residual stress using the thermal physical properties and boundary conditions, which is a temperature variation by heat transfer analysis [7]. The commercial code ANSYS 12 was used for the nonlinear heat transfer analysis and stress analysis. Figure 4 shows 3D FEM meshed model of piping. Element type was selected for 70, 3D thermal solid model and 45, 3D structural solid model. The number of node was 14904, and the number of elements was 12558.

2.4. For Evaluating Residual Stress Test. We used the instrumented indentation technique to evaluate the residual stress values in the GTAW area (see Figure 5). The measuring positions of residual stress, as seen in Figure 5, are 5, 10, and 30 mm spot from the welding center line.

3. Results and Discussion

3.1. Fabrication of the SCC. The stress corrosion crack was fabricated using the custom-made manufacturing system. Figure 6 shows the temperature and pressure variation during the test. The maximum temperature and pressure, which were measured at 358°C and 157 bar by thermocouple and pressure sensor, were similar environmental condition in the nuclear power plant. It was confirmed that the new forming equipment for artificial stress corrosion cracks could be simulated by the environmental conditions in the NPP. The vapor pressure was decreased after about 5 hours.

It was confirmed that the pipe was fractured by stress corrosion crack. This means that the crack was already initiated before leaking. The vapor pressure induced hoop stress in the pipe. Circumferential stress in a cylindrical shaped part as a result of internal or external pressure is

TABLE 1: Mechanical properties of STS 304.

Properties	Modulus of elasticity	Yield strength	Tensile strength	Elongation	Hardness (Hv 1)
STS304	193 GPa	410 MPa	669 MPa	66.5%	200

TABLE 2: Welding conditions of GTAW.

Welding current (A)	90
Welding voltage (V)	21
Welding speed (cm/min)	30
Shielding gas	Ar 100%

TABLE 3: Experimental conditions for giving residual stress.

Specimen number	Welding pass (on the same line)
W1	1
W2	5
W3	10
W4	13
W5	15

TABLE 4: Physical properties of the STS 304 according to temperature.

Temperature	30	200	400
Specific heat (cal/g-k)	0.114	0.119	0.123
Poisson's ratio	0.290	0.304	0.321
Young's modulus (MPa)	197227.1	182054.5	164204.461
Thermal expansion (l/c)	$1.63E-05$	$1.63E-05$	$1.6282E-05$
Thermal conductivity (cal/s-cm k)	0.037	0.049	0.062
Yield strength (MPa)	258.608	169.209	125.321
Temperature	600	800	1000
Specific heat (cal/g-k)	0.131	0.143	0.150
Poisson's ratio	0.337	0.354	0.362
Young's modulus (MPa)	146354.401	128504.3	119592.7
Thermal expansion (l/c)	$1.6282E-05$	$1.63E-05$	$1.63E-05$
Thermal conductivity (cal/s-cm k)	0.076	0.089	0.098
Yield strength (MPa)	113.0189	91.448	88.350

FIGURE 4: Meshed model of piping.

① 5 mm
② 10 mm
③ 30 mm

from welding center line

FIGURE 5: Evaluation of residual stress using the instrumented indentation technique.

called hoop stress. In a closed pipe such as our specimen, force applied to the cylindrical pipe wall by a rising inner pressure will ultimately induce hoop stress. During the test, maximum vapor pressure was 157 bar; that is, hoop stress of the inner surface was more than 87% of yield stress. It is estimated that stress corrosion crack was accelerated by additional hoop stress as well as susceptible material, corro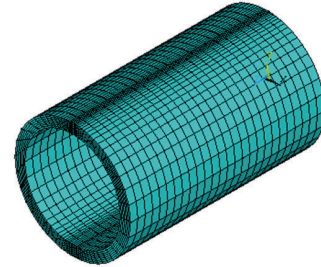siv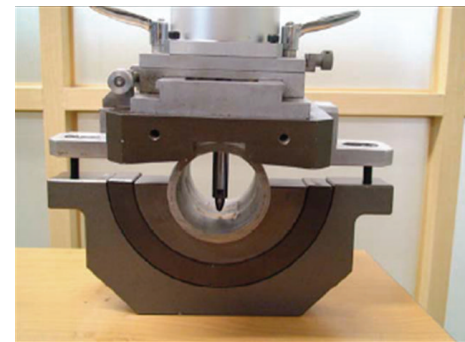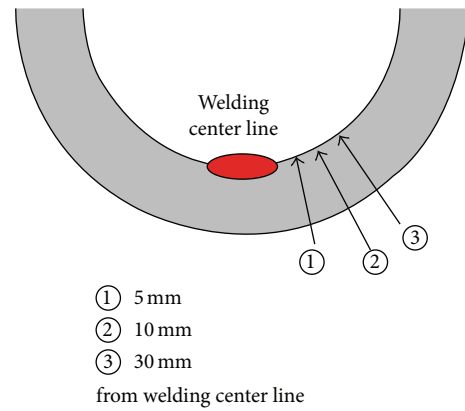e environment, and including residual stress. Many cracks in the inner surface (a top and bottom view) of the pipe were observed by the visual test. Figure 7 shows the outer shape of the specimen and cross section (×12.5) of the inner surface pipe at the cutting 1. Figure 8 is the optical microscope fractography of points (a), (b), (c), and (d) at cutting 1. It is confirmed that the cracks were propagated along the grain boundary. The intergranular stress corrosion cracks were clearly revealed, which was a typical character for primary water stress corrosion crack in major pipes of pressurized water reactor.
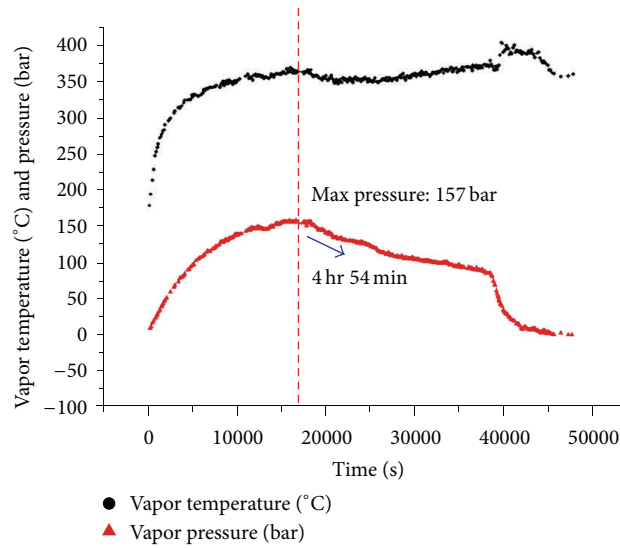
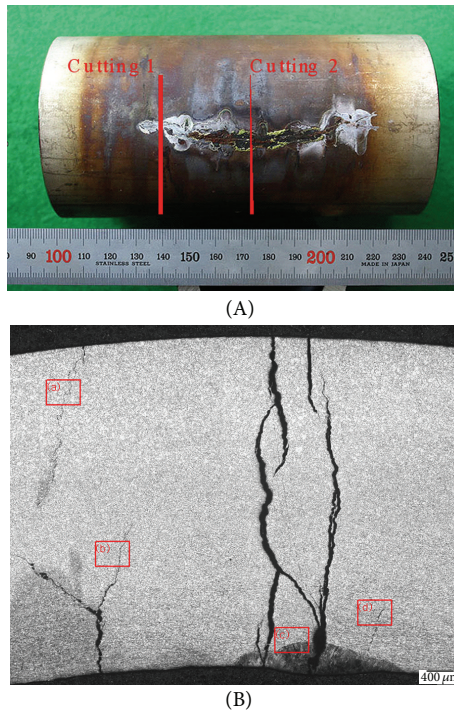Figure 6: Temperature and pressure in STS 304 pipe.

(A)

(B)

Figure 7: Outer shape of the specimen and cross section.

3.2. The Results of FEM Analysis. Because the melting point of STS 304 was about 1400°C, the bead temperature of the first welding pass was decided as 1400°C and it was assumed that the temperature would be increased by additional welding pass. The heating time was the same as welding time. The cooling time was decided as 10 min in the FEM analysis, because the experimental cooling time was 10 min. The heat input of the pipe (volume energy per hour) was modified by a temperature of the HAZ (Heat Affected Zone). The temperature variation calculated by thermal transfer analysis was used as boundary condition for analysis of the residual

stress in the pipe. Figure 9 shows a temperature gradient of the specimen after first welding pass.

Analysis was bilinear kinematic hardening method using Von Mises or hill plasticity. Figure 10 shows thermal properties of bilinear kinematic hardening for STS 304.

Figure 11 shows the results of circumferential (hoop) maximum tensile residual stress in the inner surface of the pipe. The residual stress is the highest at 90~100 degree position which was well corresponded to position of crack appearance. The tensile residual stress of the FEM analysis confirmed that the number W1 specimen is the lowest, and
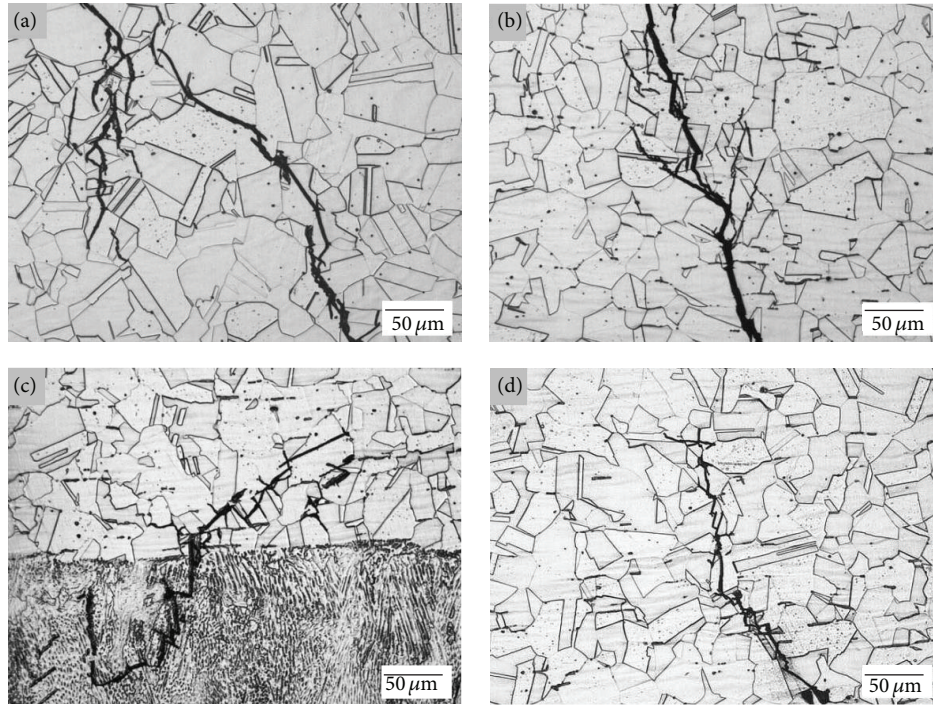
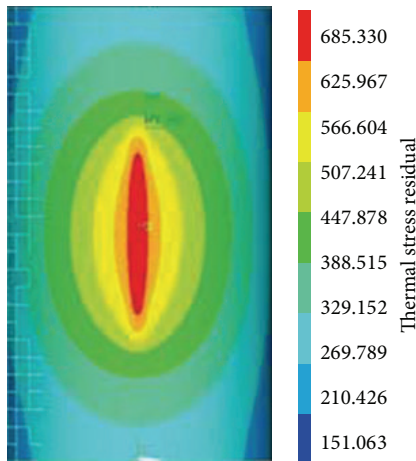FIGURE 8: Fractography of points (a), (b), (c), and (d) at cutting 1.

FIGURE 9: Temperature gradient of specimen after first welding pass.

$T1 = 30.000$
$T2 = 200.00$
$T3 = 600.00$
$T4 = 1000.0$
$T5 = 1400.0$

FIGURE 10: Bilinear kinematic hardening table for STS 304.

the others are of similar level. So, we selected and evaluated an instrumented indentation test for the specimens of number W1 and number W3.

3.3. The Effect of the Residual Stress. Figure 12 shows the result of residual stress for W1 and W3. The maximum position of the residual stress is about 15 mm from welding center line. The residual stress value of W3 was about 20 MPa higher than that of W1. This means that increasing of welding pass has made a residual stress higher than the first welding pass. Table 5 shows relationship between number of welding pass and the fracture time of pipe. All the experimental conditions
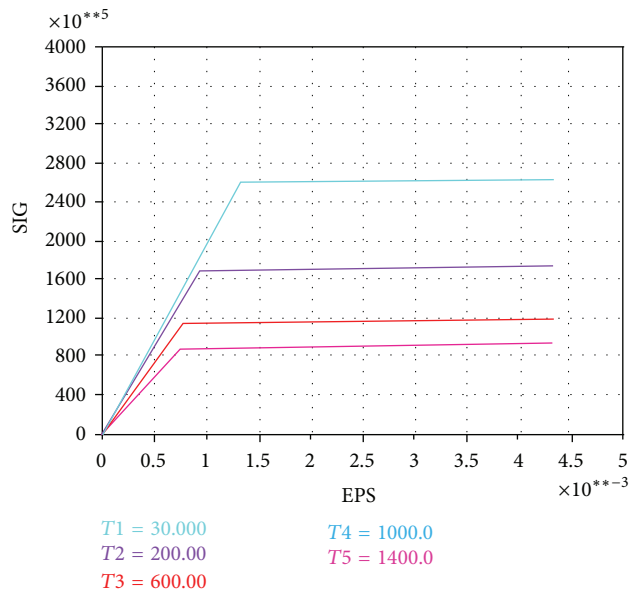
such as corrosion environment, heating temperature, and welding condition are the same. So it can be considered that difference of through-wall fracture time is effects of residual stress. The fracture time of the specimen W5 that was welded by 15 pass was relatively shorter than other conditions. And it is well corresponded to the highest tensile residual stress at the 90~100 degree position in Figure 11.

Figure 13 shows a shape and position of artificial stress corrosion crack using the SCC forming device. Even though
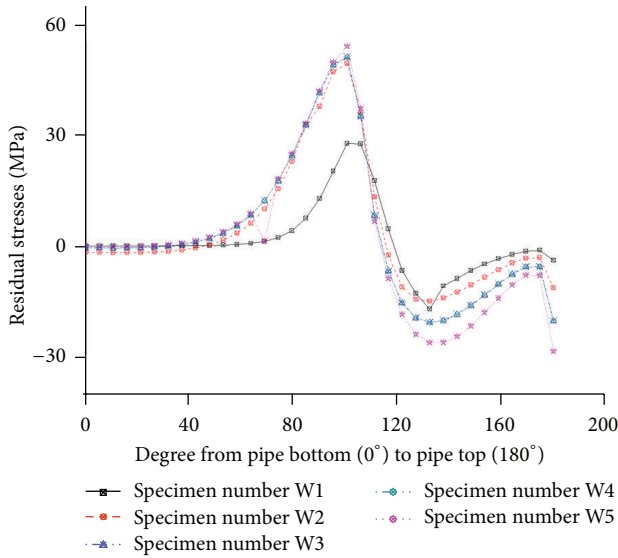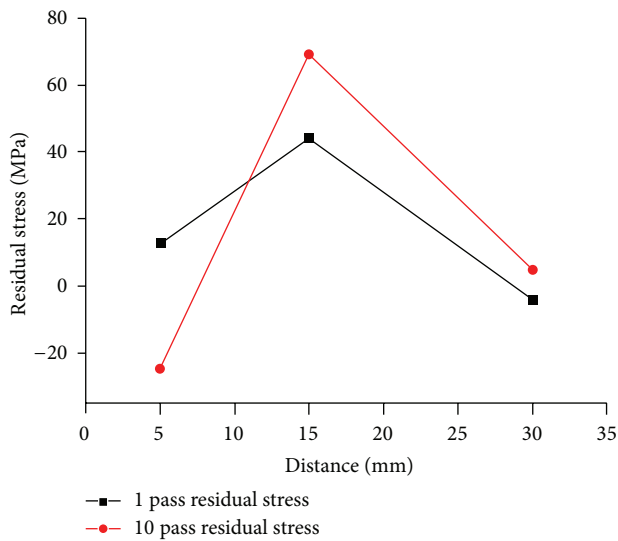
FIGURE 11: Hoop residual stress distribution.

FIGURE 12: Residual stress graph on inner surface of STS304 pipe.

TABLE 5: The fracture time of STS 304 pipe.

Specimen number	Pass number	The fracture time (min)	Inner pressure
W1	1	787	192
W2	5	646	120
W3	10	132	127
W4	12	323	144
W5	15	294	157

the SCC was initiated at a random position, it was confirmed that SCC was affected by a residual stress in the same environment.
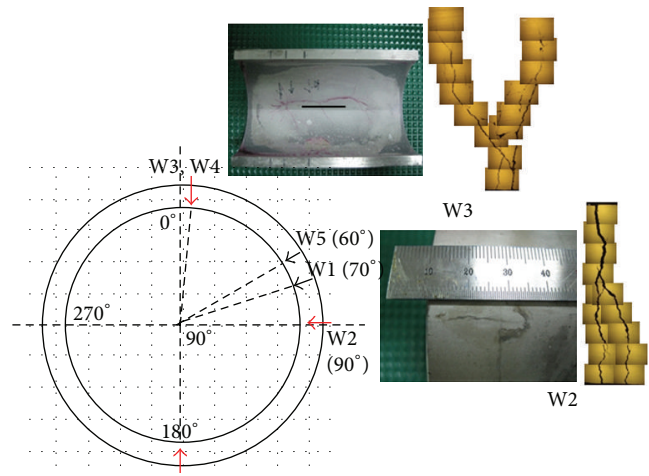

FIGURE 13: Artificial SCC shape and position according to experimental conditions.

4. Conclusions

(1) The custom-made device was used, which simulated an environment condition of NPP (nuclear power plant), for fabricating the stress corrosion crack in the inner pipe wall. And stress corrosion crack was artificially produced on STS 304 pipe by a welding residual stress.

(2) The residual stress was increased by increasing welding pass. The fracture time of the pipe by stress corrosion cracking was decreased by increasing residual stress according to welding heat input. Even though the SCC was initiated at a random position, it was confirmed that SCC was affected by a residual stress under the same environment.

(3) The new system was developed for manufacturing stress corrosion crack in the inner surface of the pipe specimen. And it is possible to manufacture mass SCC production of real size pipes in our system.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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