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An Evaluation on the Effect of Residual Stress and Phase Transformation Improvement by Welding in Half Nozzle Repair Method of BMI Nozzle

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1. Introduction

Domestic and international operating nuclear power plants are composed of Alloy 600 (Alloy 82/182) dissimilar metal welding portion in J-Groove form in various parts such as reactor, pressurizer, hot and cold pipe, etc. Due to the complex factors such as tensile residual stresses and corrosive environments, these welding parts are also increasing the possibility that can occur Primary Water Stress Corrosion Crack (PWSCC) according to the increase of operation life. In particular, BMI (Bottom Mounted Instrumentation) Nozzle is less sensitive to PWSCC generation of Alloy 600 material because the operation temperature is in the relatively low temperature region. But, it is very important to ensure the maintenance of the technical preparation for the damage because Nozzle is installed at reactor bottom head which is not possible to replace. A damage of Reactor Vessel BMI Nozzle under operation was confirmed as No.1 and No.46 Nozzle was observed to find acid precipitate while inspecting the reactor vessel bottom head of STP unit 1 in April 2003. Thus maintenance technology was developed such as Half Nozzle Repair in order to prevent damage of J-Groove welding including BMI Nozzle. Half Nozzle Repair maintenance technology shown in Figure 1 is sealed by plugging into the same material with pipe basic material, after cutting and boring to the near location of BMI Nozzle bottom basic material. In the case of Pad welding, while meeting ASME Code Case N-638-5[4] requirements, the welding was carried out from 1st layer to 3rd layer required by the weld geometry design requirements using temper bead welding process parameters when welding procedure applied for Alloy 52 weld filler metal was satisfied. And, in case of J-Groove welding, after cutting J-Groove satisfied the condition required by welding geometry design, new Nozzle of Alloy 690 material is inserted. And then welding applied for welding process parameters is performed when welding procedure applied for Alloy 52 weld filler metal is satisfied. Accordingly, this study is performed ATTB (Ambient Temperature Temper Bead) effectiveness conducting on bottom head and residual stress state evaluation for inner surface of Nozzle after Alloy 690 Nozzle and J-Groove welding using the Finite Element Analysis (FEA) .

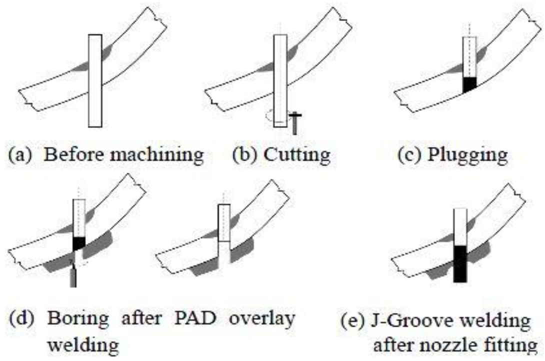

Figure 1. Welding Procedures of Half Nozzle Repair

2. Half Nozzle Repair FEA Method and Procedure

The Studies on improving weld residual stress and phase transformation by Half Nozzle Repair method were performed using the modules of Visual Environment of welding construed only code SYSWELD[2]. FEA procedures for Half Nozzle Repair welding were carried out as shown in Table 1.

FE modeling has applied the BMI Nozzle shape and dimensions of the actual local nuclear power plant were developed by the Visual Mesh module of SYSWELD. Welding heat sources of Pad and J-Groove was welded to bottom head and Nozzle of Alloy 690 material was extracted by the Visual Weld module using results performed Gas Tungsten Arc Welding (GTAW) in Bead On Plate. Finally FEA was performed using the Visual Weld module of SYSWELD for Pad welding, removal of Pad and Nozzle after welding, insertion of new Nozzle of Alloy 690 material, J-Groove welding, and 4 cycles for normal operation. Lastly, Post Processing was used for the Visual Viewer module of SYSWELD.

Table 1. Procedures of FEA for Half Nozzle Repair

FE Modeling	→	*Heat Source Fitting*	→	*Pad Weld Setup*	→
J-Groove Weld Setup	→	*Plant Operation Setup(4 Cycle)*	→	*Post Processing*	

(15.51MPa, 298℃)

2.1 FEA Modeling

In this study, Geometry and dimensions of Pad and J-Groove welding on Half Nozzle Repair method for the analysis target BMI Nozzle is shown in Figure 2. In addition, the model of the Pad and J-Groove welding by Half Nozzle Repair method developed for the FE Modeling is shown in Figure 3. 2D axisymmetric model was used for the modeling, and in case of Pad and J-Groove, 0.5 mm size of the quad and triangle element was adopted for the meshing. As a result of the modeling process, the modeling mesh is composed of 19,687 pieces of 2D element, 8,419 pieces of 1D element and 20,084 pieces of node.

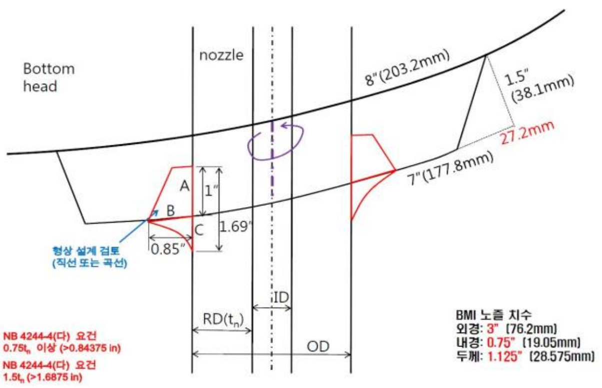

Figure 2. Geometry and Dimensions of Pad and J-Groove Welding

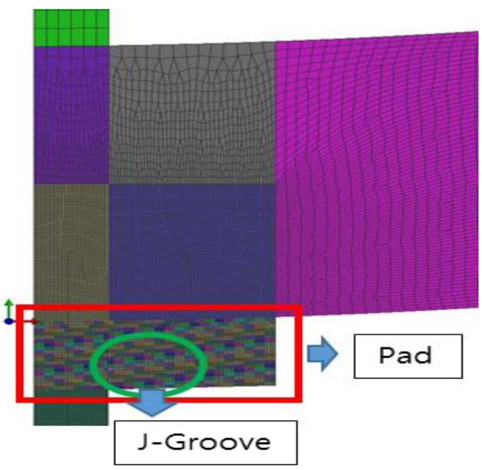

Figure 3. Pad and J-Groove Welding Modeling

2.2 Material Property

The Half Nozzle Repair welding materials for the specific BMI Nozzle are shown in Table 2. Equivalent materials in SYSWELD Database[5] were applied for this study, because of the difficulty of obtaining the material properties depending on the temperature change.

Table 2. Material Specifications

Designation	As-designed Material	Equivalent Material for FEA
Bottom Head	SA-508 Cl.3	A508
Upper Nozzle	Alloy 600	Alloy 600
Bottom Nozzle	Alloy 690	Alloy 690
Pad	Alloy 52/152	Alloy 152
J-Groove	Alloy 52/152	Alloy 152

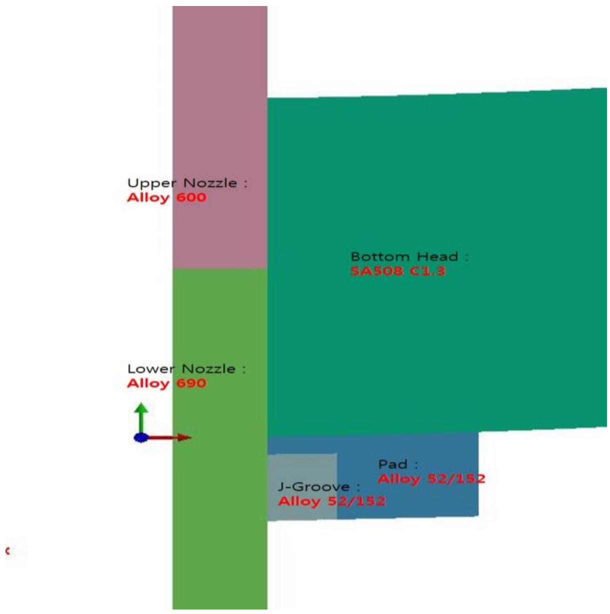

Figure 4. Materials of Each Part

2.3 Welding Variable

FEA of the Half Nozzle Repair welding performs welding analysis of largely two times including Pad welding analysis of bottom head and J-Groove welding analysis of Pad and Alloy 690 Nozzle. In order to analyze FEA for Pad welding and J-Groove welding, welding variable of WPS (Welding Procedure Specification), PQR (Procedure Qualification Record) used in the actual Nuclear Power Plant were applied for FEA. In this study, it is assumed that Pad welding has welding efficiency of 80%, J-Groove welding has welding efficiency of 50%, and after extracting each Heat Source model and thermal cycles, they are applied for welding input heat. In particular, It was analyzed by applying the ATTB (Ambient Temperature Temper Bead) welding method suggested in ASME B&PV Code Case N-638-5[4] in order to verify the effect of the tempering by welding Pad of bottom head basic material as low alloy steel material. Pad and J-Groove welding variable that need welding by Half Nozzle Repair method is shown in Table 3.

Table 3. Welding Variable of Each Welding[6]

Designation	Pad	J-Groove
Welding Method	Machined GTAW	Machined GTAW
Input Heat (J/mm)	944.4(1st) 1172.2(2nd) 1159.9(3rd) 1905.5(remaining)	3813.5
Efficiency (%)	80	50
Velocity (mm/s)	1.905	0.847
Pass between Temperature(℃)	150	149
Filler Material	ERNiCrFe-7A	ERNiCrFe-7A

3. Analysis of Results for the Half Nozzle Repair Welding

3.1 Analysis of Residual Stress Distribution

The residual stress distribution after Pad welding, J-Groove welding and 4-Cycle operation according to the Half Nozzle Repair welding is shown in Figure 5. The tensile stress of 360 MPa from the inner diameter contacting with the primary water was generated in case of Hoop stress based on the area from the inner diameter contacting with the primary water to nozzle and J-Groove welding portion. Tensile stress was reduced gradually as going to the center of the nozzle, and the outer of the nozzle generated about 580 MPa as increasing the stress in the center of the nozzle due to the thermal contraction of the J-Groove welding, and the generally high tensile stress was generated for the stress state of the nozzle and J-Groove welding portion. In case of Axial Stress, the insignificant tensile stress, approximately 43 MPa, was generated, and as moving to the J-Groove welding portion, 180 MPa stress was generated by increasing the tensile stress due to the contraction heat stress. In the nozzle and J-Groove welding portion, the high tensile stress was generated in the whole part as increasing the tensile stress continuously.

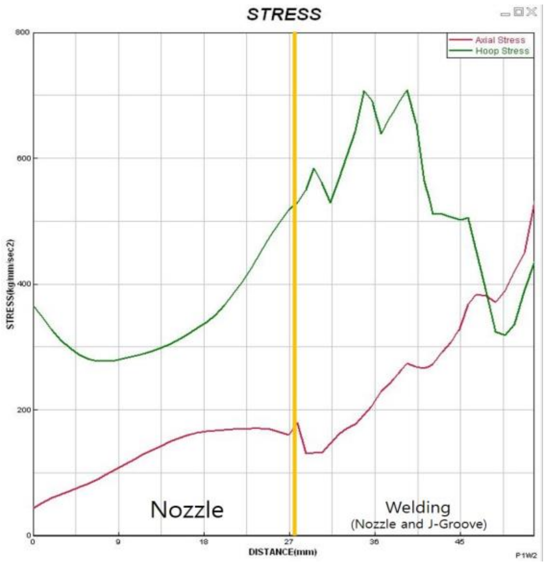

Figure 5. Analysis of Residual Stress (Nozzle and Welding)

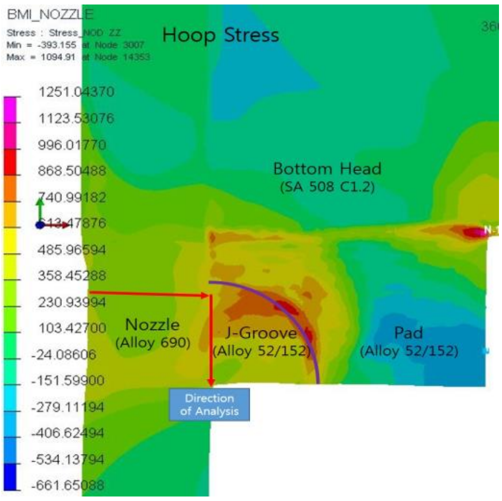

Figure 6. Distribution of Hoop stress

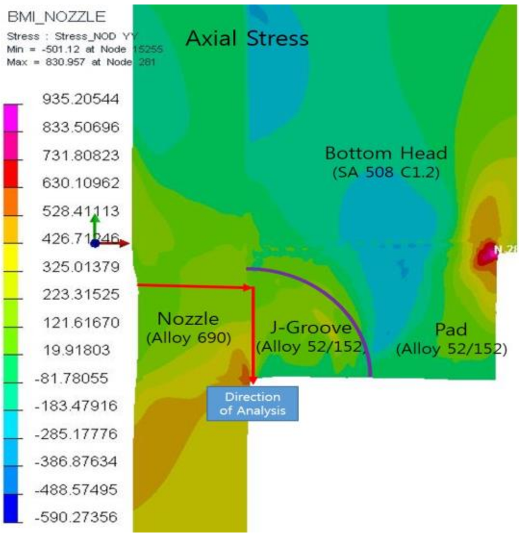

Figure 7. Distribution of Axial Stress

3.2 Phase Transformation Analysis

It has been known that the SA-508 Cl.3 steel which is used in the bottom head material contains the main alloy elements such as C, Mn, Ni, and Mo. It is the thick low alloy ferritic steel and can have the formation of acicular ferrite structure which has excellent toughness in the welding zone by providing the appropriate heat input[7]. In this study, phase transformation in the Heat Affected Zone (HAZ) microstructure during ATTB welding of SA-508 Cl.3 materials and the result is as followed.

3.2.1 Phase Transformation of As-Designed Condition

The bottom head is composed of the ferrite structure, the nozzle consists of austenitic structure, and the Pad is composed of Not Yet Deposited Material.

3.2.2 Phase Transformation of Half Nozzle Repair Welding Condition

Figure 8 and 9 show the microstructure change of the bottom head low alloy steel area related to the welding process by Half Nozzle Repair method. Martensite and Tempered Martensite structure performed HAZ until approximately 4~6 mm deep subsurface of the basic material during welding 1st layer of Pad as shown in Figure 8. Martensite structure was reduced to about 50% after the tempering process of HAZ by the welding heat during welding 2nd layer of Pad, and the Tempered Martensite structure was increased to 45%. Figure 9 shows the uniform distribution of these two structures to the entire HAZ.

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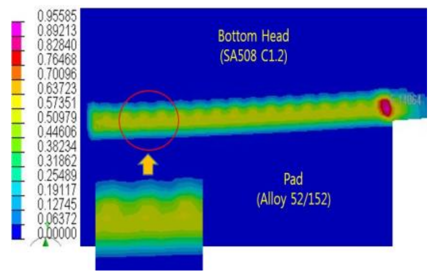
<tr><td>Martensite</td><td>
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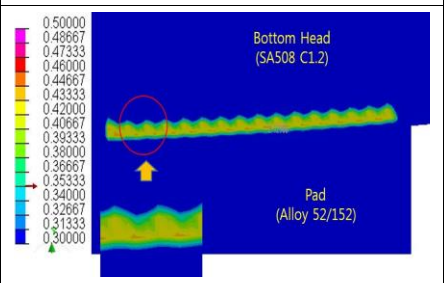
<tr><td>Tempered Martensite</td><td>
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Figure 8. Phase distribution after welding 1st layer of Pad

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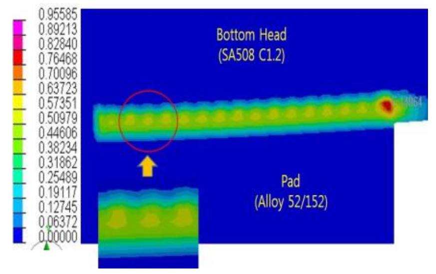
<tr><td>Martensite</td><td>
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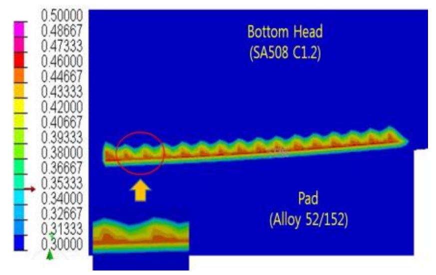
<tr><td>Tempered Martensite</td><td>
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Figure 9. Phase distribution after welding 2nd layer of Pad

4. Review of Analysis Results

4.1 Review of Results for Residual Stress

Analysis results in this study is identified that stress state of welding portion for the nozzle and J-Groove from the inner diameter and the outer diameter of the nozzle considering the critical point against PWSCC.

1) In the inner diameter of the nozzle contacting with the primary water, a little amount of Hoop Stress occurs similar to the yield strength of Axial Stress even if J-Groove welding performs, and it can be seen that tensile stress is increased from the inner diameter to the outer diameter by the effect of contraction heat stress of the J-Groove welding.
2) For the welding portion of the nozzle and J-Groove, the high tensile residual stress is caused in the outer diameter of the nozzle due to the compression after welding.
3) Although the distribution of the tensile residual stress of nozzle inner surface that contact with primary water is judged to be good, but as moving to welding, the increase of the tensile residual stress is expected to be disadvantageous in terms of PWSCC. So it will be necessary for additional method to be able to mitigate residual stress.

4.2 Review of Results for Phase Transformation

After the review of the changes in phase transformation of the basic material for the bottom head by the Half Nozzle Repair method during Pad welding, the following results can be obtained.

1) Martensite which is the rapid quenched microstructure is generated to the subsurface 4~6

mm approximately after welding 1st layer of Pad in the bottom head low alloy steel.

2) Thereafter, when 2nd layer of Pad and subsequent layers are welded by using welding parameters applied to ATTB welding method, it is found that the quenched microstructure in the low alloy steel surface is tempered by the welding heat. However, it could be verified that numerically about 50% quenched microstructure remains in the HAZ evenly and the only remaining 45% improves to be the Tempered Martensite microstructure.
3) In addition, it is identified that a few of quenched microstructure is not tempered completely but exist in the very small area in HAZ of the Weld Toe which is the end of Pad weld zone even though ATTB welding method is applied.

5. Acknowledgement

This study was carried out in support of research fund of the KEPCO International Graduate School (KINGS) in 2015.

6. Conclusions

In this study, it is evaluated that the effect of Pad welding for the Half Nozzle Repair method in the BMI the main instrument of NPP using SYSWELD which is the weld analysis code. The result of evaluation can be obtained as the following.

1) In order to prevent PWSCC of the BMI nozzle, the Half Nozzle Repair method was performed. As the result, the material Alloy 690 which has the strong corrosion resistance, one of the main factors of PWSCC, was replaced to prevent PWSCC. However, the higher tensile stress, another factor of PWSCC, than yield strength (350MPa) was occurred for Alloy 690 in the inner diameter of the nozzle contacting with the primary water in terms of the Hoop Stress. But compared to the yield strength, it cannot be seen much difference, so the prevention of PWSCC can be estimated. However, additional mechanical surface enhancing procedure such as pinning after welding is required so as to reduce the high tensile stress of the entire welding portion.
2) During welding the material that requires PWHT by the ATTB welding method, embrittlement quenched microstructure is improved, but only the half of it is tempered. This result is required to demonstrate the integrity through the experimental method or verification or procedure.
3) It is required that the strict control of the heat input during welding and mechanical processing of the weld bead after 1st Pad layer welding to minimize or prevent the occurrence of embrittlement quenched microstructure which is generated sectionally in the HAZ of the Weld Toe which is the end of Pad.

The reliability for the Pad welding of Half Nozzle Repair method and J-Groove welding applied to the activities in the NPP maintenance and replacement through the FEA method were reviewed in this study. And the experimental method will be performed additionally in the future for the validation of the result of the study.

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