Development of Welding Methods for Dissimilar Joint of Alloy 690 and Stainless Steel for PWR Components

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PWR nuclear power plants extensively use alloy 690 materials with higher chromium content in view of ensuring corrosion resistance. In order to select the optimal welding material fabricating components intended for use in PWR nuclear power plants, evaluation tests were conducted with various alloy 690 welding materials. In addition, suitable welding conditions were selected for the dissimilar metal joints where it is harder to perform welding. The welding conditions were validated by simulating the dissimilar metal piping of the actual equipment. As a result, the defect was not found in several test, excellent joints could be obtained.

1. Introduction

In recent years, alloy 690 materials are used in Pressurized Water Reactor (PWR) nuclear power plants for making main components including piping to replace the conventional alloy 600 materials in view of its superior resistance to stress corrosion cracking. The generally used alloy 690 welding materials included INCONEL Welding Electrode 152 (ENiCrFe-7), a coated welding electrode containing 30% chrome, and INCONEL Filler Metal 52 (ERNiCrFe-7) known for Gas Tungsten Arc Welding (GTAW), etc. These materials are known for susceptibility to Ductility Dip Cracking (DDC). In response, INCONEL Welding Electrode 152M (ENiCrFe-7) and INCONEL Filter Metal 52M (ERNiCrFe-7A, hereinafter FM52M) were developed to reduce DDC and are presently used in practice. This kind of cracking can still occur in the joints of a thick wall pipe with high restraint. For this reason, many manufacturers of welding materials and research institutes are engaged in active research on cracking prevention and development of welding materials.(1)-(4)

As a manufacturer of Boiling Water Reactor (BWR) nuclear power plants, we have fabricated a large amount of power generation equipment. In the meantime, we already offer components for PWR nuclear power plants and are developing a new business in this area. In particular, we are consolidating our manufacturing technology for the main components of the AP1000, Generation III + PWR reactor by Westinghouse Electric Company of the United States, including a Reactor Vessel (RV) and Steam Generator (SG), while pursuing fabrication of sound dissimilar metal joints free of cracking in the extremely thick interfaces between stainless steel and alloy 690 buttering area such as joint of nozzle and safe end. **Figure 1** shows the main components of a PWR nuclear power plant.

This paper reports on our selection of the optimal welding materials and establishment of a method to select adequate welding conditions for parts with high restraint involving the use of alloy 690 welding materials. In addition, we present the results from the simulation of the dissimilar metal piping welding of the actual equipment using these selected welding materials and conditions.

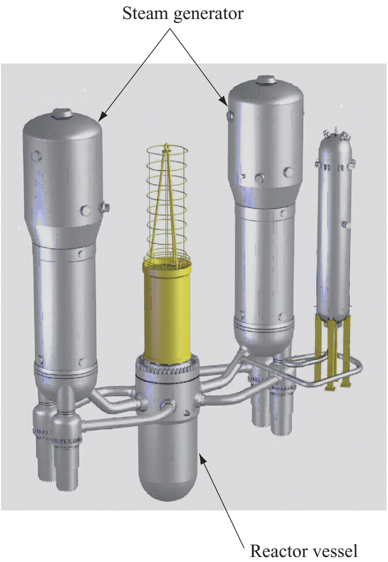


Fig. 1 Main equipment of PWR nuclear power plant

2. Testing method

2.1 Welding material property evaluation

In addition to commercially available alloy 690 welding materials such as FM52M, several kinds of newly developed welding materials with controlled alloy element content were used for the testing. Filler-A, -B, and -C are materials corresponding to ERNiCrFe-7 whereas FM52M and Filler-D correspond to ERNiCrFe-7A. The chemical compositions of the welding materials used in the tests are presented in **Table 1**.

(1) Varestraint test

A Spot Varestraint test was conducted with a test piece having a thickness of 5 mm for evaluating hot cracking susceptibility. The schematic illustration of the Varestraint test is shown in **Fig. 2**. In this test, bead on plate welding was performed with GTAW at the center of the test piece that is fixed onto the bending block. The yoke is fall rapidly on the both edges of specimen at the same time of arc disappeared. In this manner, the test simulates the strain and artificially induces the hot cracking that occurs during welding work. After applying the strain and subsequent cooling, the surface of test piece is observed with an optical microscope to measure the maximum crack length and total crack length of the cracking that appeared near the welded area. The hot cracking susceptibility of each welding material was evaluated from the relationship between the indices of crack length and amount of given strain. Varestraint welding conditions are shown in **Table 2**.

(2) Hot ductility test

A hot ductility test was conducted with each welding material to examine the ductility behavior at a high temperature and thereby evaluate the degree of ductility dip. The testing temperature was from 800 to 1 200°C. Comparison was made by reducing the area after the tensile test. The conditions for hot ductility test are presented in **Table 3**.

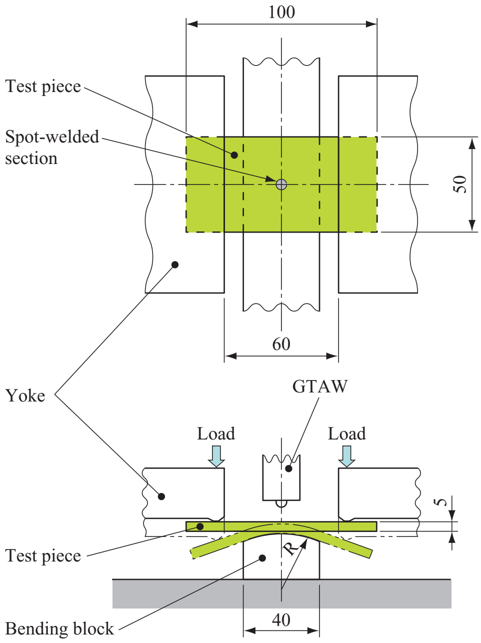


Fig. 2 Schematic illustration of Varestraint test (unit : mm)

Table 2 Varestraint test condition

Items	Unit	Specification
Current	A	65 - 80
Voltage	V	14
Shielding gas	—	Ar

Table 3 Hot ductility test condition

Items	Unit	Specification
Testing temperature	°C	800 - 1 200
Heating ratio	°C/s	16.7 - 21.7
Cross head speed	mm/s	0.025
Atmosphere	—	Ar

2.2 Welding test

A welding test was performed with the welding materials chosen after the welding material property evaluation. The occurrence of cracks was examined. In addition, welding conditions were changed during the welding test to check the impact of the welding conditions on the cracks. The test was also performed with welding materials (Filler-A) with high cracking susceptibility for the sake of comparison.

(1) Dissimilar metal joint test

A test piece of narrow groove weld was used for the simulation of a dissimilar joint between low-alloy steel with alloy 690 buttering and stainless steel to check for the occurrence of cracks by cross-section observation after the welding.

Base Metal: ASME SA302C (500 × 150 × 75 t)
JIS G4304 Type316L (500 × 150 × 75 t)

Table 1 Chemical compositions of filler materials used (wt%)

Tested material	Chemical composition (wt%)													
	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Co	Nb+Ta	Al	Ti	Fe
ERNiCrFe-7	< 0.04	< 0.50	< 1.0	< 0.02	< 0.015	28 - 31.5	REM	< 0.50	< 0.30	—	< 0.10	< 1.10	< 1.0	7.0 - 11.0
ERNiCrFe-7A	< 0.04	< 0.50	< 1.0	< 0.02	< 0.015	28 - 31.5	REM	< 0.50	< 0.30	< 0.12	0.5 - 1.0	< 1.10	< 1.0	7.0 - 11.0
FM52M	0.02	0.09	0.8	0.003	0.001	30.06	59.54	0.01	0.02	0.027	0.83	0.11	0.224	8.22
Filler-A	0.01	0.11	0.16	0.005	< 0.001	29.6	REM	0.01	< 0.01	—	0.05	0.21	0.39	9.9
Filler-B	0.01	0.12	0.16	0.005	0.001	29.9	REM	0.5	0.01	0.01	0.05	0.21	0.3	8.8
Filler-C	0.022	0.2	0.49	0.001 3	0.000 3	29.7	58.6	0.001	0.001	0.002	0.001	0.006	0.52	8.7
Filler-D	0.025	0.2	0.51	< 0.002	< 0.001	29.6	59.5	< 0.01	< 0.01	< 0.002	0.74	0.01	0.66	8.38

Welding material : FM52M, Filler-A
ASME SFA5.11 ERNiCrFe-7 or 7A
Test specimen (mm) : 500 × 300 × 75 t

(2) Circular patch test

A test piece was used to simulate a J weld joint of a reactor vessel head to check for the occurrence of cracks by cross-section observation after the welding.

Base Metal: ASME SA302C (300 × 300 × 75 t)
JIS G4304 Type304L (ϕ 102 × 75 t)
Welding material : Filler-D, Filler-A
ASME SFA5.11 ERNiCrFe-7 or 7A
Test specimen (mm) : 300 × 300 × 75 t
(groove depth 36 mm)

3. Results and review

3.1 Welding material property evaluation

Figure 3 presents an example of the observation of surface cracks in the Varestraint test. The relationships between each amount of strain and the total crack length of the DDC and liquation cracking are shown in **Fig. 4**. The results from the test concerning the DDC demonstrated extremely short total crack length and small cracking susceptibility in FM52M and Filler-D (ERNiCrFe-7A) containing Nb. In contrast, the total crack length of liquation cracks is extremely short in Filler-A and Filler-C (ERNiCrFe-7) that do not contain Nb, whereas welding materials containing Nb exhibit greater crack lengths. The increased susceptibility to liquation cracking by the addition of Nb has already been reported and our test results concur with the past research.(5) In terms of crack lengths, however, the total length is around 5 mm even when approximately 6% strain was given, remaining at quite a low level in comparison to the past research results. It is considered, therefore, that liquation cracking susceptibility is sufficiently low.

The results of the hot ductility test are presented in **Fig. 5**. Reduction in ductility was observed in hot ductility tests at a temperature around 1 100°C for all of the welding materials. The tendency observed for each welding material in terms of ductility at a temperature of 1 100°C matches the tendency in terms of the DDC length in the Varestraint test. With respect to DDC, simplified evaluation is thought to be possible by hot ductility tests.

The results of the cracking susceptibility test demonstrated low DDC susceptibility of welding materials containing Nb, namely, FM52M and Filler-D. These were selected as optimum welding materials.

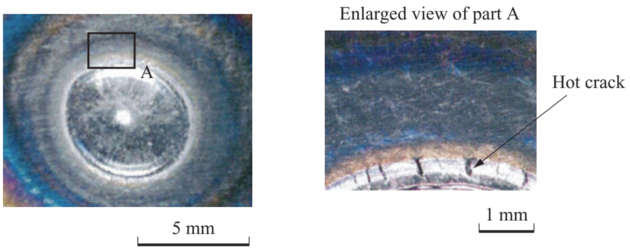
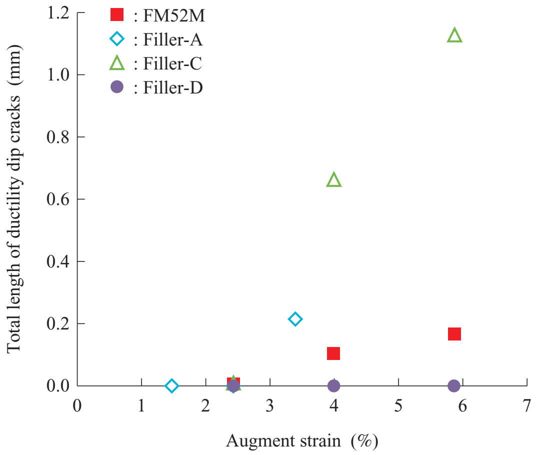


Fig. 3 Example of hot crack in Varestraint test

(a) Ductility dip cracking susceptibility



(b) Liquation cracking susceptibility

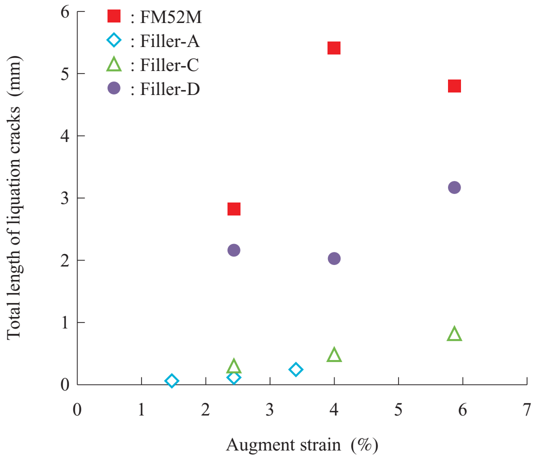


Fig. 4 Results of Varestraint test

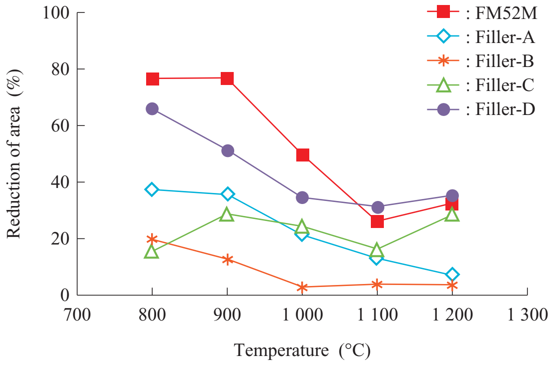


Fig. 5 Results of hot ductility test

3.2 Welding test

A number of DDC were observed in each welding cracking test. **Figure 6** shows an example crack in the dissimilar metal joint test. A fracture surface observed in a welding crack is shown in **Fig. 7**. The fracture surface is flat and shows no trace of melting, which is typically characteristic of DDC. Occurrence of DDC was confirmed in the circular patch test (**Fig. 8**).

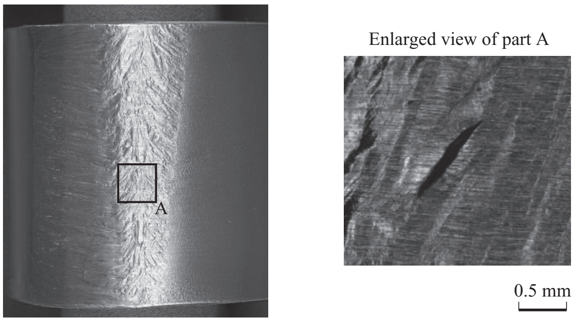


Fig. 6 Example of DDC in dissimilar joint test (FM52M)

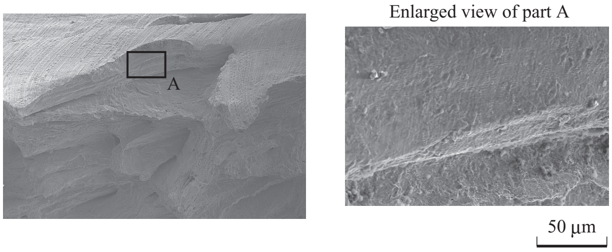


Fig. 7 Fracture surface of DDC in dissimilar joint test (FM52M)

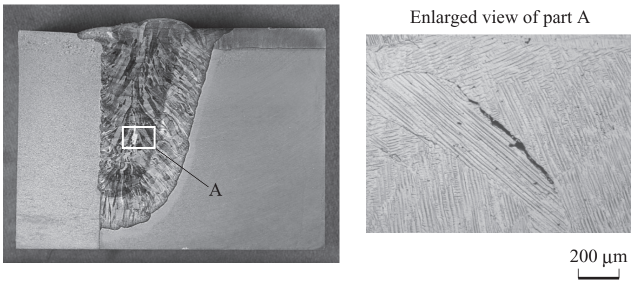


Fig. 8 Example of DDC in circular patch test (Filler-A)

Welding conditions other than heat input that can impact cracking include the amount of wire being supplied. For this reason, evaluation was made using *Power Ratio*, which took into account various welding parameter. The calculation formula (1) for *Power Ratio* is as follows. The compared results of the relationship between the *Power Ratio* and number of cracks observed in respective welding tests are shown in **Fig. 9**.

$$\textit{Power Ratio} = \frac{\text{Welding current} \times \text{Arc voltage}}{\dfrac{\text{Wire cross-sectional area of wire} \times \text{Wire feed speed}}{\text{Travel speed}}} \quad \cdots\cdots\cdots (1)$$

From the data was organized according to the index, two types of welding tests showed a tendency for the number of observed cracks to increase along with the increase of *Power Ratio*. The comparison of welding materials in terms of the occurrence of cracking showed that numerous cracks appeared with Filler-A much like the results from the welding material evaluation test. The results coincided with one another for the most part. In terms of the shape of the test piece, the number of cracks increased significantly in the circular patch test compared to the dissimilar metal joint welding test. Frequent cracking is due to the extremely high degree of constraint associated with the shape of the test piece, as well as the increase in the number of times the material is reheated as the circular patch test involves two to three passes for welding one layer as opposed to the one pass for welding one layer of a narrow groove in the dissimilar metal joint narrow groove welding test.

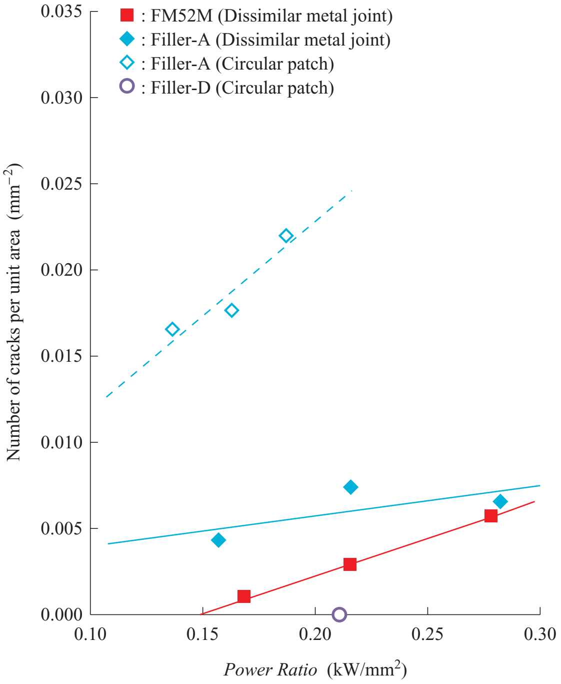


Fig. 9 Relationship between number of occurrences of DDC and *Power Ratio*

The selected welding conditions based on the test results are *Power Ratio* of 0.15 (kW/mm^2) or less for FM52M and 0.20 (kW/mm^2) for Filler-D.

4. Qualification test with dissimilar metal pipe joints

Dissimilar metal pipe joints were welded to simulate joint of nozzle and safe end of RV by applying a selected welding material and conditions. All position welding was performed to examine the influence of the position on the occurrence of cracking.

Figure 10 is the view of the welding test, wherein FM52M was chosen as the welding material with the condition of *Power Ratio* being 0.15 (kW/mm^2) or less.

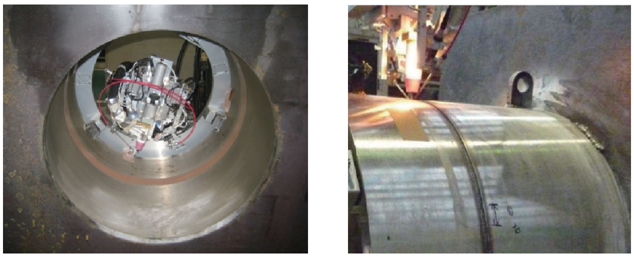
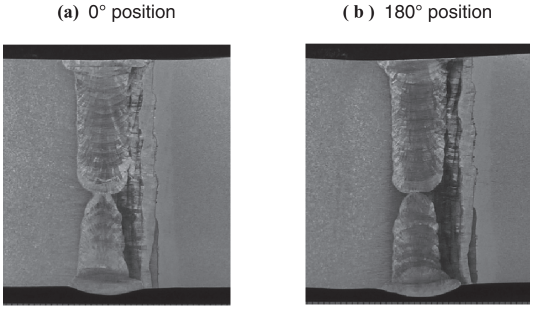

(a) Inside
(b) Outside

Fig. 10 Situation of dissimilar metal pipe joint welding



(a) 0° position　　(b) 180° position

Fig. 11 Macrostructures of cross section for dissimilar metal pipe joint welding

Table 4 Results of side bend test for dissimilar metal pipe joint welding

Test piece number	Results	QW-163 *1
SB-1	No defects	Acceptable
SB-2	No defects	Acceptable

(Note) *1 : Standard defined in Section IX of the American Society of Mechanical Engineers (ASME)

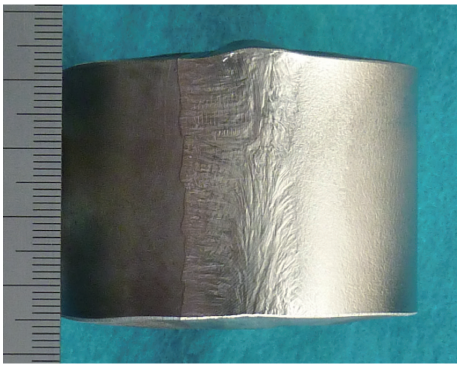


Fig. 12 Results of side bend test for dissimilar metal pipe joint welding

Figure 11 presents an example of the cross-sectional observation after the welding was performed. Excellent welding was confirmed as no cracks were found in the cross-sectional observation in any of the four directions 90 degrees apart. The side bend test showed no defects and validated the adequacy of the selected range of welding conditions.

Table 4 presents the results from the side bend test (qualification test) and **Fig. 12** shows the appearance of the test piece after the side bend test (qualification test).

5. Conclusion

The following conclusions were drawn from the review described above.

(1) The hot cracking susceptibility of each welding material was compared in the welding material property test. The test indicated the low cracking susceptibility of FM52M and newly developed Filler-D. These were chosen as the welding materials that can be applied to joints.

(2) Examination of the relationship between hot crack and welding conditions was made with a test piece simulating the dissimilar metal joint in RV/SG of PWR. The examination indicated that hot crack increases linearly with increasing *Power Ratio* that incorporates the welding condition.

By this result, a range of welding conditions was selected to prevent cracks for each welding material.

(3) Welding of dissimilar metal pipe joints was performed, applying the selected welding conditions. As a result, sound joints without any cracks were obtained.

— Acknowledgements —

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