A Structural Stainless Steel with Excellent Corrosion Resistance in Welding: JFE410RW†

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Abstract:

A newly developed stainless steel JFE410RW is superior in corrosion resistance at weld heat affected zone (HAZ) area. Its main usage is coal and iron ore wagon bodies. Two main elements are essential for intergranular corrosion resistance of weld HAZ. (1) The structure of weld HAZ must be martensite. (2) Precipitation of Cr carbide and nitride must be prevented by adding Titanium to stabilize C and N. JFE410RW is produced smoothly as hot coil products, and shows good mechanical properties and good toughness at low temperatures.

1. Introduction

The recent upturn in business in China and other countries has pushed up the demand for steel products, and increases in the mining outputs of coal and iron ore, the raw materials for steel, are helping to meet the higher demand. As a result, the production of rail wagons to carry coal and iron ore is also on a rising trend.

Because mined coal contains ample sulfur, the materials used for the rail wagons must have good sulfuric acid resistance, particularly intergranular corrosion resistance at the welds. Australian mining companies and railways therefore use stainless steels for their rail wagons, and they have long been studying how to select the stainless steels they use[1–3].

JFE Steel has been manufacturing JFE410RW for this application since 2005. This paper describes how JFE Steel focused on the intergranular corrosion resistance of welds in the development of JFE410RW, how the company determined the chemical composition of this stainless steel, and the results that have followed from the chemical composition ultimately determined.

2. Experiment Method

2.1 Test Materials

Tests were performed with JFE410DH[4] (a material developed earlier for structural purposes), a new steel produced by adding Ti to JFE410DH, and five other steels produced by adjusting the values of Mn, Ni, and Ti in different proportions. Thus, the seven steels shown in **Table 1** were produced and used for the tests.

Steel plates of these steel grades were cut, annealed, ground and pickled. Test pieces for double-fillet welding, double-butt welding of two kinds of plate thicknesses, and arc spot welding of a 3 mm thick plate were prepared. The test pieces for the corrosion test were cut out of each weld, and the effect of steel compositions on corrosion resistance was investigated by subjecting the test pieces to the salt spray test and the modified Strauss test. The toughness of the welds was also investigated.

2.2 Fabricating Process

A 50 kg ingot was produced using a small vacuum melting furnace, then rough-rolled and finish-rolled by hot rolling. A 5.2 mm thick steel plate and 3.2 mm thick steel plates were fabricated.

The rough rolling was performed by reheating the ingot (160 × 160 × 250 mm) to 1 170°C, rolling it into a hot strip of 22 mm (thickness) × 180 mm (width) × 1 400 mm (effective length) by eleven passes at a finishing delivery temperature of 780°C, and then air cooling the hot strip to room temperature. Next, the hot strip was

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Table 1 Chemica l composition of the samples

(mass%)

	C	Si	Mn	P	S	Cr	Ni	Ti	N	Ti/C+N
JFE410DH	0.008 0	0.18	1.49	0.029	0.002	11.03	0.28	0.001	0.005 5	0.08
JFE410DH+Ti	0.009 7	0.18	1.55	0.028	0.002	11.10	0.30	0.140	0.007 5	8.14
HiNi-HiMn	0.021 0	0.39	1.85	0.030	0.002	11.09	0.81	0.195	0.013 2	5.70
LowNi-HiMn	0.022 0	0.33	1.85	0.028	0.001	11.00	0.36	0.196	0.007 2	6.72
LowNi-LowMn	0.021 8	0.28	1.44	0.029	0.002	11.12	0.36	0.196	0.018 4	4.88
LowNi-LowMn-LowCN	0.015 9	0.38	1.44	0.028	0.002	11.03	0.35	0.190	0.009 6	7.45
HiTi-HiMn	0.015 7	0.28	1.95	0.029	0.002	11.03	0.41	0.269	0.006 7	12.01

divided into seven equal parts and cut into small pieces of 200 mm in (length). The small pieces were descaled, reheated, finish rolled by three passes into steel plates of 5.2 mm (thickness) × 180 mm (width) × 600 mm (effective length), and then rolled by five passes into steel plates of 3.2 mm (thickness) × 180 mm (width) × 800 mm (effective length).

Air-cooled steel plates were cut into the sizes of the test pieces for welding and then annealed at 690°C for 10 hours at a cooling rate of 20°C. The thicknesses of the two kinds of steel plates were then adjusted to 5 mm and 3 mm, respectively, by machining, and the steel plates were pickled and used to prepare the welding test materials.

2.3 Welding Method

The welding was performed by the gas metal arc welding (GMAW) method using MGS-309LS wires of 1.2 mm in diameter (Kobe Steel Corp.) and a shielding gas with a composition of 98% Ar and 2% O_2 at a flow rate of 20 *l*/min. The flat position was adopted for the welding of all test materials. The welding conditions for the test materials were as shown in **Fig. 1** and **Table 2**.

A Y-groove was prepared in the double-butt weld of a 5 mm thick plate. The welding was performed by making a first pass on the side without a groove and a second pass on the grooved side.

2.4 Test Pieces for Welding

The shape and surface condition of each test piece for welding were obtained by the following methods:

(1) Test Pieces for Double-fillet Welding

A lower plate was obtained by cutting a flat plate of 400 mm (length) × 60 mm (width) out of a test material, annealing it, and then grinding a 40 mm portion in the middle part of a 60 mm wide weld surface. An upright plate was obtained by annealing a flat plate of 400 mm (length) × 40 mm (width), grinding the surface along a 20 mm length on the weld side, and then pickled. The lower plate and the upright plate were assembled into a T-shaped test piece of 400 mm in (length) and then double-fillet welded was performed from both sides under the conditions shown in Table 2.

(2) Test Pieces for Double-butt Welding

A flat plate of 400 mm (length) × 40 mm (width)

Table 2 Welding condition

Welding method	GMAW (Gas sealed Metal Arc Welding) method
Welding wire	MGS-309LS 1.2 mmϕ (C: 0.02 mass%, Si: 0.8 mass%, Mn: 1.8 mass%, Ni: 13.3 mass%, Cr: 23.6 mass%)
Sealed gas	98%Ar-2%O_2
Flow rate	20 *l*/min

	Welding condition	3 mm thickness	5 mm thickness
(1)	Double fillet weld (i) First fillet 0.3 kJ/mm (ii) Second fillet 0.8 kJ/mm	○	—
(2)	Double butt weld (i) First fillet 0.6 kJ/mm (ii) Second fillet 0.6 kJ/mm	○	○
(3)	Arc spot	○	—

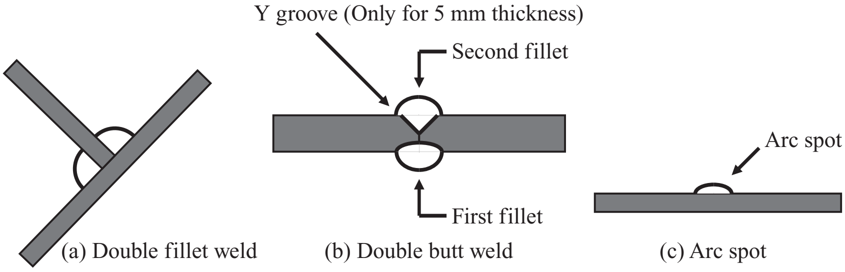

Fig. 1 Welding method

was cut out of a test material, annealed, and ground across the full width on one side and along the full length on the butt surface side. No groove was prepared for the 3 mm thick material, and a 2 mm deep grooved surface angled at 45° was worked into one side of the 5 mm thick material. After pickling, double-butt welding was performed under the conditions shown in Table 2.

(3) Test Pieces for Arc Spot Welding

After annealing a 400 mm long, 60 mm wide flat plate shaped identically to the lower plate for double-fillet welding, a 40 mm portion of the middle part of the 60 mm wide weld surface was ground and annealed. The arc spot welding was performed at a rate of three arc spots per 400 mm length.

2.5 Corrosion Test

2.5.1 Test method

(1) Salt Spray Test

The salt spray test was conducted in accordance with the neutral salt spray test specified in ASTM B 117 (ASTM: American Society for Testing and Materials). A 5% NaCl test solution was atomized at 35°C in a test vessel. The test time was 96 hours. The corrosion condition was observed at the finish of the test.

(2) Sulfuric Acid-Copper Sulfate Corrosion Test

The sulfuric acid-copper sulfate corrosion test was performed as a modified Strauss test in accordance with ASTM A 262 practice E and ASTM A 763 practice Z. $Cu/6\%CuSO_4/0.5\%H_2SO_4$ was used as the test solution. A test piece with polished end surfaces was immersed in this boiling solution for 20 hours to observe the corrosion condition.

When the test was finished, the surface of the test pieces was completely blackened with corrosion, preventing observation of the structure. Therefore, a polished end surface of the test piece ground to a depth of about 20 μm ground and observed under an optical microscope to examine the microstructure.

2.5.2 Test pieces

(1) Test Pieces for Salt Spray Test

(a) Test pieces for double-butt welding

Three corrosion test pieces of 80 mm (length) × 60 mm (width) were cut out of the prepared butt weld for each steel grade. To remove the effect of the scale formed during annealing, a 60 mm wide tape was applied to the back surface. The test pieces thus prepared were subjected to the slat spray test.

(b) Test pieces for arc spot welding

A sample with arc spots placed in three places in the length direction was cut from the 400 mm long test piece. Next, a 50 mm wide strip of tape was applied over the middle of the back surface, and a 30 mm wide strip of tape was applied over an area of about 12 mm by folding it back from the end portion of the back surface to the base metal side on the front surface side. The coverage of tape in this fashion removed the effect of the scale during annealing, which typically remains as a residue on the back surface and in the width-direction. Test pieces thus prepared were subjected to the slat spray test.

(2) Test Pieces for Sulfuric Acid-Copper Sulfate Corrosion Test

Two corrosion test pieces of 30 mm (length) × 30 mm (width) × 15 mm (height) were cut out of the double-fillet weld prepared for each steel grade, buried together in resin as a set, and buff-polished at the end surfaces. The test pieces thus prepared were subjected to the corrosion test.

2.6 Evaluation of Weld Toughness

2.6.1 Test method

The toughness of the double-butt weld was evaluated by a method in accordance with the Charpy impact test method specified in JIS Z 2242.

The test was conducted at temperatures of +50°C to −100°C.

2.6.2 Test pieces

The front and back surfaces of the double-butt weld prepared with the plate thickness of 5 mm were ground to a plate thickness of 3 mm. Next, by cutting out a 2 mm V-notch, a weld metal portion of 55 mm (length) × 10 mm (width) was produced in the 50% position of the plate thickness. The test pieces thus prepared were subjected to the Charpy impact test.

3. Results

3.1 Salt Spray Test

The results of the 96 hours salt spray test conducted on the test pieces for the double-butt welding are shown in **Photo 1**.

Although rust was observed in all of the test pieces, none of the pieces showed deep corrosion in the heat affected zone. No difference were observed in the test pieces for arc spot welding.

3.2 Sulfuric Acid-Copper Sulfate Corrosion Test

The results of the modified Strauss test conducted on the test pieces for double-fillet welding are shown

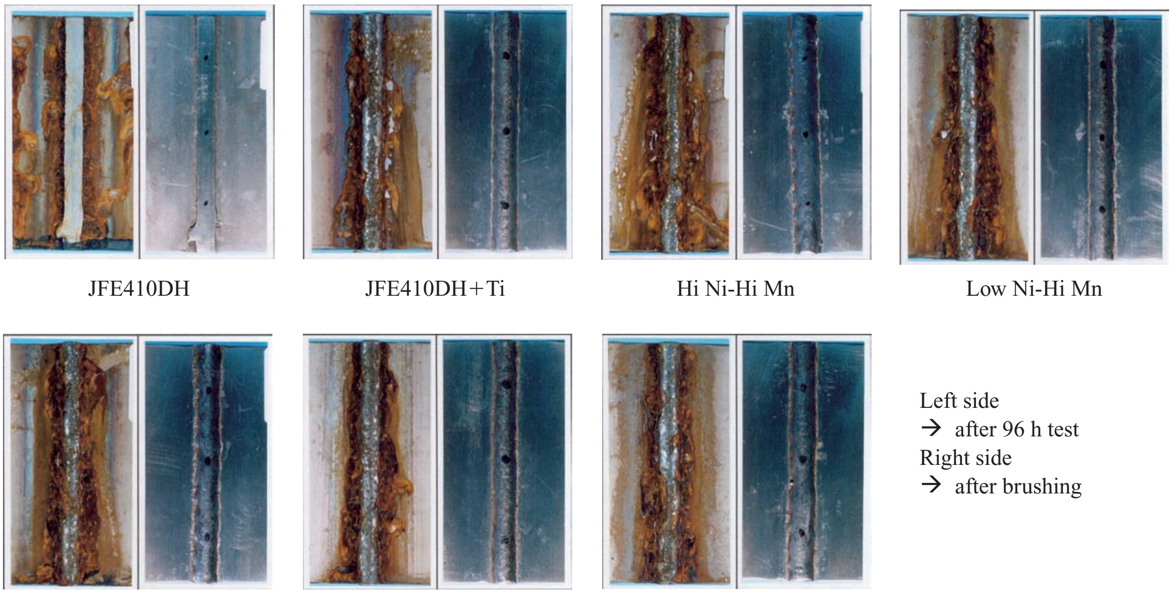

Photo 1　Results of salt spray test

in **Table 3**. The numerals ① to ④ in Table 3 denote the positions of the heat affected zones shown in **Photo 2**.

In Table 3, the results obtained in the four positions in the two samples are indicated by the following symbols:

○ : No corrosion
△ : Slight corrosion
× : Deep corrosion or intergranular corrosion

Table 3　Results of modified Strauss test

Sample	Position at weld			
	①	②	③	④
JFE410DH	○△	○○	××	△△
JFE410DH+Ti	△△	○△	○×	○○
Hi Ni-Hi Mn	○○	○○	△△	○○
Low Ni-Hi Mn	○○	○○	△△	○○
Low Ni-Low Mn	○○	○△	△×	○○
Low Ni-Low Mn-Low CN	○△	○△	△×	○○
Hi Ti-Hi Mn	○△	○△	△△	○○

○ ···No corrosion
△ ···Slight corrosion
× ···Deep corrosion or intergranular corrosion

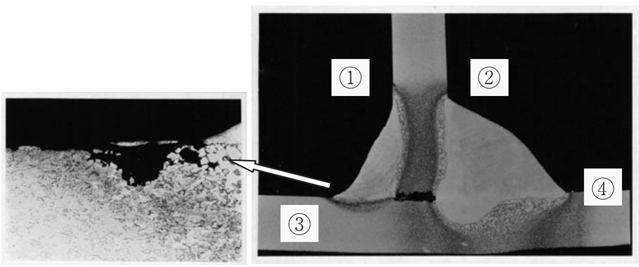

Photo 2　Results of modified Strauss test (JFE410DH + Ti)

In all of the welds, the corrosion occurred at positions in heat-affected zones with enlarged grains at the ends of the beads. In position ③ of Table 3, deep corrosion or intergranular corrosion of the kind shown in Photo 2 was observed in some types of test pieces.

When the corrosion resistance of the tested steel grades was rated qualitatively from the results of Table 3 and the results of an observation carried out under a stereoscopic microscope, the Hi Ni-Hi Mn steel showed the best corrosion resistance and the Low Ni-Hi Mn steel came in second place.

3.3 Evaluation of Weld Toughness

Table 4 shows the results of the investigation of the toughness of the test pieces for double-butt welding. In the test, the absorbed energy transition temperature was defined as the equivalent of 1/2 of the absorbed energy at the minimum temperature at which the ductile fracture rate becomes 100%.

The transition temperatures of JFE410DH and JFE410DH + Ti were both lower than −100°C and very good. In the other steels produced by way of trial, the

Table 4　Energy transition temperature

Sample	Energy transition temperature (°C)
JFE410DH	<−100
JFE410DH+Ti	<−100
Hi Ni-Hi Mn	−30
Low Ni-Hi Mn	−30
Low Ni-Low Mn	−10
Low Ni-Low Mn-Low CN	−15
Hi Ti-Hi Mn	−25

transition temperatures were –10°C to –30°C. Thus, no great difference was observed. That is, the transition temperatures of the low-C, low-Ti steels were good.

4. Discussion

4.1 Relationship between the Corrosion Resistance of the Welds and the Chemical Compositions

Photo 3 shows the structures in position ② of the heat affected zone.

(1) In all of the welds, corrosion occurred in the positions in heat affected zone with enlarged grains at the ends of the beads, and deep corrosion or intergranular corrosion was observed in position ③ of Table 2, i.e., the part with the smallest heat input.

(2) There was a difference in the microstructure of the heat affected zone with enlarged grains. The 410DH and Hi Ni-Hi Mn steels had martensite, whereas other steels produced by way of trial had ferrite of enlarged grains.

(3) The Hi Ni-Hi Mn steel with added Ti and the martensitic heat affected zone showed the best corrosion resistance.

On the basis of the three findings described above, we can conclude that two factors are requisite for the corrosion resistance of welds:

(a) The heat affected zone has martensite.

(b) The addition of Ti prevents the precipitation of carbonitrides of Cr at the grain boundaries.

Carbonitrides of Cr are known to appear in the heat affected zone of stainless steel. This tends to deplete the steel of Cr at the grain boundaries and compromises the corrosion resistance[5,6]. From the results of the present test, the mechanism that prevents the precipitation the greater part of C is prevented by the formation of martensite during the cooling of the heat affected zone appears to prevent the intergranular corrosion, and Ti appears to stabilize the C and N, which precipitate in partly formed ferrite.

The deep corrosion or intergranular corrosion observed in position ③ in Photo 3 (that is, the part with the smallest heat input) might be explained by potential formation of carbonitrides by Ti even when C and N precipitate. It might be thought that in other positions, even if C and N precipitate, carbonitrides were capable of being formed by Ti because the heat input is large. But on the other hand, in the postion ③ carbonitrides of Cr appear, becanse the heat input is small and there are not enough engergy to form carbonitrides by the Ti in the ferrite structure. Thus, practically speaking, the most important item might be the corrosion resistance in the areas with heat input as low as that in the arc spots.

5. Results of Production in Actual Equipment

5.1 Chemical Composition

Based on the above-described investigation results,

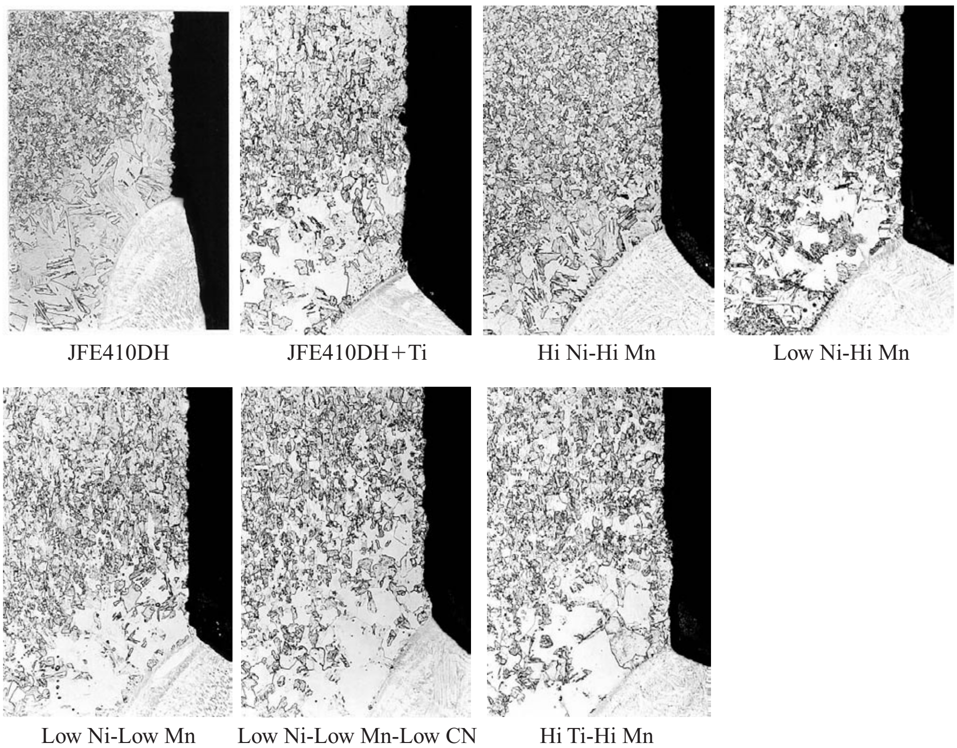

Photo 3 Results of modified Strauss test

Table 5 Chemical composition of JFE410RW

(mass%)

	C	Si	Mn	P	S	Cr	Ni	Ti	N
Specification	≦0.025	≦1.00	1.00–2.00	≦0.040	≦0.030	10.90–12.50	—	4 (C+N)–0.30	≦0.020
Typical	0.021	0.30	1.78	0.025	0.002	11.05	0.75	0.22	0.014

Table 6 Typical data of JFE410RW

Density (at 20˚C)	Thermal expansion coefficient (−20–+50˚C)	Mechanical properties			
		YS	TS	El	HB
7.731 g/cm^3	10.0×10^{-6}/˚C	401 N/mm^2	519 N/mm^2	28.8%	155

YS: Yield strength TS: Tensile strength
El: Elongation HB: Brinell hardness

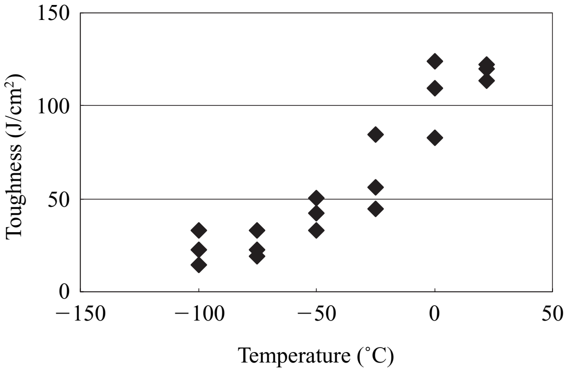

Fig. 2 Impact value on welding HAZ

JFE410RW was manufactured using actual equipment. **Table 5** shows the specification for the chemical composition and an example of the chemical composition. The Hi Ni-Hi Mn steel, the steel with the best corrosion resistance, was adopted. We note, however, that the corrosion of the Low Ni-Hi Mn steel was also only slight. Thus, we speculate that the heat-affected zone of the Low Ni-Hi Mn steel could presumably develop martensite if the amount of N was increased to the same amount used in the Hi Ni-Hi Mn steel. Therefore, the lower limit to Ni was not specified.

5.2 Physical Properties and Mechanical Properties

Table 6 shows examples of the physical properties and mechanical properties of JFE410RW produced in actual equipment. The mechanical properties are good and there is no problem in working the steel plates of JFE410RW.

5.3 Toughness

Even in the low temperature region of −20°C, welds show toughness of not less than 50 J/cm^2 or so (**Fig. 2**).

This may be because of the low-C martensite of the heat-affected zone.

6. Concluding Remark

JFE410RW has obtained material certifications in Australia and other countries, and its sales volumes are increasing smoothly. **Photo 4** shows an example of an application of JFE410RW to a coal wagon. JFE Steel intends to expand the application of JFE410RW to other uses in addition to iron ore and coal wagons in the future.

Photo 4 Coal wagon

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