

Development of Corrosion Resistant Steel for Extended Painted Life “EXPAL™”

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Abstract:

EXPAL™ has been developed as corrosion resistant steel that reduces life cycle costs by extending the paint life of painted steel structures. The developed steel forms a protective rust layer under paint film by the effect of corrosion resistant elements. Protective rust layer suppresses the corrosion of steel and paint blistering. Repainting interval estimated from the accelerated corrosion test is more than twice that of the conventional steel, and hence the number of repainting can be reduced. In addition, the developed steel meets the chemical composition and mechanical properties standards of JIS G 3106 and has the same weldability and weld joint properties as those of the conventional steel.

1. Introduction

In recent years, increases in the cost of operation and maintenance (O&M) and cost of deterioration upgrades of bridges, port and harbor structures and other social infrastructure have been forecast¹⁾, and the results of a trial calculation indicate that these costs will reach 1.3 times their current levels 30 years from now²⁾. For this reason, it can be thought that the needs for longer life of social infrastructure and reduction of its life cycle cost (hereinafter, LCC) will also increase in the future. Corrosion is one cause of deterioration of steel structures. Since corrosion is generally severe in regions with high concentrations of airborne salt, such as marine and coastal areas, a heavy duty coating (C-5 paint system) is applied in these environments, particularly to prevent corrosion of bridges, but because the expected life of the C-5 paint system is 30 years³⁾,

repainting will be necessary 3 times, assuming the service life of a bridge is 100 years. In order to reduce LCC, it is necessary to reduce the number of times repainting is required, and for this, it is necessary to extend the paint life. Corrosion of painted steel structures occurs mainly from the points of origin, including paint film defects such as pinholes, the corners of members, where the paint film thickness tends to become thin, and crevice parts, but it is impossible to eliminate these potential causes of corrosion completely. Paint life in severe corrosion environments is determined by factors such as corrosion of the substrate steel originating from paint film defects, and paint blistering and peeling accompanying corrosion. Accordingly, it is possible to suppress blistering and peeling of the paint film and extend paint life by enhancing the corrosion resistance of the steel.

Based on the background described above, JFE Steel developed a corrosion resistant steel for extended painted life (EXPAL™), a corrosion resistant steel in which corrosion, blistering and peeling occurring from paint film defects are suppressed and paint life is extended by improving the corrosion resistance of the steel⁴⁾. This report describes the painted corrosion resistance of the developed corrosion resistant steel, the mechanical properties of the base metal and welded joints and the expected effects of application to actual structures.

2. Corrosion Resistance Design of Developed Steel

Figure 1 shows the concept of the corrosion resis-

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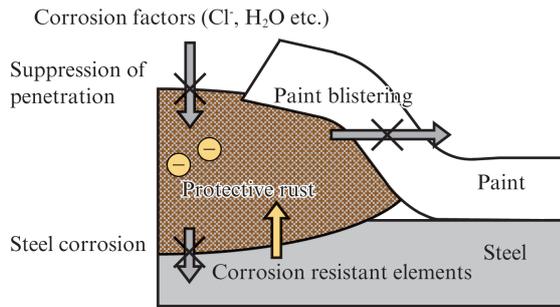


Fig. 1 Concept of development of corrosion resistant steel

tance design of the developed steel. The developed steel prevents paint blistering by suppressing the corrosion reaction of the substrate steel from paint film defects. The corrosion reaction is suppressed by improving the protective property of the rust layer which protects the substrate steel. As methods for improving the protective property of the rust layer, a method in which penetration of corrosion factors is physically suppressed by refining the rust particles of the protective rust layer⁵⁾, and a method in which penetration of chloride ions is electrochemically suppressed by imparting cation selective permeability to the rust layer⁶⁾ are known. The corrosion resistance design of the developed steel was carried out with the aim of utilizing both the physical and electrochemical protective actions, and also utilizing the synergistic effect with zinc (Zn) provided by the zinc-rich paint used in the C-5 paint system. Refinement of the rust particle size and cation selective permeability are described in detail in section 4.2.

Based on the above-mentioned corrosion resistance design, and various corrosion tests and electrochemical studies, optimum corrosion resistance composition, Cu-Ni-Sn-W-added steel, was developed.

3. Experimental Method

3.1 Corrosion Tests

In order to evaluate the painted corrosion resistance of the developed steel, a laboratory accelerated corrosion test and an atmospheric exposure test were conducted.

As the test steels, the developed steel and a hot-rolled steel plate for welded structure use (JIS G 3106; hereinafter, conventional steel) were used. The dimensions of the test pieces taken from these test steels were 5 mm^t × 70 mm × 50 mm for the laboratory corrosion test, and 5 mm^t × 150 mm × 70 mm for the atmospheric exposure test. After blasting treatment, the test pieces were coated with the C-5 paint system shown in Table 1. It may be noted that the C-5 paint system is recommended for application to newly-constructed

Table 1 Paint system

Paint system	Paint name	Target film thickness (μm)
Protective coat	Inorganic zinc rich paint	75
Mist coat	Epoxy resin paint	—
Base coat	Epoxy resin paint	120
Middle coat	Epoxy resin paint	30
Top coat	Fluoro resin paint	25
Total film thickness (μm)		250

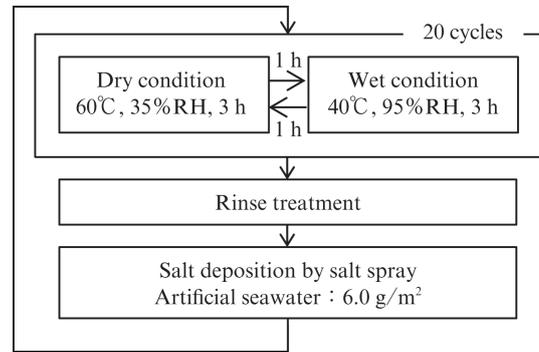


Fig. 2 Condition of accelerated corrosion test

bridges^{3, 7)}. After coating, linear paint film defects with a width of 0.7 mm and a length of 40 mm (laboratory corrosion test piece) or 80 mm (atmospheric exposure test piece) reaching the base steel were made on the coated test pieces using a plastic cutter (MB-2P, manufactured by NT Incorporated), and the samples were subjected to the respective corrosion tests.

The conditions of the laboratory accelerated corrosion test are shown in Fig. 2. Based on a corrosion test method (ISO 16539: 2013) in which the blistering mode of painted steel plates reportedly shows a high correlation with corrosion in the actual environment⁸⁾, the salt deposition process was performed 1 time each week, and 6.0 g/m² of salt was deposited with artificial seawater.

The atmospheric exposure test was carried out for a period of 4.2 years in Okinawa, which is a severe corrosion environment with a high concentration of airborne salt. As the test piece position and exposure environment, the test pieces were placed in a horizontal position under the eaves of the test facility, simulating an environment where deposited airborne salt is not washed off by rain, as this is a severe corrosion environment in actual structures.

After the respective corrosion tests were completed, the area of paint blistering that had occurred around the paint film defect was measured by image analysis of photographs of the appearance of the test pieces, and the one-side average blister width (hereinafter, paint blistering width) was calculated from the area of the paint blistering.

3.2 Analysis of Rust Layer

The following analysis was conducted to verify the refinement of rust particles by the corrosion resistant elements and the cation selective permeability of the rust layer.

Refinement of the rust particles was evaluated by observing the rust layer that had formed on the test pieces after the corrosion tests with a scanning transmission electron microscope (STEM). The samples for observation were prepared by cutting out thin films from the rust layer by a focused ion beam technique.

Cation selective permeability was evaluated by the membrane potential of the rust layer. The test steels used here were the conventional steel and a model steel in which W was added (hereinafter, W bearing steel), as in the developed steel. In the W bearing steel, 0.3 mass% of W was added in order to evaluate the tendency of ion selective permeability due to addition of W. A sample with dimensions of $0.05 \text{ mm}^t \times 10 \text{ mm} \times 10 \text{ mm}$ was taken from this test steel, and a test piece consisting of only the rust layer was prepared by eliminating the steel by corrosion in a 3-week accelerated corrosion test under the conditions shown in Fig. 2. This test piece was placed between two cells so that its two sides were in contact with KCl solutions of various concentrations, and a 0.1 mol/L KCl aqueous solution was introduced into cell (a1) on one side, and either a 0.1 mol/L or a 0.001 mol/L KCl aqueous solution was introduced into cell (a2) on the other side. All KCl solutions were adjusted to pH 4 with HCl. The potential difference between the reference electrodes (Ag/AgCl/saturated KCl) of each of the two cells was then measured, and the potential difference approximately 8 h after the start of the measurement was used as the membrane potential. The membrane potentials of commercially-available anion or cation selective permeable membranes (SELEMION AMV-N, CMV-N, manufactured by AGC Engineering Co. Ltd.) were also measured to verify the validity of the obtained data.

4. Experimental Results and Discussion

4.1 Evaluation of Painted Corrosion Resistance

Figure 3 shows the temporal changes in the appearance of the paint blistering area and the paint blistering width after a 64-week laboratory accelerated corrosion test. Although corrosion and paint blistering occurred at the paint film defect on both the conventional steel and the developed steel, the blistering on the developed steel was small in comparison with that on the conventional steel. From the temporal change in the paint blistering width shown in Fig. 3 (b), an incubation

period, during which the progress of blistering was delayed in the initial stage of corrosion, could be confirmed in both the conventional steel and the developed steel. This is considered to be an effect of the Zn in the inorganic zinc-rich paint layer of the C-5 paint system⁹⁾. Increases in the paint blistering width could be seen after 12 weeks in the conventional steel and after 16 weeks in the developed steel. However, the blistering width of the developed steel showed a smaller value than that of the conventional steel over the entire period after 12 weeks, and at 64 weeks, the blistering width of the developed steel was 33 % smaller than that of the conventional steel.

Next, Fig. 4 shows the appearance of the test pieces and the results of measurements of their paint blistering after the atmospheric exposure test for 4.2 years in the Okinawa region. The paint blistering width of the developed steel was small, confirming that the developed steel also demonstrates a paint blistering width suppression effect in the actual environment like that observed in the laboratory accelerated corrosion test.

Figure 5 shows the results of a calculation of the paint life extension effect of the developed steel, using the results of the laboratory accelerated corrosion test and the atmospheric exposure test. The acceleration scale factor in the laboratory accelerated corrosion test relative to the atmospheric exposure test was 2.0. Therefore, on the x-axis in Fig. 5, the time in the laboratory corrosion test was converted to the actual environment-equivalent time by multiplying the laboratory test time by a factor of 2.0. Here, the acceleration scale factor of the laboratory corrosion test relative to the atmospheric exposure test was obtained as follows: (1) The paint blistering widths of the conventional steel and the developed steel after 64 weeks in the laboratory corrosion test were 6.2 mm and 4.2 mm, respectively; therefore, the time required for the blistering width of the conventional steel and the developed steel to reach 6.2 mm and 4.2 mm in the atmospheric exposure test was calculated. (2) Based on (1), the acceleration scale factors obtained from the ratio of the periods in the two tests were calculated (conventional steel: 2.1, developed steel: 2.0), and the acceleration scale factors of the conventional steel and the developed steel were averaged, resulting in the above-mentioned scale factor of 2.0. It may be noted that the scale factor was calculated as 2.6 in a report by Miura et al.⁴⁾, but we recalculated the scale factor based on the results of the longer atmospheric exposure test in the present research (the test duration in Miura et al. was 2 years). Although the repainting interval of the developed steel increased from 70 years to 73 years as a result of this change in the scale factor, as described below, there was no change in the number of repainting or in the results

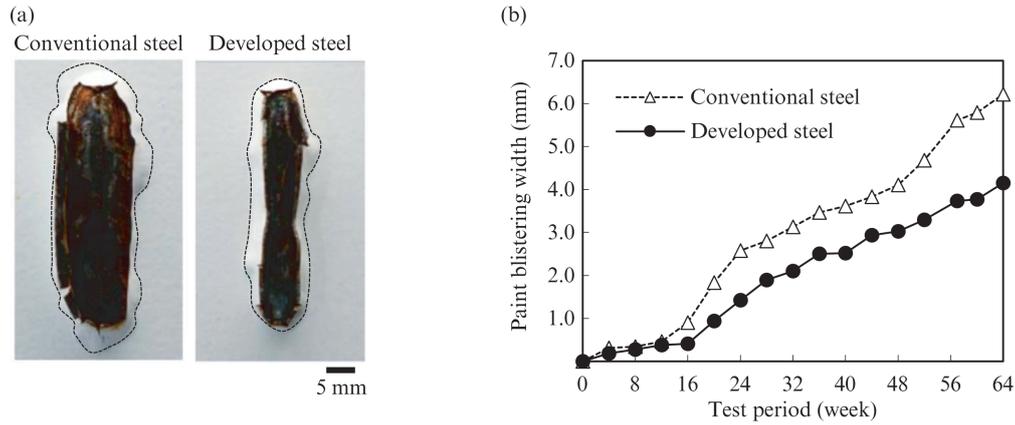


Fig. 3 Results of laboratory accelerated corrosion test : (a) appearance of paint blistering area, (b) change in paint blistering width

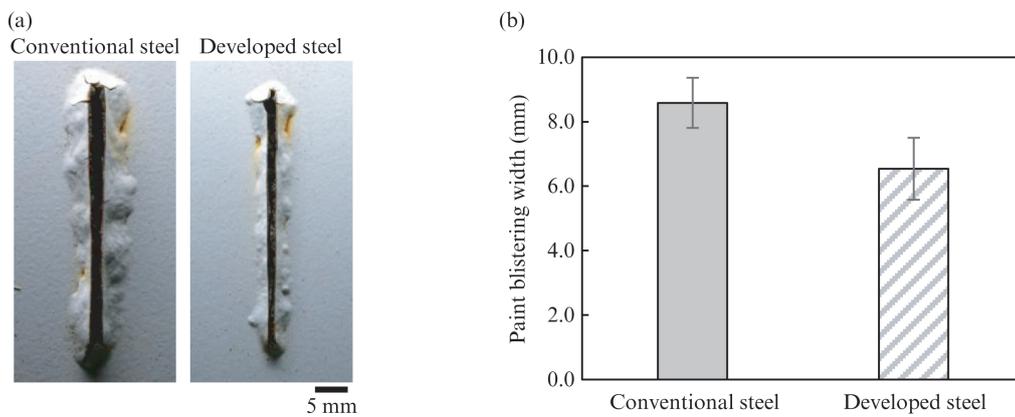


Fig. 4 Results of exposure test for 4.2 years in Okinawa : (a) appearance of paint blistering area, (b) paint blistering width

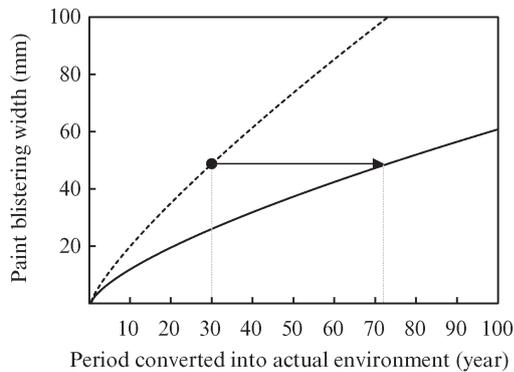


Fig. 5 Effect of extending repainting interval

of the trial calculation of LCC.

Next, the method of calculating the paint life extension effect of the developed steel will be explained. The main cause of paint blistering in this test is corrosion of the substrate steel and the accompanying formation and growth of rust, which is common to the mechanism of corrosion loss of weathering steels. Therefore, the paint life extension effect of the developed steel was calculated by approximation by the power regression curve¹⁰⁾, which is generally used in predictions of the corrosion loss of weathering steels. In this calculation,

the incubation period in the initial stage of corrosion is excluded. That is, the paint blistering width of the conventional steel after 12 weeks and that of the developed steel after 16 weeks were used. The repainting period of the conventional steel in severe corrosion environments, where corrosion controls the life of a bridge, is 30 years³⁾. From the power regression approximation curve, the paint blistering width of the conventional steel after 30 years is 49 mm. From this, the time until the developed steel reaches the same paint blistering width is calculated as 73 years. Accordingly, it can be estimated that the interval until repainting is extended to 73 years by the developed steel, in comparison with the 30 year repainting interval of the conventional steel. Based on this, in comparison with the conventional steel, it is thought that the repainting interval can be extended by 2.4 times by applying the developed steel.

4.2 Results of Analysis of Rust Layer

Figure 6 shows the results of the STEM observation of the rust layer. The broken lines in the HAADF-STEM images show one rust particle. The rust particles observed in the developed steel were fine in comparison

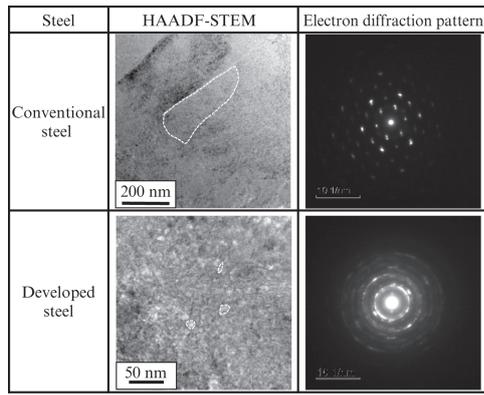


Fig. 6 STEM observation of rust layer formed in accelerated corrosion test

with the conventional steel. The electron diffraction images show a spotty shape for the conventional steel and a ring shape for the developed steel. This means that a large number of rust particles exist in the 200 nm irradiation range of the electron beam in the developed steel. Moreover, the electron diffraction pattern also revealed that the rust layer of the developed steel consists mainly of Fe_3O_4 . Based on these facts, it can be thought that fine rust particles form on the developed steel, and these fine particles suppress penetration of corrosion factors in the rust layer to the surface of the base steel. Here, it may be noted that Samusawa et al.⁵⁾ examined the corrosion suppression effect of rust refinement using classical molecular dynamics, and clarified the fact that the mobility of water molecules between rust particles decreases in the case of fine Fe_3O_4 particles as compared with coarse particles.

Next, Fig. 7 shows the results of the evaluation of cation selective permeability. For comparison, the figure also shows the results of measurements of the membrane potentials of the commercial anion and cation selective membranes. A negative membrane potential slope shows anion selectivity, and a positive slope shows cation selectivity. The slope of the W bearing steel is positive, and the slope is also steep in comparison with that of the conventional steel, indicating strong cation selective permeability. This means the W bearing steel suppresses penetration of chloride ions in the rust layer in comparison with the conventional

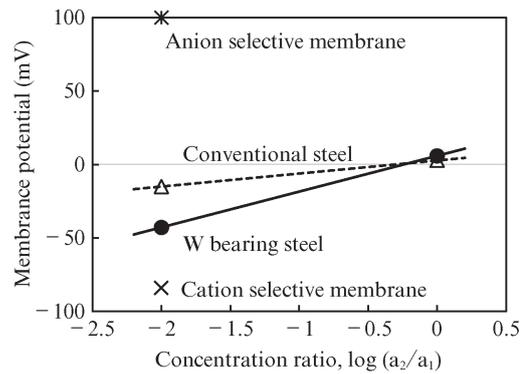


Fig. 7 Measurement of membrane potential

steel. In this connection, Itagaki et al.¹¹⁾ performed measurements of the membrane potential of artificially-synthesized rust membranes, and as a result, experimentally clarified the fact that a rust layer on which WO_4^{2-} was adsorbed showed cation selective permeability. As a computational science approach, using the ESM-RISM (effective screening medium-reference interaction site model) method, Samusawa et al.⁶⁾ showed that chloride ions are excluded at the surface of a rust layer on which WO_4^{2-} had adsorbed.

5. Mechanical Properties of Developed Steel

5.1 Chemical Composition and Mechanical Properties

Table 2 shows the chemical composition of the developed steel produced by an actual mill. Cu, Ni, Sn and W are added as corrosion resistant elements. Table 3 shows the tensile properties, Charpy impact properties and Z-direction (through thickness) tensile property of the base metal. The developed steel satisfies the chemical composition, tensile properties and Charpy impact properties specified in JIS G 3106, and its Z-direction tensile property also satisfies the standard value for Z35 grade in JIS G 3199, indicating satisfactory lamellar tearing resistance.

5.2 Weldability and Mechanical Properties of Welded Joints

Table 4 shows the results of a y-type weld crack test

Table 2 Chemical composition of developed steel

Grade	Chemical composition (mass%)									Ceq ^{*1}	P _{CM} ^{*2}
	C	Si	Mn	P	S	Cu	Ni	Sn	W		
490 MPa	0.12	0.34	1.31	0.008	0.001	Add	Add	Add	Add	0.36	0.20
570 MPa	0.09	0.34	1.54	0.007	0.002	Add	Add	Add	Add	0.40	0.19

*1) $C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$

*2) $P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B$

Table 3 Mechanical properties of developed steel

Steel	Grade	Thickness (mm)	Tensile test ^{*3}				Charpy impact test ^{*4}			Z-direction tensile test ^{*5}	
			Specimen	YS (N/mm ²)	TS (N/mm ²)	El (%)	Position	Test temp. (°C)	Absorbed energy (J)	RA (%)	
										Each	Ave.
Developed steel	490 MPa	25	JIS 1A	427	542	25.7	1/4t	0	347	83, 82, 83	83
		50	JIS 1A	458	558	34.7	1/4t	0	315	72, 76, 77	75
	570 MPa	25	JIS 5	523	651	39.4	1/4t	-5	258	80, 80, 79	80
		50	JIS 5	607	698	39.2	1/4t	-5	280	76, 76, 73	75
JIS G 3106 Spec.	SM490YB -Z35	16<t≤40	JIS 1A	≥355	490	≥19	1/4t	0	≥27	≥25	≥35
		40<t≤75	JIS 1A	≥335	~610	≥21					
	SM570 -Z35	16<t≤40	JIS 5	≥450	570	≥26	1/4t	-5	≥47	≥25	≥35
		40<t≤75	JIS 5	≥430	~720	≥20					

*3) C direction *4) L direction *5) JIS G 3199, Z35

Table 4 Results of y-type weld crack test of developed steel

Grade	Welding process ^{*6}	Welding consumable ^{*7}	Thickness (mm)	Preheating temperature to prevent root cracking (°C)
SM490YB	SMAW	LB-W52CL	50	0
	GMAW	DW-50WCL	50	25
SM570	SMAW	LB-W62CL	50	0
	GMAW	DW-60WCL	50	25

*6) SMAW: Shielded Metal Arc Welding, GMAW: Gas-shielded Metal Arc Welding

*7) LB-W52CL (4.0 mm), DW-50WCL (1.2 mm ϕ), LB-W62CL (4.0 mm), DW-60WCL (1.2 mm ϕ); KOBE STEEL, Ltd.

of the developed steel. Root cracking was not observed in shielded metal arc welding (SMAW) with a preheating temperature of 0°C or in gas-shielded metal arc welding with a preheating temperature of 25°C. **Table 5** shows the mechanical properties of the welded joints. From the viewpoint of corrosion resistance of painted steel, a welding consumable manufactured by Kobe Steel, Ltd. for nickel-added weathering steel was used here. The mechanical properties of the welded joints

using the developed steel satisfied the standard of JIS G 3106, and the welded joints displayed properties equal to those of welded joints using the conventional steel.

6. Effect of Life Cycle Cost Reduction

A trial calculation of the LCC of a bridge in case the developed steel is applied was performed. The assumptions of the trial calculation were as follows:

- The bridge is used in a severe corrosion environment with a high concentration of airborne salt, such as a coastal area.
- Maintenance and repairs are limited to repainting.
- Material, construction and other costs are calculated by reference to construction price, etc., assuming that the bridge is a steel 3-span continuous non-composite minimized I-girder bridge with a bridge length of 114 m and a steel weight of 211 t.
- The repainting interval is extended from the 30 years of the conventional steel to 73 years by applying the developed steel.

Figure 8 shows the results of the trial calculation of LCC. The initial cost when the conventional steel is

Table 5 Mechanical properties of welded joint of developed steel

Steel	Grade	Thickness (mm)	Welding process ^{*8}	Welding consumable ^{*9}	Heat input (kJ/mm)	Tensile test	Charpy impact test		
						TS (N/mm ²)	Test temp. (°C)	Notch position	Absorbed energy (J)
Developed steel	490 MPa	25	GMAW	DW-50WCL	2.0	553	0	Weld metal HAZ 1 ^{*10}	116 166
	570 MPa	50	SAW	US-W62CL ×MF-38	4.1	604	-5	Weld metal HAZ 1 ^{*10}	86 202
JIS G 3106 Spec.	SM490YB	—	—	—	—	≥490	0	—	≥27
	SM570	—	—	—	—	≥570	-5	—	≥47

*8) GMAW: Gas-shielded Metal Arc Welding, SAW: Submerged Arc Welding

*9) DW-50WCL (1.2 mm ϕ), USW-62CL (4.0 mm ϕ)×MF-38: KOBE STEEL, Ltd.

*10) Position of 1 mm from fusion line

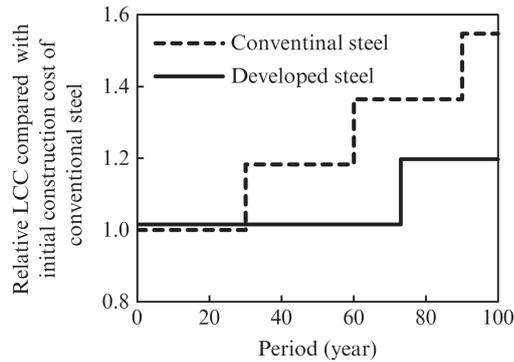


Fig. 8 Calculation examples of life cycle cost



Fig. 9 Appearance of tank applied with developed steel

applied is defined as 1, and the results are shown as relative values with respect to that value. In this trial calculation, the initial cost of using the developed steel is slightly higher than that of the conventional steel, but because repainting is reduced from 3 times to 1 time, a substantial reduction in repainting costs is achieved over a 100 year period. Based on the results of this trial calculation, in comparison with the conventional steel, it is thought that repainting costs can be reduced by 64 % by applying developed steel, even considering the higher initial cost of the developed steel.

7. Application to Actual Structure

A paint life extension effect can be expected in bridges and construction and industrial machinery, tanks, etc. located in coastal areas by using the developed steel. The developed steel has already been applied to coastal structures such as storage tanks (Fig. 9) and cranes, and application to bridges is also planned.

8. Conclusion

This report described the painted corrosion resistance, mechanical properties of the base metal and welded joints and expected effect of application to actual structures of a corrosion resistant steel for extended paint life (EXPAL™) developed by JFE Steel

Corporation. The main points of the paper are summarized below.

- (1) In the developed steel, a protective rust layer is formed under the paint by using a combination of corrosion resistant elements which are added to the steel to refine rust particles and impart cation selective permeability to the rust layer. This protective rust layer suppresses paint blistering by preventing corrosion of the base steel, which is achieved by preventing penetration of corrosion factors to the steel surface.
- (2) In a 64-week laboratory accelerated corrosion test, the developed steel reduced the paint blistering width by 33 % in comparison with the conventional steel. Furthermore, a reduction in the paint blistering width similar to that obtained in the laboratory test was also observed in a 4.2 year atmospheric exposure test in the Okinawa region.
- (3) The repainting interval of the developed steel estimated from the laboratory accelerated corrosion test was 73 years, compared to 30 years for the conventional steel, thereby extending the repainting interval by 2.4 times.
- (4) The developed steel satisfies the standard values for all strength grades in JIS G 3106. It also satisfies the standard value for Z35 (through-thickness tensile property) in JIS G 3199, and thus has satisfactory lamellar tearing resistance. Weldability and the properties of welded joints were on the same levels as those of the conventional steel.
- (5) A trial calculation of the life cycle cost of a bridge in which the developed steel is applied was performed, focusing on repainting costs. Assuming a 100-year service period, a 64 % reduction in repainting costs in comparison with the conventional steel is thought to be possible by applying the developed steel, even considering the higher initial cost of the developed steel.

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