Development of New Weathering Steel for High Salinity Environment for Coastal Use

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Abstract:

The new high performance weathering steel was developed with less nickel content than conventional Ni added weathering steel to be applicable in the region of large amount of airborne salt. It was verified that the developed steel had almost same corrosion resistance as conventional Ni added weathering steel (JFE-ACL-Type1, 1.5Ni-0.3Mo bearing steel). The mechanical properties of a base material were satisfied the specification of conventional weathering steel (JIS G 3114, JIS SMA) and the weldability and properties of welded joint were equivalent to JIS SMA. Developed steel has an advantage in economical efficiency by applying the new alloy design reducing the amount of expensive alloying elements.

1. Introduction

Increases in the operation and maintenance (O&M) costs and deterioration upgrade costs of social infrastructure are expected in the future, and a trial calculation based on an estimate ¹⁾ by Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) indicated that these costs will increase to approximately 1.2 times their current levels by around 2050. Accordingly, the need for reduction of the life cycle cost (LCC) of steel structures which are expected to be used over the long term is also predicted to increase in the future. In the field of bridges, weathering steels, which make it possible to reduce LCC, are currently applied to about 20% of bridges ²⁾. Because weathering steels can be applied in an unpainted condition, they make an important contribution to lower LCC by reducing the

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maintenance costs associated with repainting $^{3)}$.

Conventional weathering steel (JIS G 3114, hereinafter, JIS SMA) can be applied without painting in regions where the amount of airborne salt does not exceed 0.05 mg•NaCl/dm²/day (hereinafter, mdd)⁴). However, JIS SMA cannot be used in environments with higher amounts of airborne salt (high salinity environments), such as regions close to the coast and regions where road deicing agents are used in wintertime. Ni added weathering steels with higher corrosion resistance are applied in such areas. Ni added weathering steels contain approximately 1.0 to 3.0 mass% of added Ni in order to increase corrosion resistance in high salinity environments ⁵⁻⁸⁾. JFE Steel developed and commercialized two types of Ni added weathering steels, JFE-ACL-Type 1 (1.5 mass% Ni-0.3 mass% Mo) and Type 2 (0.3 mass% Cu-2.5 mass% Ni), corresponding to the severity of the environment where the bridge is to be constructed, and these Ni added weathering steels already have a record of use in many bridges.

However, because Ni is an expensive raw material, the high content of Ni in Ni added weathering steels has become a factor in higher production costs. Although Ni added weathering steels are applied in regions that exceed the applicable range of JIS SMA, this sometimes leads cost increases because both JFE-ACL-Type 1 and Type 2 have excessive corrosion resistance for the corrosion environment. Therefore, a new material with excellent economy and appropriate corrosion resistance for intermediate corrosion environments had been demanded.

To meet this need, JFE Steel developed a new weathering steel (LALACTM-HS) which holds the Ni

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content to a low level and can also be used without painting in high salinity environments ⁹⁾.

This report describes the corrosion resistance concept for securing high corrosion resistance while holding the Ni content to a low level, and the results of verification of the corrosion resistance of the steel designed on the basis of that concept and the mechanical properties required in steel for structural use.

2. Corrosion Resistance Design

Ni added weathering steels applicable to high salinity environments contain a large amount of added Ni, which is widely dispersed in the rust layer and forms a dense rust layer which suppresses corrosion by preventing penetration of Cl to the steel surface ^{5–6}. However, the large amount of Ni that must be added to these steels is an issue. In JIS SMA, corrosion is suppressed because added Cu, Ni and Cr form a dense rust layer with a high protective property ^{10–14}, but among these elements, Cr has an adverse effect on corrosion resistance in high salinity environments in some cases.

In this development, we discovered that Sn and Nb display high corrosion resistance in high salinity environments, even when added in trace amounts, and added these elements to form a highly-protective dense rust layer without depending on heavy addition of Ni. These elements form a dense rust layer by concentrating locally in the lower layer of the rust layer, thereby suppressing penetration of chloride ions to the steel surface. The protective property was enhanced by adding the same levels of Cu and Ni as in JIS SMA, and deterioration of corrosion resistance in high salinity environments was avoided by not adding Cr. The corrosion resistance design described above made it possible to secure satisfactory corrosion resistance in high salinity environments, while also holding Ni addition to a low level.

Figure 1 shows a schematic diagram of the mecha-



Fig. 1 Corrosion resistant mechanism of developed steel

nism of corrosion resistance. Cu and Ni are dispersed in the inner layer rust, and a dense rust layer is formed by concentration of Sn and Nb. Penetration of the chloride ion, which is a corrosion factor, is suppressed by the dense rust layer formed in this manner, and as a result, the corrosion reaction is suppressed.

3. Experimental Method

3.1 Atmospheric Exposure Test

An atmospheric exposure test was carried out to evaluate corrosion resistance in an actual environment. As the atmospheric exposure test method, assuming a severe actual environment in which deposited salt is not washed away by rain water, the under-the-eaves exposure test method was adopted, as rain does not fall on the samples. The test materials were the developed steel (0.3 mass% Cu-0.3 mass% Ni-Sn-Nb added steel), JIS SMA (0.3 mass% Cu-0.5 mass% Cr-0.2 mass% Ni added steel) and JFE-ACL-Type 1 (1.5 mass% Ni-0.3 mass% Mo added steel). After the test pieces were recovered and the rust was removed, the test pieces were weighed, and the amount of corrosion was evaluated by calculating the average thickness loss of one side from the difference of the steel weight before and after the test and the surface area of the test piece.

3.2 Analysis of Rust Layer

Characterization of the rust layer of the developed steel was carried out by the following procedures.

1) Observation of rust layer cross section by polarization microscope

After the atmospheric exposure test, specimens for observation were prepared by cutting the test pieces and embedding the specimens in epoxy resin, followed by dry-type ethanol polishing and diamond spray finishing.

2) Quantitative evaluation of rust composition by XRD

The rust layer that had formed on the test pieces was classified as an upper layer consisting of loose scale and a lower layer tightly adhering to the base steel, and was removed with a scraper and recovered. The lower layer of the recovered rust was pulverized and tested as powdery rust. The measurement was conducted using CuK α beam radiation under the conditions of 40 kV, 40 mA and a step angle of 0.02°.

3) Evaluation of elemental distribution in rust layer by EPMA

As specimens, the specimens used in the observation of the rust layer cross section with the polarization microscope were used. The EPMA observation conditions were an accelerating voltage of 15.0 kV, irradiation current of 5.0×10^{-7} A, beam diameter of 1 μ m and irradiation time of 25 ms.

4) Fineness evaluation of rust layer by STEM selectedarea electron diffraction

Specimens were prepared by cutting out a thin film from the rust layer using a focused ion beam. The conditions of the selected-area electron diffraction by STEM were 200 kV and an aperture size of 200 nm.

4. Experimental Results and Discussion

4.1 Evaluation of Corrosion Resistance by Atmospheric Exposure Tests

Figure 2 shows the time-dependent change of corrosion loss when the developed steel, JFE-ACL-Type 1 and JIS SMA were exposed in a beach environment in Okinawa for 3 years. The amount of airborne salt in the exposure test area was 0.77 mdd. Here, the test pieces were exposed in a high salinity environment in order to compare the salt corrosion resistance of the developed steel and the other steels. From Fig. 2, it can be understood that the corrosion loss of the developed steel was smaller than that of JIS SMA by a wide margin, and was almost the same as that of JFE-ACL-Type 1. This result confirmed that the developed steel has higher corrosion resistance than JIS SMA in high salinity environments, and has substantially the same corrosion resistance as JFE-ACL-Type 1.

Next, atmospheric exposure tests were conducted in various other regions with different amounts of airborne salt in order to clarify the applicable limit of the developed steel with respect to airborne salt. **Figure 3** shows the relationship between the corrosion loss of the developed steel after a 1-year exposure test and the amount of airborne salt. The corrosion loss of the developed steel has a positive correlation with the amount of airborne salt. The salt resistance performance of the developed steel was evaluated on the basis of these atmospheric exposure test results. According to a Technical Report of the Japanese Society of Steel Construction¹⁵⁾, when evaluating the applicability of weathering steels in a short period, application is judged possible if the amount of corrosion loss in a 1-year atmospheric exposure test is 0.03 mm or less. When this criterion was applied to the results of the atmospheric exposure tests in the present research, it was estimated that the developed steel can be applied at airborne salt levels of up to 0.27 mdd.

The applicable distance from the coastline on the Sea of Japan (Kanazawa) was estimated for the developed steel and JFE-ACL-Type 1 by the corrosion prediction equation. The results showed that JFE-ACL-Type 1 is applicable at a minimum distance of 1.6 km from the coastline, and the developed steel can be applied at a minimum distance of 4.4 km. In contrast, the distance for application of JIS SMA in the same environment is at least 20 km from the coastline ³). Based on these calculations, the developed steel can be used as a substitute for JFE-ACL-Type 1 in 85% of the applicable range of JFE-ACL-Type 1 in coastal regions: $(20 \text{ km} - 4.4 \text{ km}) \times 100 / (20 \text{ km} - 1.6 \text{ km}).$

4.2 Analysis of Rust Layer Structure

In order to study the mechanism of corrosion resistance of the developed steel, an analysis of the rust layer that formed on the specimens in the atmospheric exposure test was carried out.

Figure 4 shows polarization microscope images of the cross sections of the rust layer of test materials exposed for 2 years in Chiba (amount of airborne salt: 0.26 mdd). It has been reported that the "dark rust layer" is a dense rust layer and is effective for securing corrosion resistance, while the "bright rust layer"



Fig. 2 Time-dependent changes of corrosion loss



Fig. 3 Relationship between corrosion loss of developed steel and amount of airborne salt

(polarization layer) contains many cracks and has a low corrosion protection property ¹⁶). In the rust layer of JIS SMA, a polarization layer also exists close to the base steel under the rust layer, and a dark rust layer has not formed continuously in the lower layer. On the other hand, in the developed steel, a dark rust layer has formed continuously in the lower layer of the rust layer. Similarly, a dark rust layer has formed continuously in the lower layer of the rust layer of JFE-ACL-Type 1. Thus, in comparison with the rust layer of JIS SMA, it is estimated that the developed steel has a function which forms a dense rust layer, like that observed in JFE-ACL-Type 1.

Next, rust samples were taken from the test materials exposed for 2 years in Chiba, and a quantitative analysis was carried out by XRD. The test materials were the developed steel, JFE-ACL-Type 1, JIS SMA and JIS SM. The results are shown in **Table 1**. In order





to evaluate the protective property of the rust layers from the results of the quantitative analysis, the various steels were compared using the rust protection index (α + am) / γ^{*17} , which is an index for evaluating the protective property of rust. Here, α : α -FeOOH, am: X-ray amorphous rust and γ^* : γ -FeOOH + β -FeOOH + Fe₃O₄. Figure 5 shows the rust protection indexes of the steels exposed for 2 year in Chiba, where larger values mean a higher rust protection property. The order of the rust protection indexes of the steels is JIS SM < JIS SMA < JFE-ACL-Type 1 < Developed steel, indicating that the developed steel shows the highest rust protection index. Based on this, it can be inferred that the developed steel forms a rust layer with a higher protective property than JIS SMA, as in JFE-ACL-Type 1.

Figure 6 shows the EPMA elemental mapping of the cross section of the rust layer of the developed steel. The elements measured here were Cl, which is the main corrosion factor, and the corrosion resistant elements Sn and Nb. The measurement range was the same position as that of the observation with the polarization microscope shown in Fig. 4. The solid white lines in the figures show the interface between the base steel and the rust layer. Cl was distributed mainly on the upper rust layer side, and the amount of Cl distribution near the interface between the base steel and the rust layer was slight. On the other hand, Sn and Nb were concentrated in the region below the broken white lines, that is, in the lower layer of the rust layer. More-



Fig. 5 Rust protection index of various steels

| Table 1 Rust composition of vario | us steels |
|-----------------------------------|-----------|
|-----------------------------------|-----------|

| α-FeOOH | | β -FeOOH | γ-FeOOH | Fe ₃ O ₄ | X-ray amorphous rust |
|-----------------|------|----------------|---------|--------------------------------|----------------------|
| JIS SM | 18.4 | 10.1 | 12.3 | 0.0 | 59.2 |
| JIS SMA | 15.9 | 13.6 | 7.1 | 0.0 | 63.4 |
| Developed steel | 16.6 | 11.5 | 5.7 | 0.0 | 66.3 |
| JFE-ACL-Type1 | 14.7 | 14.9 | 3.5 | 0.0 | 67.0 |

over, the position where Sn and Nb had concentrated coincided with the region observed as a dark rust layer in the polarization microscope image shown in Fig. 4. Based on these results, it can be estimated that penetration of Cl to the interface between the rust layer and the base steel was suppressed by concentration of the



Fig. 6 EPMA mapping of cross section of rust layer a) Cl b) Sn c) Nb

rust resistant elements to the lower rust layer.

Figure 7 shows an electron diffraction image of the Sn, Nb-enriched region of the rust layer. Since the image displays a halo pattern, which is obtained from the amorphous structure of the rust layer, it can be inferred that a fine, amorphous rust layer has formed.

Based on the analytical results, it is thought that the developed steel shows excellent corrosion resistance because a dense rust layer is formed by the effect of the corrosion resistant elements, and this dense rust layer suppresses penetration of the corrosion acceleration factor Cl through the rust layer.

5. Mechanical Properties of Developed Steel

The following presents the results of an evaluation of the mechanical properties required in steels for structural use, using plates of the developed steel pro-



Fig. 7 Electron diffraction image of rust layer at Sn and Nb concentrated area

| Table 2 | Chemical composition of developed st | teel |
|---------|--------------------------------------|------|
|---------|--------------------------------------|------|

| | Curada | Chemical composition (mass%) | | | | | | | Con | م | |
|--------------------------|---------|--|------|------|-------|-------|------|------|--|-------|------|
| | Grade | С | Si | Mn | Р | S | Cu | Ni | Corrosion resistant elements | Ceq | PCM |
| | 400 MPa | IPa 0.08 0.20 0.96 0.009 0.002 0.30 0.30 | 0.26 | 0.15 | | | | | | | |
| Developed 49 steel 57 | 490 MPa | 0.08 | 0.53 | 1.62 | 0.008 | 0.003 | 0.32 | 0.32 | Total content of Nb, Sn shall be less than 0.15 | 0.38 | 0.20 |
| | 570 MPa | 0.08 | 0.48 | 1.57 | 0.008 | 0.003 | 0.31 | 0.31 | | 0.36 | 0.19 |

Ceq = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14

 $P_{\rm CM} = C + \text{Si}/30 + \text{Mn}/20 + \text{Cu}/20 + \text{Ni}/60 + \text{Cr}/20 + \text{Mo}/15 + \text{V}/10 + 5\text{B}$

| Table 3 | Mechanical | properties of | developed | steel | |
|---------|------------|---------------|-----------|-------|--|
| | | | | | |

| | Th | | | Tensi | Charpy impact test | | | |
|---------------------------------|----------|--|--|-------------------------|--------------------|--------|--------------------|-----------|
| | Grade | (mm) | $\begin{array}{c} \text{YS} (\text{N/mm}^2) \\ 16 < t \leq 40 \end{array}$ | TS (N/mm ²) | Specimen | El (%) | Test temp. (°C) | vE (J) |
| | 400 MPa | 25 | 354 | 456 | JIS 1A | 29 | 0 | 268 |
| Developed steel | 490 MPa | 25 | 471 | 549 | JIS 1A | 31 | 0 | 312 |
| | 570 MPa | 25 | 523 | 642 | JIS 5 | 39 | -5 | 218 |
| | SMA400CW | 16 <t≦50< td=""><td>235≦</td><td>400~540</td><td>JIS 1A</td><td>21≦</td><td>0</td><td>47≦</td></t≦50<> | 235≦ | 400~540 | JIS 1A | 21≦ | 0 | 47≦ |
| JIS G 3114 - Specification - | SMA490CW | 16 <t≦50< td=""><td>355≦</td><td>490~610</td><td>JIS 1A</td><td>19≦</td><td>0</td><td>47≦</td></t≦50<> | 355≦ | 490~610 | JIS 1A | 19≦ | 0 | 47≦ |
| | SMA570W | 16 <t< td=""><td>450≦</td><td>570~720</td><td>JIS 5</td><td>26≦</td><td>-5</td><td>47≦</td></t<> | 450≦ | 570~720 | JIS 5 | 26≦ | -5 | 47≦ |

YS: yield strength, TS: tensile strength, El: elongation, vE: absorbed energy, Position of charpy impact test: 1/4t

duced with actual equipment.

Table 2 shows an example of the chemical composition of the developed steel. Cu, Ni, Sn and Nb were added as corrosion resistant elements. **Table 3** shows an example of the tensile properties and Charpy impact properties of the developed steel for each strength grade. The developed steel satisfied the standard values for mechanical properties of JIS SMA 400CW, 490CW and 570W. **Table 4** shows the results of a y-groove weld cracking test conforming to JIS Z 3158 using the tensile strength 490 MPa class and 570 MPa class developed steel. The preheating temperatures for preventing root cracking were 0°C and 25°C, and weldability was satisfactory.

Table 5 shows an example of the mechanical properties of welded joints of the TS 490 MPa class and 570 MPa class developed steel. The welded joints were prepared using a welding consumable for use with the Ni added weathering steel (JFE-ACL-Type 1). The welded joints using the developed steel exceeded the standard values for the strength of TS 490 MPa class and 570 MPa class steel plates, and also had satisfactory flexural properties. From this, it can be said that welding similar to that with the conventional steel is possible in application to actual bridges.

| Table 4 | Weldability of developed steel |
|---------|--------------------------------|
|---------|--------------------------------|

| | | | | | Preheating |
|--------------------|---------|--------------------|---------------------|-------------------|---|
| Grade | | Welding process | Welding consumables | Thickness (mm) | temperature to prevent root cracking (°C) |
| Developed steel | 490 MPa | CMAW | ID W52CI | 25 | 0 |
| | | SMAW | LD-WJ2CL | 50 | 0 |
| | | GMAW | MV 50WCI | 25 | 0 |
| | | | MA-JUWCL | 50 | 0 |
| | 570 MD | SMAW | I D W62CI | 25 | 0 |
| | | SMAW | LD-W02CL | 50 | 25 |
| | 570 MPa | CMAW | DW (OWCI | 25 | 0 |
| | | GMAW | Dw-60WCL | 50 | 0 |

SMAW: Self Metal Arc Welding, GMAW: Gas Metal Arc Welding, Welding consumable: KOBE STEEL, Ltd.

6. Application to Actual Structures

The developed steel has already been applied to bridges in Japan. **Figure 8** shows an example of application to a bridge with a length of 194 m on an expressway. In addition to bridges, the developed steel can also be applied to various other steel structures such as steel towers located in regions near the coast.

7. Conclusion

A new weathering steel (LALACTM-HS), which can be applied without painting in high salinity environments near the coastline and in regions where road deicing agents are used in winter, was developed. The features and mechanical properties of the developed steel are summarized below.

(1) It was found that corrosion resistance in high salinity environments can be enhanced without heavy addition of nickel by adding Sn, Nb, Cu and Ni as effective elements for improvement of corrosion resistance, and a new weathering steel with corrosion resistance approximately equal to that of JFE-



Fig. 8 Appearance of the bridge in which developed steel is applied

| Grade | | Waldaina | Thielenase | Walding | Heat input (kJ/mm) | Tensile test Charpy impac | | py impact test | |
|-------------------------------|----------|----------|------------|--------------------|-----------------------|---------------------------|------------|----------------|-------------|
| | Grade | process | (mm) | consumable | | TS | Test temp. | Notch | $_{v}E_{0}$ |
| | | | | | | (N/mm^2) | (°C) | position | (J) |
| Developed steel | 490 MPa | GMAW | 25 | DW-50WCL | 2.0 | 556 | 0 | Weld Metal | 121 |
| | | | | | | | | HAZ1 | 257 |
| | 570 MPa | SAW | 50 | US-W62CL ×MF-38 | 4.1 | 641 | -5 | Weld Metal | 86 |
| | | | | | | | | HAZ1 | 295 |
| JIS G 3114 Speci- fication | SMA490CW | _ | _ | _ | _ | ≧490 | 0 | - | ≧47 |
| | SMA570W | _ | _ | _ | _ | ≧ 570 | -5 | _ | ≧47 |

Table 5 Mechanical properties of developed steel

GMAW: Gas Metal Arc Welding, SAW: Submerged arc welding, TS: tensile strength, vE: absorbed energy, Welding consumable: KOBE STEEL, Ltd., HAZ1: Position of 1 mm from fusion line

ACL-Type 1 in high salinity environments was developed.

(2) The developed steel possesses mechanical properties, weldability and welded joint performance equal to those of JIS SMA in all the strength grades of tensile strength 400, 490 and 570 MPa class, and has a product lineup equivalent to JIS SMA400AW, 400BW, 400CW, 490AW, 490BW, 490CW and 570W.

Because the developed steel can be used in steel structures in high salinity environments without painting, this new product makes an important contribution to reduction of the life cycle cost (LCC) of steel structures by reducing maintenance and operation costs associated with repainting, etc.

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