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Coating Deterioration and Corrosion Behavior of Ship Using Corrosion Resistant Steel for Ballast Tank “JFE-SIP^{TM}-BT”†

SHIOTANI Kazuhiko[*1]   NAKAMURA Masayoshi[*2]

Abstract:

The corrosion resistant steel for ballast tank “JFE-SIP^{TM}-BT”, which prolongs coating life by preventing coating deterioration, has been developed. The developed steel has been applied to ballast tanks of a very large ore carrier (VLOC). This paper reports evaluation results on coating deterioration and corrosion behavior of the developed steel after 5-year use. The parts applied were upper deck plates and longitudinal members of upper deck of ballast tanks. Doubling plates were welded to upper deck plates of ballast tanks and were coated simultaneously with the upper deck plates. The coating deteriorated area, corrosion depth and corrosion volume of the developed steel were 75%, 84%, and 58% of those of the conventional steel, respectively. The deteriorated length at the edge of longitudinal members in the developed steel was about 65% of that in the conventional steel. The prevention effect of coating deterioration by the developed steel was confirmed under the actual ballast tank condition.

1. Introduction

When a ship sails without cargo, seawater is loaded in its ballast tanks to stabilize the ship. Although a heavy duty coating is applied to the ballast tanks to withstand corrosion by seawater, the coating is affected by a deterioration process which includes rusting, blistering of coating film by rust, etc.[1)]. Therefore, recoating is sometimes necessary, but the high cost is a problem. As an additional problem, scaffolding is necessary when performing recoating, but depending on the location, it may be difficult to assemble scaffolds; and, in some cases, recoating may also be difficult. Therefore, from the viewpoint of life cycle cost reduction, JFE Steel began development of a corrosion resistant steel which suppresses coating deterioration (rusting, blistering by rust) and makes it possible to prolong the coating life (period until recoating).

Figure 1 shows the concept of the development of this corrosion resistant steel for ballast tanks. The deterioration process of coatings can be divided into a stage in which there is no deterioration of the coating (1st Stage) and a stage in which the steel material corrodes and the coating deteriorates (2nd Stage). The developed corrosion resistant steel suppresses deterioration of the coating in the latter stage and thereby prolongs the coating life. As shown in Fig. 1, the concept of corrosion prevention is based on formation of a protective rust layer, which suppresses permeation of corrosion factors to the substrate surface, on the substrate steel by the

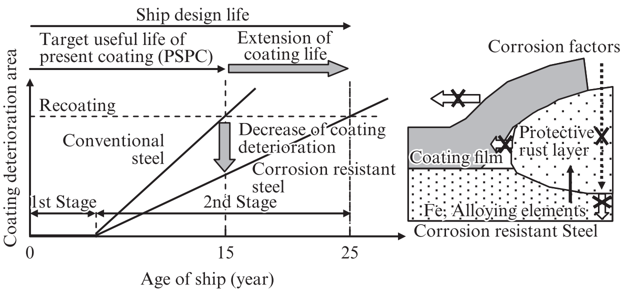

Fig. 1 Concept of development

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*1 Senior Researcher Manager,
Corrosion Resistant Steel Res. Dept.,
Steel Res. Lab.,
JFE Steel

*2 Staff Manager,
Plate Sec., Products Design & Quality Control for Steel Products Dept.,
West Japan Works,
JFE Steel

action of alloying elements in the steel. As the coating life, assuming the present coating life is 15 years (target useful life in coating specifications provided by PSPC[2)]), the aim is to extend this to 25 years, which is the general ship design life[3, 4)].

Coating deterioration of the area around the upper deck is most severe in ballast tanks[5)]. First, therefore, JFE Steel carried out a study of the corrosion environment around the upper deck in an actual ballast tank[5)]. The results revealed that this corrosion environment is characterized by repetition of dryness and wetness. The conditions for laboratory corrosion tests were determined based on the results of these measurements[6)], and the coating deterioration behaviors of steels with various compositions were observed and evaluated. Those results were also verified by exposure tests of coupons in the ballast tanks of an actual ship, which were conducted over a maximum period of 2 years[7)]. The product which was developed as a result of this research is the corrosion resistant steel for ballast tanks, JFE-SIP™-BT.

The developed steel was applied to an actual ship. This paper presents the results of an evaluation of the deterioration behavior of the coating after use for approximately 5 years, together with the results of an evaluation of the corrosion behavior of the steel. The developed steel was applied to the upper decks of ballast tanks and to the longitudinal members of the ballast tank upper decks. Sample plates (doubling plates) were welded to the upper decks of the ballast tanks, and the coating deterioration behavior and corrosion behavior from artificial scratches on the coating were observed. In the longitudinal members, the coating deterioration behavior at the edges of the members was observed.

2. Experimental Method

2.1 Test Ship and Doubling Plates

The test ship was a very large ore carrier (VLOC). JFE-SIP™-BT was applied to No. 5WBT, as shown in **Fig. 2**. The test parts were the upper deck and the longitudinal members of the upper deck. The coating specification was tar epoxy 150 μm×2 coats. The route of this ship is mainly a round-trip voyage between the Philippines and Brazil. The ballast tanks are filled with seawater when sailing without cargo and are not filled when sailing loaded.

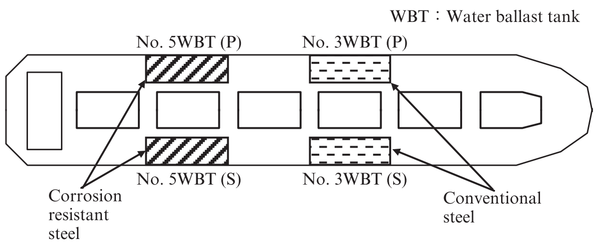

Fig. 2 Application tank of corrosion resistant steel and investigation tank of conventional steel

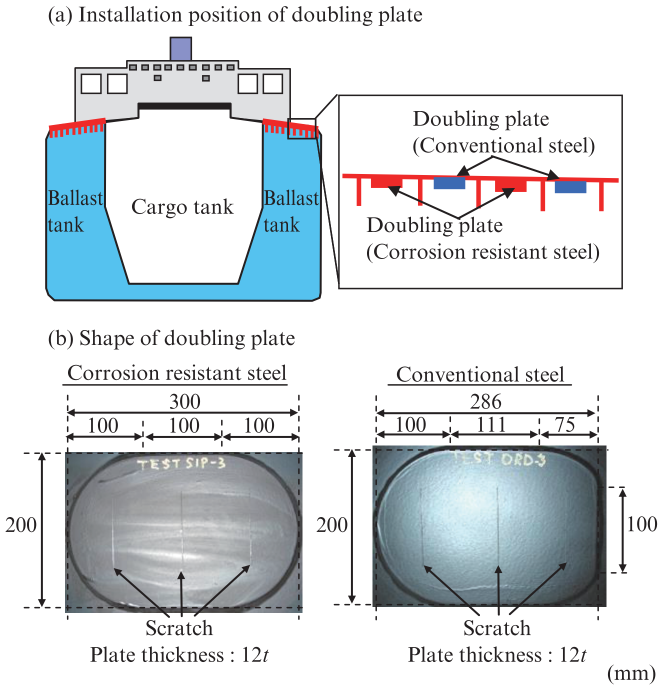

Fig. 3 Installation position and shape of doubling plate

In order to simulate the progress of coating deterioration from coating defect parts (progress of rust and blistering of coating film by rust), elliptical doubling plates were prepared, as shown in **Fig. 3**, and installed on the upper decks of No. 3WBT and No. 5WBT. The doubling plate preparation and installation process was as follows: (1) Shop primer was coated on the plates with a target film thickness of 15 μm, and the plates were mounted on the upper deck by fillet welding. (2) The plates were coated with tar epoxy with a specification of 150 μm×2 coats at the same time on the hull. (3) Three scratches (length: 100 mm each) extending to the steel substrate were made on each of the doubling plates. Comparatively wide scratches were made at the scratches on the two sides using a BM-2P acrylic cutter (manufactured by NT Inc.), and a comparatively narrow scratch was made at the center scratch using a HB5K cutter (Olfa Corp.). Two conventional steel plates and 2 corrosion resistant steel plates were installed in each of the four ballast tanks shown in Fig. 2, for a total of 16 doubling plates.

2.2 Evaluation of Coating Deterioration and Corrosion Behavior

2.2.1 Doubling plates

Photographs of all the doubling plates were taken about 5 years after completion of the ship. In addition, all the plates were recovered by cutting the fillet welds,

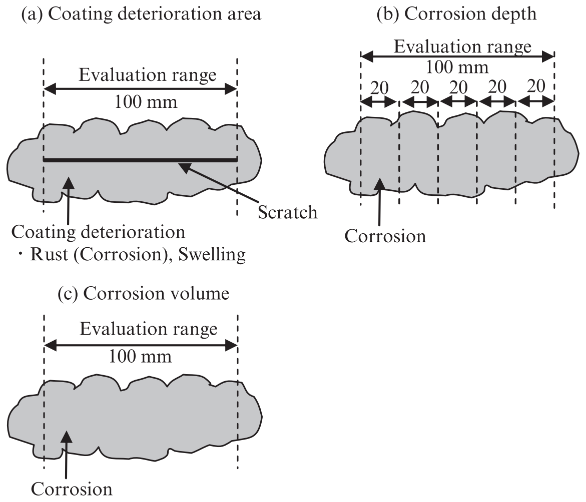

Fig. 4 Evaluation range of coating deterioration area, corrosion depth and corrosion volume at scratch part on doubling plate

and the coating films and rust were removed from the plates. As evaluation items, the coating deterioration area, corrosion depth, and corrosion volume at the scratched parts were measured. The evaluation range is shown schematically in **Fig. 4**. As the coating deterioration area, the areas of rust and blistering of coating film by rust were measured in the range of the scratch length of 100 mm, as shown in Fig. 4 (a). For the corrosion depth, as shown in Fig. 4 (b), the corrosion region was divided into 5 regions with a length of 20 mm each in the range of the 100 mm scratch length, and the maximum corrosion depth in each region was measured with a depth gauge. The average of the maximum corrosion depths in each of the five corrosion regions was used as the corrosion depth. For corrosion volume, as shown in Fig. 4 (c), the corrosion depth was measured at a pitch of 0.3 mm in the directions parallel and perpendicular to the scratches in the range of the 100 mm scratch length by using a laser roughness meter (LJ-V7200, manufactured by Keyence Corp.), and the corrosion volume was obtained by adding the results. The measured values of the above-mentioned coating deterioration area and corrosion volume were then converted to values per 10 mm of scratch length.

2.2.2 Upper deck longitudinal members

As an evaluation of the hull, about 5 years after completion, the edges of the longitudinal members of the upper deck along the inspection route were photographed continuously, and the number of points displaying coating deterioration (hereinafter, coating deterioration number) and the lengths of the individual deterioration points on the edges were measured from the photographs. The frequency of coating deterioration by coating deterioration length and the ratio of the coating deterioration length to the total edge length were also obtained. The evaluated tanks were No. 3WBT, where conventional steel was used, and No. 5WBT, where the corrosion resistant steel was applied. The total lengths of the evaluated edges were 172 m for both the conventional steel and the corrosion resistant steel.

2.3 Observation of Rust Particles

The rust that formed under the doubling plate coating films on the conventional steel and corrosion resistant steel were sampled and their particles were observed with an transmission electron microscope (TEM).

3. Experimental Results

3.1 Coating Deterioration Behavior and Corrosion Behavior

3.1.1 Doubling plates

Figure 5 shows the coating deterioration area at the wide scratches on the doubling plates and the typical appearance of coating deterioration. Although corrosion and coating deterioration in the form of coating film blistering by rust occurred at the scratched parts, the average value of the coating deterioration area of the corrosion resistant steel was 75% that of the conventional steel. It may also be noted that the coating deterioration area at the narrow scratches was limited to a reduction of about 5% from that of the wide scratches.

The corrosion depth at the wide scratches showed an

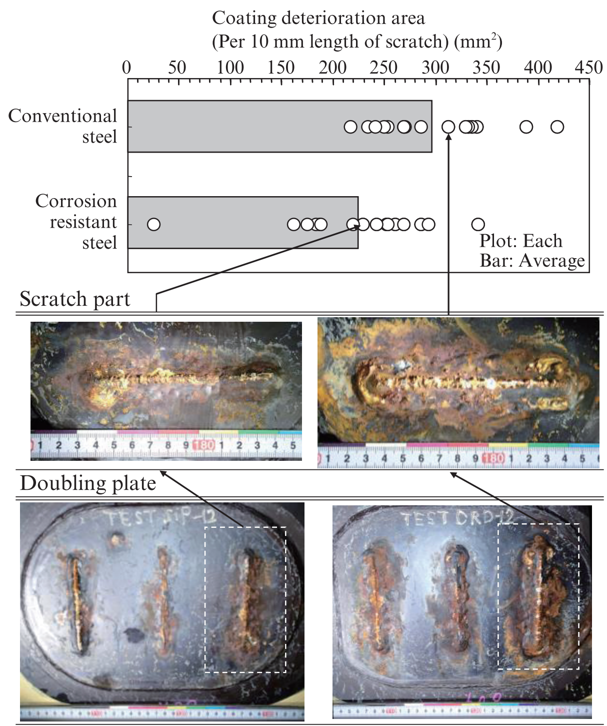

Fig. 5 Coating deterioration area at wide scratch part of doubling plate and typical appearance (No. 3WBT, No. 5WBT)

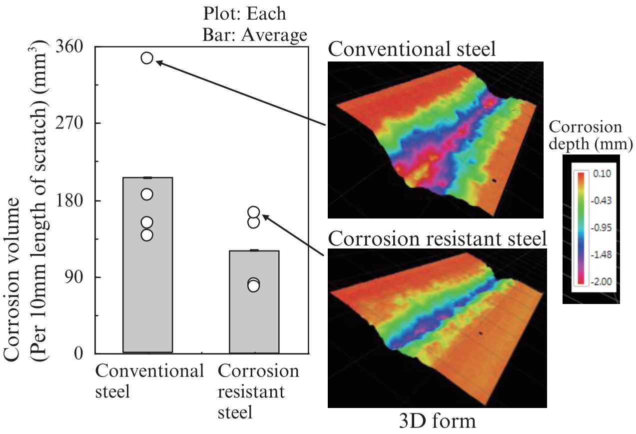

Fig. 6 Corrosion volume at wide scratch part of doubling plate (No. 3WBT, No. 5WBT)

average value of approximately 1.8 mm in the conventional steel; on the other hand, the corrosion depth of the corrosion resistant steel was approximately 1.5 mm, or 84% that of the conventional steel[8)].

Figure 6 shows the results of measurements of the corrosion volume of the wide scratches on the doubling plates of the conventional steel and corrosion resistant steel. The figure, which also shows 3-dimensional images, is a comparison of the corrosion resistant steel and the conventional steel at the scratches where the largest corrosion volumes were measured. The corrosion volume of the corrosion resistant steel was approximately 50% that of the conventional steel. Moreover, the average value of the corrosion volume of the corrosion resistant steel was 58% that of the conventional steel.

3.1.2 Upper deck longitudinal members

Figure 7 shows (1) the cumulative total of the coating deterioration lengths, (2) the accumulation of ratio of the coating deterioration length to the total edge length, and (3) the frequency of the coating deterioration number for each coating deterioration length on the edges of the upper deck longitudinal members. Regarding (3), a difference of about 10% was found between the coating deterioration number of the conventional steel (209 deteriorated points) and that of the corrosion resistant steel (187 points). Therefore, for the frequency of the coating deterioration number by coating deterioration length of the conventional steel and corrosion resistant steel, the coating deterioration numbers at the coating deterioration lengths concerned were allocated on the basis of the total coating deterioration number of the respective steels. On the horizontal axis, for example, the plot 10–20 mm means 10 mm < length ≤ 20 mm.

From Fig. 7, the cumulative coating deterioration length is approximately 8 400 mm for the conventional steel and approximately 5 600 mm for the corrosion resistant steel, and the ratios of the coating deterioration length to the total edge length are 4.9% and 3.2%,

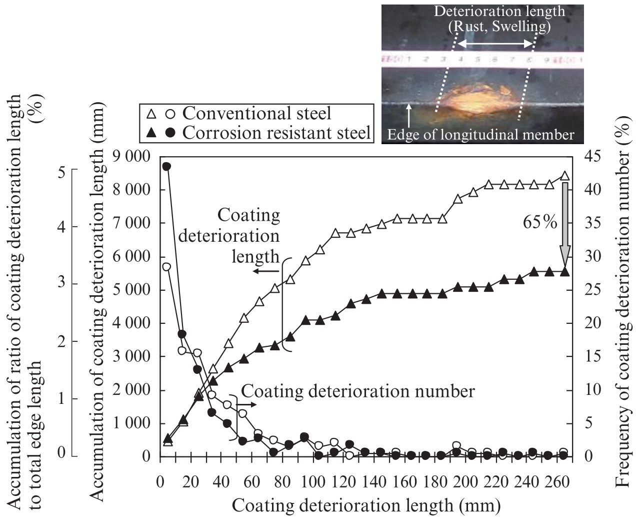

Fig. 7 Coating deterioration length, ratio of coating deterioration length and frequency of coating deterioration number at edge of upper deck longitudinal member

respectively. In other words, the ratio of the coating deterioration length of the corrosion resistant steel is reduced to approximately 65% that of the conventional steel. Regarding the frequency of the coating deterioration number, in the corrosion resistant steel, lengths of ≤ 20 mm showed a high frequency distribution and the frequency of coating deterioration numbers in the range from 20 mm to 80 mm was small. Based on this fact, the corrosion resistant steel suppresses the progress of coating deterioration in the edge direction. Thus, it was found that the corrosion resistant steel displays a coating deterioration prevention effect even in hulls which have not been artificially damaged.

3.2 Rust Particles of Conventional Steel and Corrosion Resistant Steel

Photo 1 shows transmission electron microscope images of the rust particles that formed under the doubling plate coating films of the conventional steel and corrosion resistant steel. The parts of the figure surrounded by broken white lines show one rust particle.

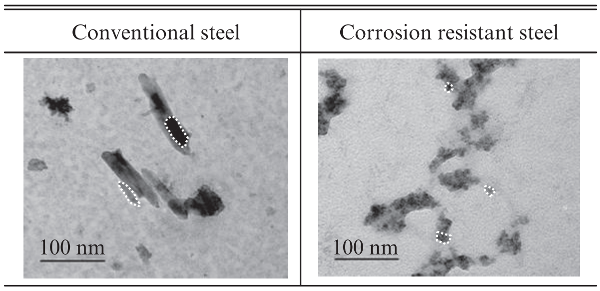

Photo 1 Transmission electron microscope images of rust particles formed under coating film on conventional and corrosion resistant doubling plates (The part enclosed by the white dotted line shows one rust particle.)

The rust particles of the corrosion resistant steel were finer than those of the conventional steel. This refinement of the rust particles is considered to contribute to suppression of corrosion loss of the steel material and to prevention of coating deterioration.

4. Discussion

4.1 Comparison of Coating Deterioration and Corrosion Behavior in Actual Ship and Laboratory Corrosion Tests

4.1.1 Comparison of coating deterioration progress behavior

The coating deterioration progress behavior of the conventional steel and the corrosion resistant steel was studied[6)] under conditions of repeated dryness and wetness with salt spray using the following laboratory corrosion test conditions to investigate the progress of coating deterioration from scratched parts of the coating : (1) Spray with 5% NaCl solution at 35°C, 2 h→ (2) 20–30% RH, 60°C, 4 h→ (3) > 95% RH, 50°C, 2 h (repeat from step (1)). As a result, it was found that the coating deterioration area of the corrosion resistant steel was approximately 70% that of the conventional steel, and the time to reach a certain coating deterioration area (600 mm^2) with the corrosion resistant steel was 1.7 times that with the conventional steel. **Figure 8** shows the transition of the coating deterioration areas in the laboratory corrosion test, together with the results of measurements of the coating deterioration area in the actual ship, considering the acceleration factor of the laboratory corrosion test, which is described in the following. Here, the coating deterioration areas at the wide scratches of the doubling plates in the actual ship were 297 mm^2/4.8 years (1 748 days) in the case of the conventional steel and 223 mm^2/4.8 years (1 748 days) in the case of the corrosion resistant steel. On the other hand, the times to these areas in the laboratory corrosion test were 167 days for the conventional steel and 206 days for the corrosion resistant steel. Accordingly, the acceleration factor of the laboratory corrosion test is approximately 10 times the actual ship. Therefore, the results for 4.8 years (1 748 days) in the actual ship can be plotted at 175 days of the laboratory corrosion test.

As shown in Fig. 8, the coating deterioration progress behavior in the laboratory corrosion test and in the actual ship are in good agreement. Thus, this demonstrates the appropriateness of the cyclic corrosion test with salt spray, and enables a quantitative confirmation of the coating deterioration prevention effect of the corrosion resistant steel in an actual ship. Moreover, from this fact, it is also considered that the time from initiation of coating deterioration to a certain area of the coating deterioration of the corrosion resistant steel will be approximately 1.7 times that of the conventional steel in actual ships.

	Laboratory test	Actual operation condition
Coating specification (Actual film thickness)	Modified epoxy 160 μm × 2 coats (350 μm)	Tar epoxy 150 μm × 2 coats (460 μm)
Conventional steel	○	●
Corrosion resistant steel	□	■

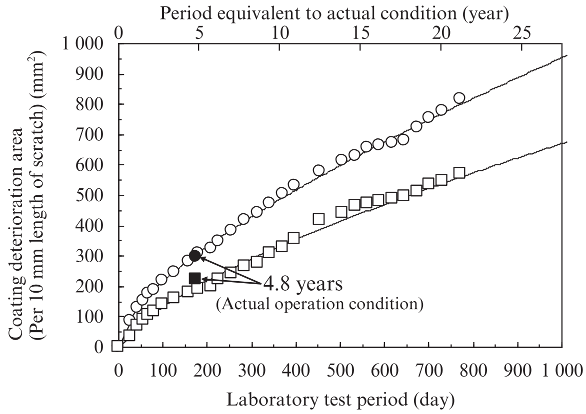

Fig. 8 Transition of coating deterioration area at scratch part on conventional and corrosion resistant steels in cyclic corrosion test with salt spray and actual operation condition

JFE Steel also performed a 2 year exposure test with coupons on another ship[7)]. In that test, the coating deterioration area of the developed steel was approximately 30% that of the conventional steel. That is, the coating deterioration prevention effect of the corrosion resistant steel is larger than that on the actual ship and laboratory corrosion test in the present research. As the reason for this difference, it is thought that the coating deterioration mechanism of the other ship was different from that of the actual ship and laboratory corrosion test in this work. The form of corrosion at the tip of coating deterioration in the actual ship and laboratory corrosion test was blistering, whereas the form of coating deterioration in the other ship was filiform corrosion. Coating deterioration mechanisms between blistering and filiform corrosion are different[9)]. Accordingly, it is thought that the effect of the corrosion resistant steel was different (displayed greater effect) on the second ship due to this difference in the coating deterioration mechanism.

4.1.2 Comparison of steel corrosion loss behavior

As a result of the investigation of corrosion loss of the steel materials in the laboratory corrosion test, with the conventional steel, corrosion through-holes exceeding the test specimen thickness of 3 mm could be seen over a wide region, but this type of corrosion was remarkable slight in the corrosion resistant steel, suggesting that the corrosion resistant steel has a corrosion depth suppressing effect[6)]. On the other hand, on the actual test ship, the corresponding depth of the corrosion resistant steel was also limited to 84% that of the conventional steel. From this, it is considered that the corrosion loss prevention effect of the corrosion resistant steel observed in the laboratory corrosion experiment can also be confirmed in the actual ship.

4.2 Coating Life Prolongation Effect of Corrosion Resistant Steel

Next, the coating life prolongation effect by application of the corrosion resistant steel is studied based on Fig. 1. Assuming the period during which coating deterioration does not occur, which was called the 1st Stage in Fig. 1, is a, and the period from the start of coating deterioration to recoating is b, the coating life with the conventional steel is given by A in Eq. (1).

$$A=a+b \quad (1)$$

In case the corrosion resistant steel is applied, there is no change in a, as this period depends on the performance of the coating. However, b is longer because the corrosion rate after the start of coating deterioration is smaller with the corrosion resistant steel. As studied in connection with Fig. 8, with the corrosion resistant steel, the time from the start of coating deterioration to a certain coating deterioration area is 1.7 times that of the conventional steel. Accordingly, the coating life B in case the corrosion resistant steel is applied is as shown by the following equation.

$$B=a+1.7\times b \quad (2)$$

On the other hand, as shown in Fig. 7, the effect of application of the corrosion resistant steel has already been demonstrated 5 years after application to the actual ship; therefore, a is considered to be shorter than 5 years. Moreover, with a tar epoxy coating of 250 μm (2 coats), which is close to the specification of the actual ship, the period until the coating condition became FAIR was about 15 years[1]. Because International Association of Classification Societies (IACS) recommends recoating when the coating condition becomes FAIR[10], $a+b=15$ years is assumed. Since $b=15-a$, $B=25.5-0.7a$ is obtained by substitution in Eq. (2). From the results of the evaluation of the actual ship, $a < 5$. Therefore, it can be estimated that $22 < B \leq 25.5$. Based on this, when the corrosion resistant steel is applied, it can be expected that the ship will not exceed the recoating standard, even assuming it goes into dry dock after 22.5 years of use, and it is considered amply possible to avoid recoating before the ship reaches the general ship design life of 25 years.

5. Conclusion

A newly-developed JFE Steel corrosion resistant steel for ballast tanks, JFE-SIP^{TM}-BT, was applied to an actual ship, and the coating deterioration behavior and corrosion behavior after use for about 5 years were investigated. Furthermore, it was compared with a laboratory corrosion test. The following conclusions were obtained.

(1) With the corrosion resistant steel, the coating deterioration area of scratched parts of doubling plates installed at the upper deck of ballast tanks on the actual ship was suppressed to 75% that of the conventional steel. Regarding the corrosion loss of the scratched parts of the doubling plates, the corrosion depth of the corrosion resistant steel was reduced to 84% that of the conventional steel, and the corrosion volume of the corrosion resistant steel was limited to only 58% that of the conventional steel.

(2) With the corrosion resistant steel, the coating deterioration length ratio of the edges of the upper deck longitudinal members on the actual ship was reduced to approximately 65% that of the conventional steel. In the case of the corrosion resistant steel, the frequency of coating deterioration having a length of 20 mm or less was larger than in the case of the conventional steel, and the frequency of coating deterioration with lengths from 20 mm to 80 mm was also smaller than that of the conventional steel. These facts confirmed that the corrosion resistant steel displayed a coating deterioration prevention effect in ship hulls which have not been subjected to artificial coating damage.

(3) The rust particles of the corrosion resistant steel were finer than those of the conventional steel.

(4) The coating deterioration progress behavior in a cyclic corrosion test with salt spray, which is a laboratory corrosion test, was substantially in agreement with that in the actual ship.

(5) The result in (4) showed the appropriateness of this cyclic corrosion test with salt spray, and also enabled a quantitative confirmation of the effect of the corrosion resistant steel in suppressing the progress of coating deterioration in this actual ship. Furthermore, in this actual ship, the time from the start of coating deterioration until the reaching a certain coating deterioration area with the corrosion resistant steel is considered to be approximately 1.7 times longer than that of the conventional steel.

(6) There is considered to be an ample possibility that recoating before the ship reaches the general ship design life of 25 years can be avoided by applying the newly-developed corrosion resistant steel for ballast tanks.

From the viewpoint of reduction of life cycle cost by extension of coating life, the authors will continue this research in the future with the aims of expanding application of this corrosion resistant steel, as well as coating simplification (e. g., reduction of the 2 coats in the PSPC coating standard[2)] to 1 coat) and reduction of the corrosion margin of steel[3, 4)].

Application of this corrosion resistant steel to the actual ship and its evaluation were carried out with the cooperation of Kawasaki Kisen Kaisya, Ltd., Taiyo Nippon Kisen Co., Ltd., and Japan Marine United Corp. The authors wish to express their deep appreciation to all those concerned.

References

1) Nippon Kaiji Kyokai. Guidance for Corrosion Protection System of Hull Structures—For Water Ballast Tanks and Cargo Oil Tanks—2nd revision. 1995.
2) Nippon Kaiji Kyokai. Guidelines for Performance Standard for Protective Coatings Contained in IMO Resolution MSC. 215 (82), 2007.
3) IACS. Common Structural Rules for Double Hull Oil Tankers. 2006.
4) IACS. Common Structural Rules for Bulk Carriers. 2006.
5) Emi, H; Kumano, A; Arima, T; Yuasa, M; Yamamoto, N; Umino, M. Journal of the Society of Naval Architects of Japan. 1993, no. 174, p. 735
6) Shiotani, K; Samusawa, I; Tachibana, S; Komori, T. Proc. ICSOT, Ambon, Indonesia, The Royal Institution of Naval Architects, 2012, p. 27.
7) Shiotani, K; Komori, T; Hoshino, T; Nishimura, K. Nakamura, M; Shiomi, H. Conference Proceedings. The Japan Society of Naval Architects and Ocean Engineers. 2010, no. 11, 2010K-G10-3, p. 481.
8) Shiotani, K; Tachibana, S; Samusawa, I; Shiomi, H; Akiyama, H; Hirasawa, H. Conference Proceedings. The Japan Society of Naval Architects and Ocean Engineers. 2013, no. 17, 2013A-GS4-5, p. 97.
9) Funke, W. Progress in Organic Coatings. 1981, no. 9, p. 29.
10) IACS. Recommendation 87 Guidelines for Coating Maintenance & Repairs for Ballast Tanks and Combined Cargo/Ballast Tanks on Oil Tankers, Rev. 1.2006.