ONBOARD EVALUATION RESULTS OF NEWLY DEVELOPED ANTI-CORROSION STEEL FOR COTS OF VLCC AND PROPOSAL FOR MAXIMUM UTILIZATION METHOD

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SUMMARY
The objective of this study is to develop a practically and technically reasonable counter measure to the risk on leakage of crude oil by corrosion perforation of the COT bottom plate. To make clear the validity, the newly developed anti-corrosion steel NSGP®-1 has been applied to all bottom plates of COTs of a newly built double hull VLCC tanker.

Prior to the application, properties not only on excellent anti-corrosion but also good mechanical properties of the steel have been evaluated in cooperation with the ship builder. At last the ship building work has been completed with no problem, showing good workability during construction.

Detailed corrosion investigation of the COT built with newly developed anti-corrosion steel was carried out at the first dock after 2year 3 month after the launching. No localized corrosion which needs to be repaired was observed, and she docked out without repair for corrosion damages. As a result, technological validity of the scientific understanding of the corrosion phenomena and development policy on anti-corrosion steel in this study was confirmed.

Based on this onboard evaluation result, the authors quantitatively investigated corrosion environment and phenomena of localized corrosion on bottom plate in detail. As a result, corrosion test method to evaluate and define anti-corrosion steel for COT bottom plate of crude oil carrier is proposed, and anti-corrosion property of the newly developed steel was scientifically clarified.

Considering the recent finding that pit growth stops at dock cleaning, a new model on maximum utilization of the anti-corrosion steel for best corrosion life cycle design of COT has been proposed. As a result, newly developed anti-corrosion steel capability to be corrosion repair free during whole ship life is derived.

NOMENCLATURE
VLCC: Very Large Cargo Carrier
SH: Single Hull Structure
DH: Double Hull Structure
COT: Cargo Oil Tank
COW: Crude Oil Washing

1. Objective
The objective of the present study is to develop an anti-corrosion steel and thereby provide a technically reasonable measure to avoid the danger of perforation of the bottom plate of a cargo oil tank (COT).

In the previous paper, the authors reported the development of an anti-corrosion steel for the COT bottom plates of a VLCC. To evaluate not only the corrosion resistance of the developed steel but also its mechanical and application properties as required for field shipbuilding work, it was used for all the COT bottom plates of a newly constructed VLCC shown in Photo 1.

Photo 1 Newly Built VLCC ‘TAKAMINE’ applying NSGP®-1.

The localized corrosion of COT bottom plates results from the combined conditions of oil coats and bottom plate water, and, statistically, the rate of its progress fluctuates as seen in Figure 1. In consideration of this, the developed steel was used for all the COT bottom plates of the ship to evaluate its corrosion-resistance performance comprehensively and statistically.

Figure 1 Statistical variation of maximum localized corrosion rate on COT bottom plate[1].

For constructing a highly reliable ship, steel material must have a wide variety of properties such as the basic mechanical properties for structural steels and good workability in field use as well as the corrosion resistance of the base metal and weld joints in the ballast environment on the back side of COT bottom plates. Before the construction of the VLCC, the authors evaluated these properties of the developed steel with the help of Nagasaki Shipyards of Mitsubishi Heavy Industries, who constructed it.

The present report describes the results of the evaluation.
of the developed steel, and based on the result, proposes a definition of corrosion-resistant steel for achieving the objective of the present study and guidelines for optimum anti-corrosion design of a ship in the whole service life.

2. MECHANICAL PROPERTIES AND SEAWORTHINESS OF DEVELOPED ANTI-CORROSION STEEL

Table 1 shows a typical chemical composition of the developed steel, NSGP®-1. This chemical composition, which was worked out based on new discoveries and the latest technologies of corrosion-resistant alloy design, meets the IACS rules, and exhibits the same mechanical properties and application performance as those of conventional shipbuilding steels, in addition to excellent corrosion resistance.

As stated in the previous report, the developed steel demonstrates a markedly lower corrosion rate than that of conventional steels in an environment of chlorides in high concentrations and strong acids simulating the localized corrosion environment to which the COT bottom plates of a crude-oil carrier are exposed.

As Figure 2 shows, the corrosion rate of NSGP®-1 in a strongly acidic and corrosive environment having a pH of 1.0 or lower is as small as approximately 0.6 mm/y; the photos of the steel surfaces after corrosion test clearly show the corrosion resistance of NSGP®-1 far superior to that of conventional steel.

Table 1 Typical chemical composition of developed NSGP®-1.

<table>
<thead>
<tr>
<th>Element</th>
<th>NSGP®-1</th>
<th>A508</th>
<th>IACS Standard (including all alloy elements)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.124</td>
<td>0.14</td>
<td>≤0.18</td>
</tr>
<tr>
<td>Si</td>
<td>0.33</td>
<td>0.20</td>
<td>≤0.50</td>
</tr>
<tr>
<td>Mn</td>
<td>1.09</td>
<td>1.05</td>
<td>0.9~1.6</td>
</tr>
<tr>
<td>P</td>
<td>0.018</td>
<td>0.01</td>
<td>≤0.035</td>
</tr>
<tr>
<td>S</td>
<td>0.031</td>
<td>0.02</td>
<td>≤0.035</td>
</tr>
<tr>
<td>Al</td>
<td>0.014</td>
<td>0.02</td>
<td>≥0.02</td>
</tr>
<tr>
<td>Cu</td>
<td>0.322</td>
<td>0.36</td>
<td>≤0.36</td>
</tr>
</tbody>
</table>

Table 2 Welding Conditions.

<table>
<thead>
<tr>
<th>Welding Rod</th>
<th>Flux</th>
<th>Backing plate</th>
<th>Grove shape</th>
<th>Pass conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>US36(4.8mmφ)</td>
<td>PF152E</td>
<td>FAB-1 Metal powder PR2</td>
<td>50° (25° each side) root gap: 2 mm</td>
<td>1000 A, 35 V, electrode speed: 35 cm/min, heat input: 102.3 kJ/cm</td>
</tr>
</tbody>
</table>

Figure 2 Anti-corrosion property of the NSGP®-1 under simulated localized corrosion environment at COT bottom.

Figure 3 Anti-corrosion property of the NSGP®-1 including weld under simulated localized corrosion environment at COT bottom. (pH=0.8, 336hrs).
Needless to say, COT bottom plates are constructed by welding, and therefore, an anti-corrosion steel for such applications must exhibit good corrosion resistance in weld joints as well.

Figure 3 shows the result of a corrosion test of welded specimens of NSGP®-1 under the same conditions as those for Figure 2. The welding of the specimens was done under the conditions of Table 2. The graphs and photos clearly show that the developed steel exhibits excellent corrosion resistance at both the base metal and weld joints.

Since the COTs of the latest VLCCs are constructed in double hull (DH) structure, the reverse side of COT bottom plates is exposed to a corrosive environment of a water ballast tank (WBT). This means that anti-corrosion steel used for COT bottom plates must have the same properties as those of conventional steels in a WBT environment.

Figure 4 compares NSGP®-1 with a conventional steel in terms of the corrosion rate and appearances of welded specimens after immersion in artificial seawater. The welding was done under the same conditions of Table 2.

From these figures, it is clear that the corrosion resistance of NSGP®-1 in a WBT environment is, in either the base metal or weld joint, the same as or better than that of conventional steels.

The evaluation results of the mechanical properties and field use performance of NSGP®-1 are shown in Figures 5 to 7.

Figure 5 shows the result of Y-groove cracking test. It was manually welding. The graph clearly shows that the weldability of NSGP®-1 is excellent, totally free from cracking.

Figure 6 shows the result of fatigue property test of the base metal and weld joints. The welding condition of Butt weld Joint is shown in the table of Figure 7. Fillet Weld T-joint was done by CO₂ welding. As is clear from the graphs, the fatigue properties of NSGP®-1 are the same as or better than those of conventional steels.

Figure 7 shows the result of Charpy impact test of various types of weld joints. The welding conditions is also shown in the Figure here. As is clear from the graphs, NSGP®-1 stably satisfies the requirements under relevant standards, demonstrating sufficiently high toughness of weld joints.

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3. Results of Application to VLCC

3.1. Application

Figure 8 shows the portions of the TAKAMINE to which NSGP®-1 was applied. It was used for all the COT bottom plates, and in the cases especially of six tanks of Nos. 3 and 4 COTs at the center of the hull, the steel was used without protective paint coating.

As had been expected from the evaluation results of the workability of NSGP®-1 prior to the shipbuilding, the steel caused no problems whatsoever in the field work, and the ship construction went as smoothly as that of any ordinary vessels.

3.2 Result of Corrosion Resistance Evaluation

3.2.1 Evaluation Results at first Dock Inspection

At a first dock inspection of the TAKAMINE after 2 years and 3 months of service, the state of corrosion of the COT bottom plates of NSGP®-1 without coating was examined in detail.

It has to be noted here that the COT insides of the TAKAMINE underwent crude oil washing (COW) after each trip; this is a very unfavourable condition with respect to the occurrence and progress of the localized corrosion of the bottom plates because, as stated in the previous report in detail, COW adversely affects the environmental insulation effects of the oil coat, which protects the internal surfaces of COTs from corrosion.

Inspectors allocated at every 1.5 m in the width direction of a COT visually inspected the corrosion condition of the entire bottom plate in the length direction removing the oil with a scraper. The inspection was repeated three times.

With the above inspection results, the TAKAMINE left the dock without any repair work at all inside the COTs. Thus, NSGP®-1 proved effective in avoiding the danger of corrosion perforation of COT bottom plates to a level where repair work of localized corrosion, which is a usual work item in periodical dock inspection of an ordinary VLCC, is absolutely unnecessary. It has to be noted that this result was obtained in spite of COW after every trip, an exceptionally tough condition from the viewpoint of corrosion prevention. This corroborates the excellent corrosion resistance of NSGP®-1 when applied to VLCC.

The above also evidences the technical correctness of the development policy of NSGP®-1 to decrease the danger of corrosion perforation of COT bottom plates due to localized corrosion discussed in the previous report.
3.2.2 Result of Detailed Quantification of Pitting Corrosion from Technical Viewpoint

It was technically difficult to quantitatively evaluate the effect of the use of anti-corrosion steel for a real VLCC based only on the results described above. Furthermore, the study results at the laboratory study stage indicated that theoretically the steel then being developed would significantly decrease the rate of corrosion in the local-corrosion environment of COT bottom plates, but it would not totally prevent it from occurring. In consideration of the above, the authors conducted another detailed inspection of the COTs focusing on shallower pitting corrosions, 2 to 4 mm in depth, which had not been practiced in usual dock inspection. The above depth range was adopted because it was practically difficult to detect a corrosion depression 2 mm or less deep.

The inspection proved very difficult because of the small corrosion depth to detect and evaluate. The result is shown in Figure 10; the maximum depth of pitting corrosions found was less than 3 mm and the number of their occurrence was very small, 30 or less per COT. Photo 4 shows an example of the pitting corrosions thus found. The size (diameter and depth) of the pit was so much smaller than that of the pitting corrosions of conventional steels that it was very close to the lower detection limit.

Figure 10 Observed pit small count being over 2mm and less than 3mm depth on COT Bottom.

Photo 4 Only very shallow pits with small counts were observed on NSGP®-1 compared to pits on conventional steel.

4. Discussion on NSGP®-1 Application to VLCC and Proposal of Optimum Method for Using Anti-corrosion Steel

4.1 Quantitative Analysis of Results of NSGP®-1 Application to Real VLCC

As stated earlier, theoretically, the developed steel was only to significantly decrease the rate of corrosion in the localized corrosion environment of COT bottom plates rather than to totally prevent it, and for this reason, it was necessary to well understand its corrosion rate behavior to make the most of its technical advantages.

Figure 11 shows the result of a extreme statistical analysis of localized corrosion rate estimated from the depth data of pits 3 mm or less in depth accumulated over a very long period. The graph shows that, as was
conventionally known, the distribution of the rate of localized corrosion of NSGP®-1 agrees with the extreme statistical distribution. The gradient of the regression curve that expresses the statistical distribution of the corrosion rate regarding an anti-corrosion steel is nearly equal to that regarding a conventional steel. It follows, therefore, that the corrosion phenomenon that has been occurring in the TAKAMINE is presumably identical to that which occurs in a VLCC of conventional steels. In addition, the graph indicates that the expected maximum localized corrosion rate of the developed steel applied to all the 15 COTs of the TAKAMINE will not surpass 4 mm in 2.5 years (= 1.6 mm/y), and no repair work will be required until next dock inspection.

Figure 11 Estimated max. pit depth for 15 COTs with NSGP®-1 by Statistical analysis.

4.2 Evaluation Method and Definition of Anti-corrosion Steel

As stated in the previous report in detail, investigations of actual VLCCs and laboratory simulation tests have made it clear that the pH inside a pit of localized corrosion is as low (acidic) as about 1.5 or less. This value of pH, however, is the one measured after wetting the corrosion pits, namely diluting the environmental ingredients, and is not necessarily accurate. This means that to define the environmental condition for evaluation of corrosion resistance of a steel, it is necessary to estimate the pH value precisely.

It is generally difficult to measure the pH value inside a localized corrosion accurately. On the other hand, it is known that the corrosion rate of ordinary carbon steel is strongly correlated with pH, and it is possible to estimate the pH inside a corrosion pit from the maximum rate of localized corrosion obtained so far through investigations of actual VLCCs. Figure 12 shows the maximum rate of localized corrosion measured in the past and the calculation result of the pH-dependence of the corrosion rate of ordinary steels. The figure indicates that the value of pH inside the corrosion pit that shows the highest corrosion rate among those occurring in a ship is estimated at 0.85 to 1.16.

The objective of the present development study is, as initially stated, to decrease the danger of perforation corrosion of COT bottom plates. Judging from the result of the above pH estimation, the corrosion-resistant properties of anti-corrosion steel should be evaluated under the condition most likely to cause corrosion, namely at a pH of 0.85 or lower with a NaCl concentration of 10 mass % at 30°C.

On the other hand, when anti-corrosion steel is applied to all the 15 COTs of a VLCC, the 50%-cumulative probability figure of the extreme statistics in Figure 13 indicates that the average corrosion rate must be 0.9 mm/y in order that the maximum corrosion depth is less than 4 mm in 2.5 years (= 1.6 mm/y) so that no repair work is not required.

This means that a steel can be used as an anti-corrosion steel for COT bottom plates if, as described above, its average corrosion rate calculated in terms of weight loss is 0.9 mm/y or less under the laboratory test condition of a pH value of 0.85 or lower.

On the other hand, since the corrosion rate of NSGP®-1 in the laboratory test to evaluate its corrosion resistance was roughly 0.6 mm/y under pH changing from 0.6 to 1.0 as seen in Figure 14, the developed steel is fully entitled for use as an anti-corrosion steel for COT bottom plates.
4.3 Proposal of Optimum Application Method of Anti-Corrosion Steel

As stated in the previous report in detail, the growth of localized corrosion of COT bottom plates is considered to halt upon cleaning of the COT inside at a dock inspection.

On the other hand, if the depth of pitting corrosion found at a dock inspection is 4 mm or less, the danger of cargo oil leakage due to corrosion perforation of COT bottom plates is negligibly small and the repair of the attacked portion is considered unnecessary.

When an anti-corrosion steel such as NSGP®-1 is used for COT bottom plates and if the ship undergoes dock inspection at an interval of around 2.5 years, then the maximum corrosion depth of all the 15 COTs will not exceed 4 mm as stated earlier, and as Figure 15 shows, the repair work of localized corrosion of the bottom plates will not be required throughout its whole service life. In other words, it is possible to achieve the object of the present development, namely to avoid the danger of cargo oil leakage due to corrosion perforation of COT bottom plates with minimum maintenance loads, by applying anti-corrosion steel to COT bottom plates and setting the interval of the periodical dock inspection at 2.5 years.

5. CONCLUSION

There have been some cases of oil leakage from VLCCs due to perforation of COT bottom plates owing to localized corrosion over the last years. To provide a rational means to prevent such danger and avoid unnecessary environmental loads, the authors developed a new anti-corrosion steel, NSGP®-1, applied it to the COTs of an actual VLCC, and examined its anti-corrosion performance comprehensively and statistically. As a result, the following findings and conclusions were obtained:

1. Prior to the application of the developed steel to an actual VLCC, its corrosion resistance and other properties were evaluated, and its mechanical and application properties were found substantially the same as those of conventionally used steels. As a result, the developed steel posed no problem in its application to an actual VLCC.

2. After 2 years and 3 months of its commissioning, the VLCC for which NSGP®-1 was used underwent a first dock inspection, where no localized corrosion whatsoever requiring repair was found to have occurred to the six COT bottom plates to which the steel was applied without protective paint coating. This means that, through application to an actual VLCC, the developed steel proved effective in achieving the following unprecedented results: to decrease the danger of COT bottom plate perforation to the degree where the repair work of their localized corrosion, which is a routine work item with ships of conventional steels, is not necessary; and that this is realized even under a condition more likely to cause corrosion than usual cases, with COW being conducted after each voyage.

3. Based on the result of the inspection and examination of shallower pits of the COT bottom plates of NSGP®-1, the authors proposed test methods regarding corrosion-resistant steel, an approach to quantitatively defining a corrosion-rate condition that an anti-corrosion steel should satisfy and a specific corrosion-rate condition for such steel. In addition, the authors also proposed that the interval between two dock inspections of a VLCC be roughly 2.5 years to make the most of the excellent performance of corrosion-resistant steel. This will ensure that the danger of COT bottom plate perforation due to localized corrosion is effectively avoided and the repair work of localized corrosion becomes unnecessary all through the service life of a VLCC.

6. Acknowledgement

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7. REFERENCES

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