An Experimental Study on the Deterioration of Surface Coating on Steel Structure

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ABSTRACT: This study aimed at clarifying the corrosion mechanism of steel with surface coating in a marine environment. The corrosion progress of steel materials with tar-epoxy coatings that had been exposed in a marine environment for one and 19 years, respectively, and a steel material with a tar-epoxy coating that had been submerged in a chloride solution at $40^{o}C$ for 1200 hours, were investigated. Some specimens were provided with artificial defects to investigate the effect of a coating defect on the progress of deterioration. In the splash zone, corrosion of steel extends from the defect in a radial direction, and the speed of corrosion depends on the size of the defect. In the tidal zone and the submerged zone, on the other hand, corrosion of steel extends in a vertical direction at the edge of the defect and not in a radial direction.

1 BACKGROUND

Steel has been used in infrastructure building as a low-cost material with excellent mechanical properties. Because of its corrosion susceptibility, steel invariably needs corrosion protection when used as a construction material. This corrosion protection has a limited life, and it is necessary to clarify the mechanism of deterioration of the corrosion protection when investigating the corrosion and deterioration processes of steel structures so that proper maintenance is achieved.

Commonly, steel structures in marine environments are provided with a surface coating as corrosion protection to prevent water, oxygen gas, and chloride ion from reaching the steel surface. When the surface coating deteriorates, the steel under the coating starts to corrode.

In the case with resin surface coating, UV ray-induced decomposition and swelling caused by water molecule penetration can lead to deterioration such as chalking, blister, cracking and delamination. In addition, ships and drifting wood colliding against the structures may cause cracking and delamination in the surface coating. Such damages in the coating cause corrosion of the steel, which leads to further delamination of the coating and accelerates the corrosion reaction of steel.

This study aims at clarifying the deterioration process of steel structures with a surface coating of tar-epoxy resin, which is a common surface coating material for steel structures in marine environments. The corrosion process of steel plates exposed in a marine environment was investigated in comparison with that of the steel plates corroded in a laboratory test. The effect of defects in the surface coating on the corrosion process was also investigated.

2 EXPERIMENTAL PROCEDURE

2.1 *Specimens*

Table 1 shows the specifications of the steel plates and surface coatings employed in this study.

Long-term exposure steel with a tar-epoxy resin coating is a 3800 mm long L-beam and had been exposed for 19 years in a coastal estuary that leads to the Pacific ocean. Steel plate specimens of 300mm (or 350mm) x 120mm were cut out from the beam. Four plates were taken from the part exposed in a splash zone, six from a tidal zone and two from a submerged zone. The surface coating that had faced to the west was investigated (Fig. 1).

Table 1. Specifications of the steel plates and surface coatings

	Steel	Surface treatment	Primer	Inner coat	Top coat
Long-term exposure	SS400*	Sand blasting	Organic zinc paint (75mm)	Tar-epoxy (300mm)	Tar-epoxy (300mm)
Short-term exposure	SS400*	Sand blasting	Organic zinc paint (25mm)	-	Tar-epoxy (400mm)
Laboratory test	SS400*	Sand blasting	-	-	Tar-epoxy (50, 100, 150mm)

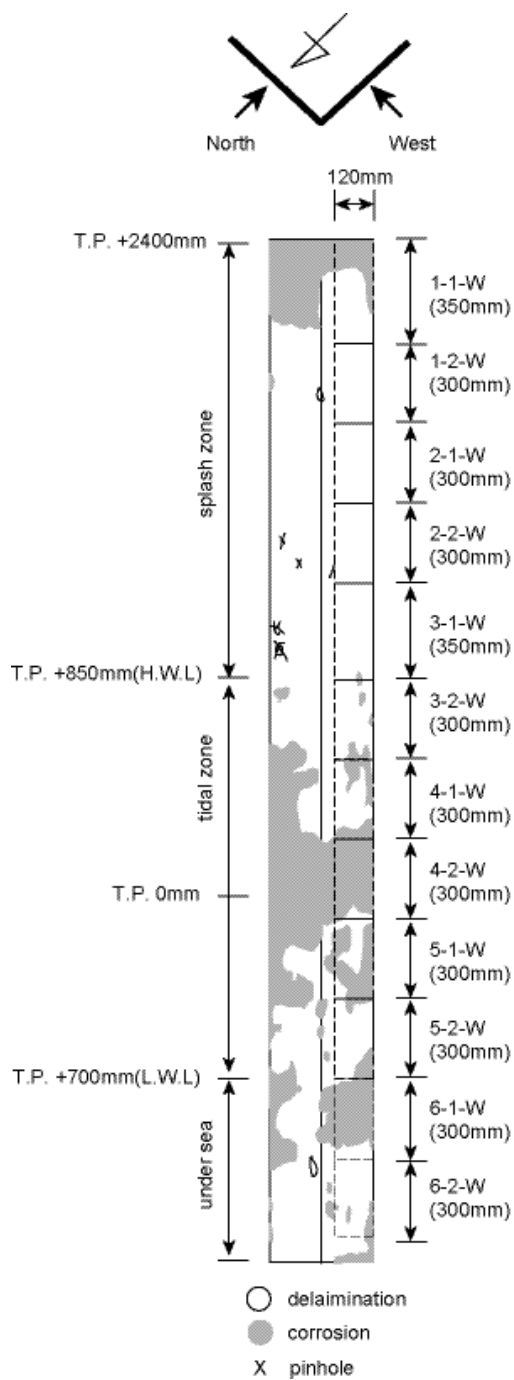*SS400: JIS G 3101 Rolled steels for general structure
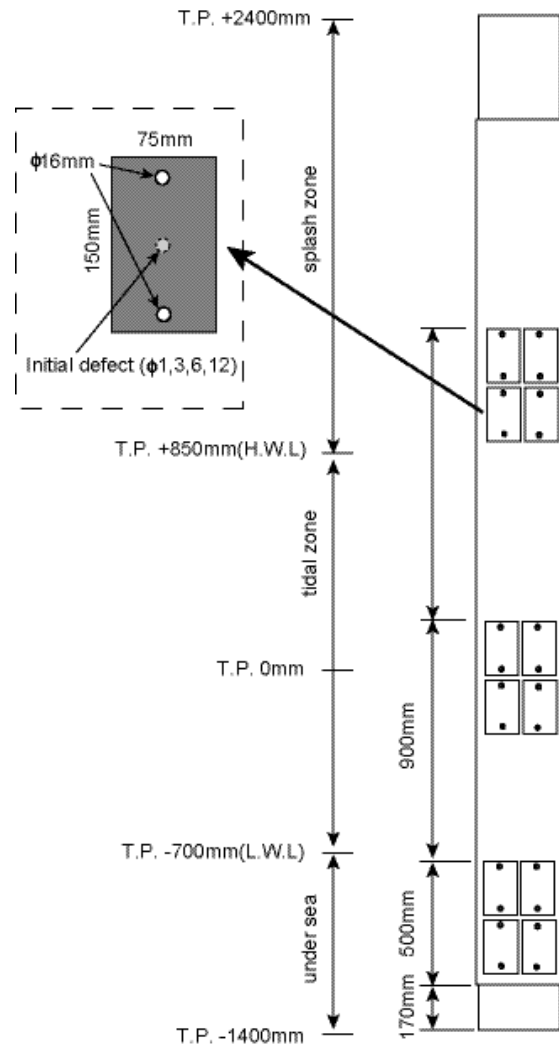
Figure 1. Long-term exposure specimen

Figure 2. Short-term exposure specimen

Short-term exposure steel and laboratory test steel are plate specimens of 75mm x 150mm with a tar-epoxy resin coating on one surface. All the other surfaces were pained thickly with epoxy resin to avoid intrusion of any substances that can cause corrosion in these surfaces. As an artificial defect, a φ1, 3, 6 or 12 mm hole was formed at the center of the tar-epoxy surface by cutting the surface coating to the bare steel surface using an end mill (Table 2-3). The short-term exposure specimens were fixed on the steel pipe pile with bolts and exposed for 1 year in a splash zone, a tidal zone and a submerged zone in the same place as the long-term exposure specimens (Fig. 2). The laboratory test specimens were submerged in a 5% NaCl solution at $40^{o}C$ for 1200 hours.

Table 2. Short-term exposure specimen

Specimen	Exposure environment	Diameter of artificial defect
AP-1, 3, 6 or 12	Splash zone	1,3,6 or 12mm
TP-1, 3, 6 or 12	Tidal zone	1,3,6 or 12mm
SP-1, 3, 6 or 12	Submerged zone	1,3,6 or 12mm

Table 3. Laboratory test specimen

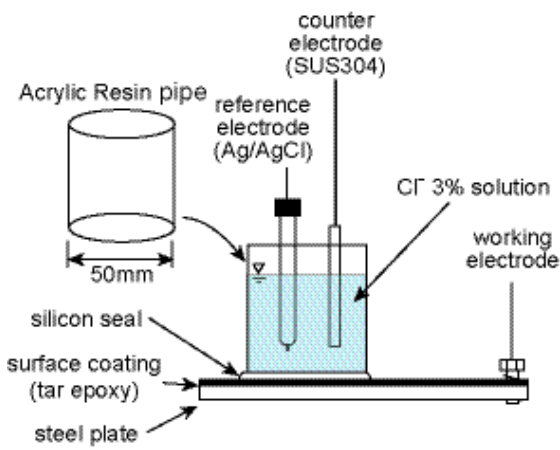| Specimen	Thickness of surface coating	Diameter of artificial defect
50-0, 1, 3, 6 or 12	50mm	0, 1,3,6 or 12mm
100-0, 1, 3, 6 or 12	100mm	0, 1,3,6 or 12mm
150-0, 1, 3, 6 or 12	150mm	0, 1,3,6 or 12mm

Figure 3. AC impedance measurement for long-term exposure specimen
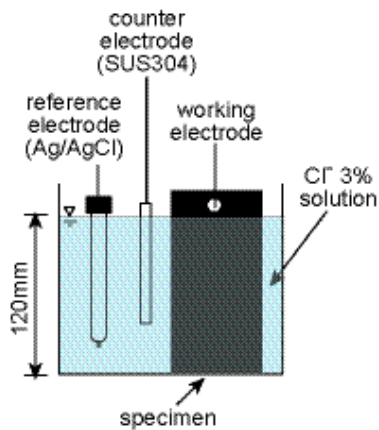

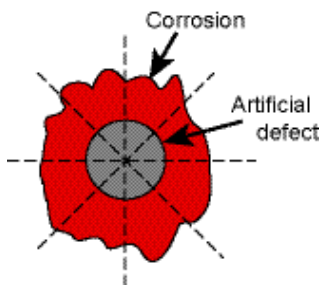Figure 4. AC impedance measurement for short-term exposure specimen and laboratory test specimen

Figure 5. Measurement of progress of corrosion area

2.2 *Meas urement*

After 19 or 1 year(s) exposure in the marine environment, or 0, 400, 800, or 1200 hours immersion in the chloride solution, the electric resistivity of the specimens was measured using an AC impedance method, with a voltage being 10mV at a frequency of 25 from 20kHz to 10mHz. The electric resistivity of the specimens here means the difference between the absolute values of resistivity at 20kHz and at 10mHz.

An acrylic cylinder was attached to the long-term exposure specimens as shown in Figure 3, with a waterproofing silicon seal. Measurement was carried out using an AC impedance method, with a NaCl solution filled

a. 2-2-W (splash zone)

b. 4-1-W (tidal zone)

c. 6-2-W (submerged zone)

Figure 6. Long-term exposure specimen

in the cylinder. The short-term exposure specimens and the laboratory test specimens were immersed into the NaCl solution of 120mm depth as shown in Figure 4 when measuring the electric resistivity using the AC impedance method.

After the resistivity measurement, delaminated surface coating was removed with a chisel, and the size of corrosion areas in the short-term exposure specimens and laboratory test specimens was measured in four directions to obtain an average width of the corroded area (Fig. 5). After that, all the surface coatings and corrosion products were removed by slight blasting, and the shape of the specimens was measured using a three dimensional laser displacement measuring system.

3 RESULTS AND DISCUSSIONS

3.1 *Outline of the deterioration*

Figure 6 shows examples of the specimens that were deteriorated during the 19 years exposure in the marine environment. As shown in this figure, debonding and delamination were observed in the surface coating and corrosion had occurred in many regions of the steel. The deterioration was more severe in the regions that had been in the tidal and submerged zones, where marine fouling organisms were observed.
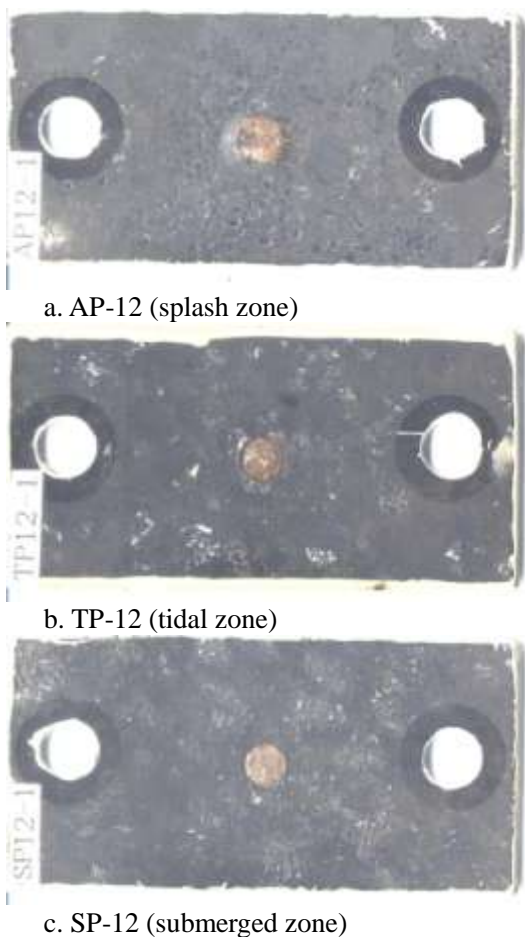
a. AP-12 (splash zone)

b. TP-12 (tidal zone)

c. SP-12 (submerged zone)

Figure 7. Short-term exposure specimen

a. 50-12

b. 100-12

c. 150-12

Figure 8. Laboratory test specimen

Figure 7 shows examples of deteriorated regions around the artificial defects in the surface coating after the one year exposure in the marine environment. Corrosion had occurred around the artificial defects, and also, the surface coating had debonded and delaminated. The latter was most evident in the specimens AP that had been placed in the splash zone, which is contrary to the fact that the long-term exposure specimens that were placed in the splash zone did not suffer either steel corrosion or severe deterioration of surface coating. This is attributable to the artificial defects formed in the short-term exposure specimens before the exposure. Also, the surface coating in the splash zone is less likely to be damaged by collision of ships or drifting wood or by fouling of marine organisms. Therefore, the above contradictory results can be explained as follows: The steel with damaged surface coating in the splash zone would deteriorate fast, but the actual corrosion progress is slow because of the less likelihood of physical damage of the steel structure in the splash zone.

Figure 8 shows examples of deteriorated regions around the artificial defects in the specimens that were submerged in the chloride solution in the laboratory at $40^{\circ}C$ for 1200 hours. In contrast to the specimens that were exposed in the marine environment, no debonding of delamination occurred in any specimens.

The results of the short-term exposure and the laboratory test will be discussed in detail in Chapter 3.3.
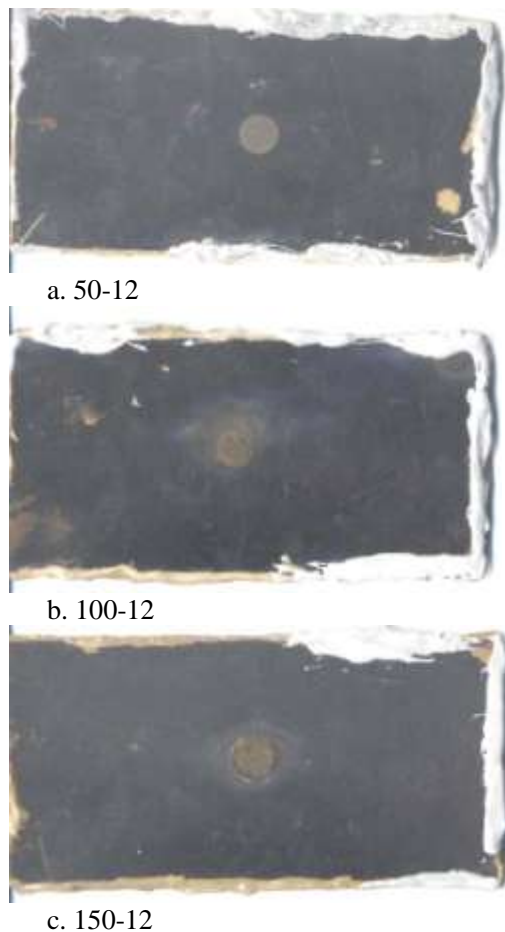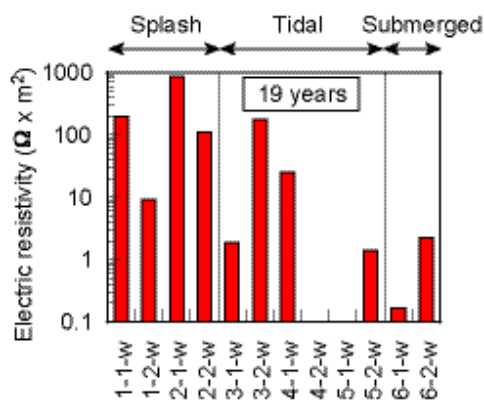

Figure 9. Electric resisivity of long-term exposure specimen

3.2 Electric resistivity

Figure 9 shows the electric resistivity of the long-term exposure specimens. Measurement using the AC impedance method was impossible in some specimens because of unstable response to the impressed voltage due to uneven deterioration distribution. However, there was a rough tendency that the specimens that had been placed in the tidal zone and in the submerged zone had a small resistivity. As mentioned in the previous section, the deterioration was severe in these specimens. Thus, the deteriorated specimens generally had low resistivity.
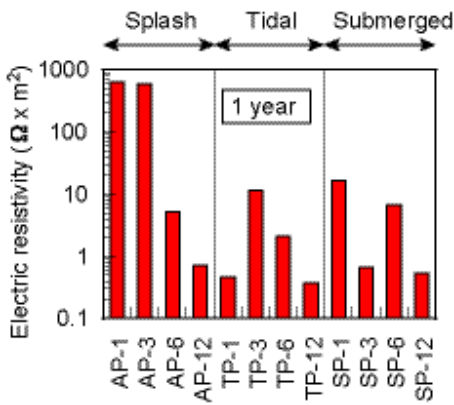
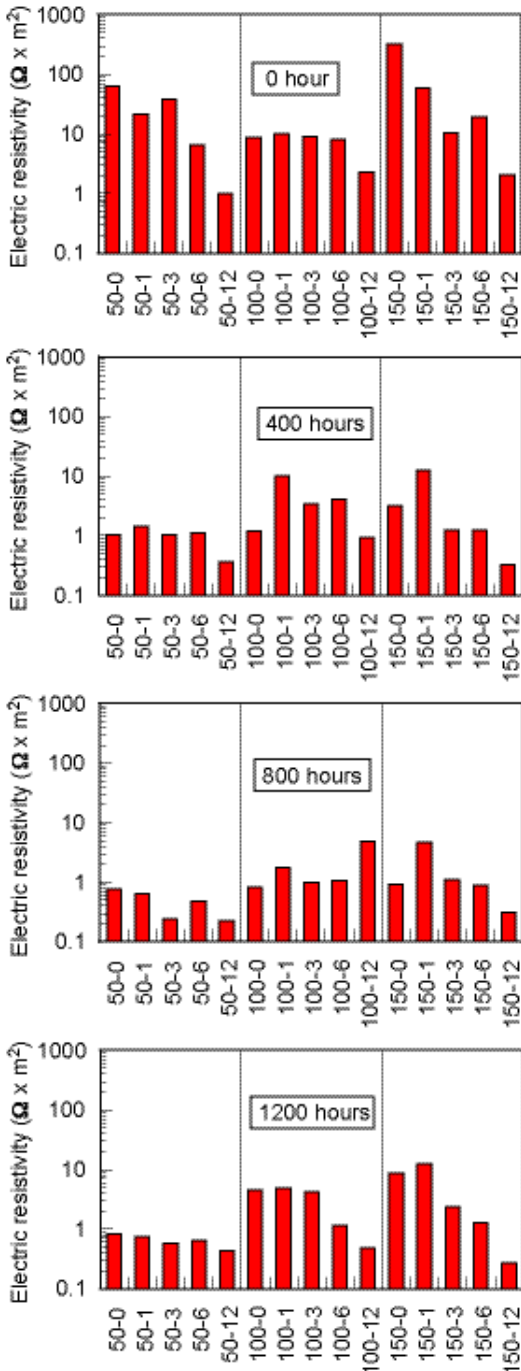Figure 10. Electric resisibity of short-term exposure specimen

Figure 11. Electric resisivity of laboratory test specimen

Figure 10 shows the electric resistivity of the specimens that were exposed for 1 year in the marine environment. The resistivity of the specimens AP, which had been exposed in the splash zone, had dependency on the diameter of the artificial defects in the surface coating, while other specimens TP and SP, which had been placed in the tidal zone and the submerged zone, respectively, did not.

Figure 11 shows the resistivity of the laboratory test specimens after the immersion in the chloride solution for 0, 400, 800 and 1200 hours, respectively. Before the immersion, the resistivity decreased in proportion to the defect size, which clearly shows that the resistivity of the specimens is depended on the diameter of the artificial defects in the surface coating. However, after the 400 hours immersion, the resistivity of the specimens with a 50mm coating did not depend on the defect size. This is because the coating has deteriorated and its resistivity has decreased, thereby making the difference between the resistivity of the surface coating and that of the defect areas smaller. On the other hand, this tendency was not observed in the specimens with a 150mm coating. Therefore, it is considered that the deterioration had progressed in the surface coating to a more than 50mm depth during the 1200 hours of immersion, but not to the depth of 150mm within that duration.

As mentioned above, the resistivity of the short-term exposure specimens TP and SP did not depend on the diameter of the artificial defects. Therefore, it is considered that, despite their short exposure duration, deterioration had progressed deeply into the surface coating as with the laboratory test specimens with a 50mm coating.

3.3 Dimensions of corrosion

3.3.1 Area of corrosion

Figure 12 shows the relationship between the size of the artificial defects and the range of corrosion measured form the edge of the defect in radial directions.

Among all the specimens, the corrosion range was largest in the specimens AP that were exposed in the splash zone. In addition, the range of corrosion after the exposure increased in proportion to the size of the artificial defects in these specimens.
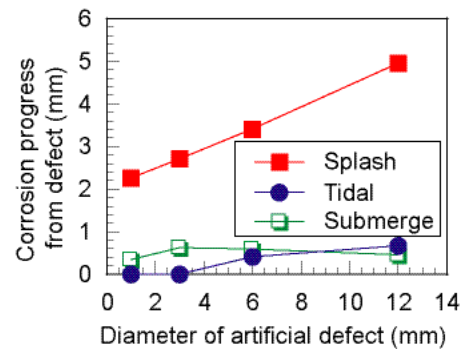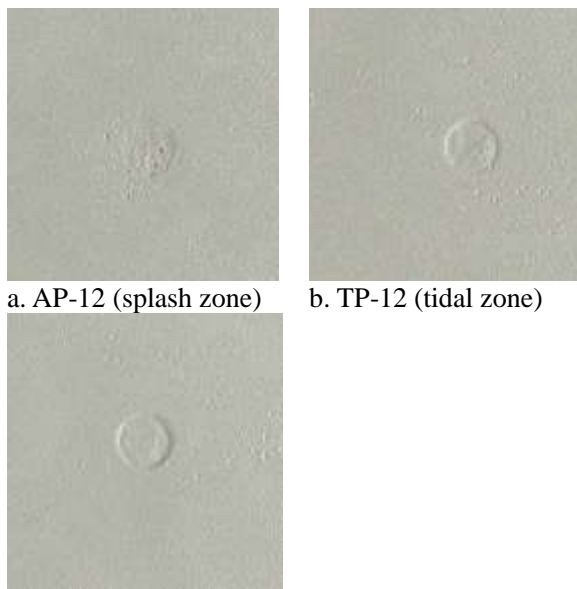

Figure 12. Progress of corrosion area in shot-term exposure specimen

a. AP-12 (splash zone)   b. TP-12 (tidal zone)

c. SP-12 (submerged zone)

Figure 13. Specimens after being removed corrosion products and surface coating

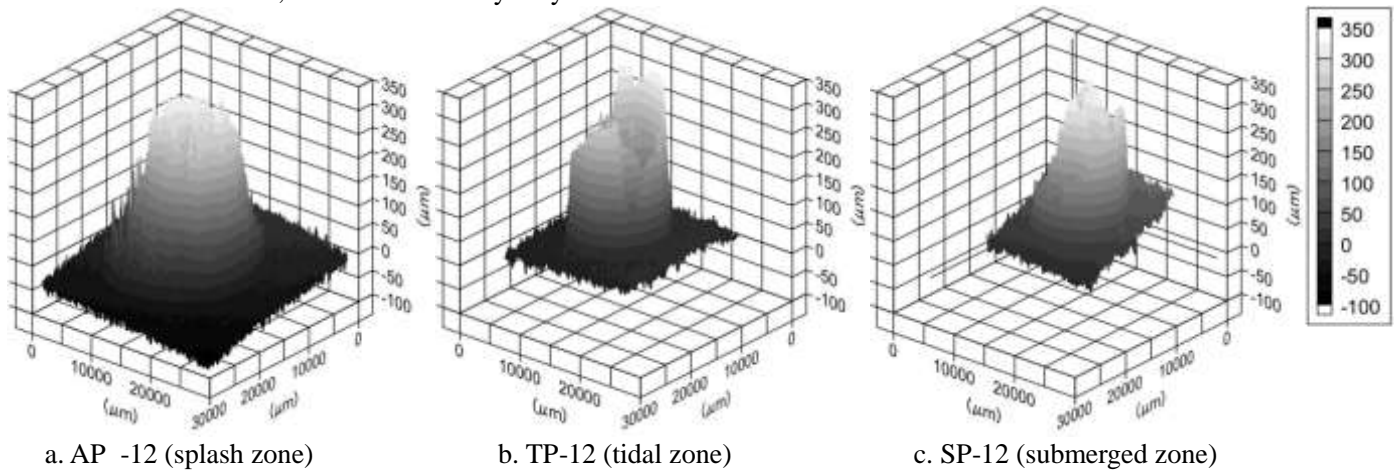progress from the artificial defects in the laboratory test specimens.

3.3.2 *Depth of corrosion*

Figure 13 shows examples of the short-term exposure specimens after the surface coating has been removed. Figure 14 shows the three dimensional shape of the corroded area of the short-term exposure specimens.

The depth of corrosion was largest at the center of the artificial defect in the specimens AP, and also, corrosion had extended from the defect in radial directions in these specimens. On the other hand, corrosion had progressed along the circumference of the artificial defects in the specimens TP and SP such that a circular groove was formed.

Figure 15 shows examples of the three dimensional shape of the corroded area of laboratory test specimens. In these specimens, corrosion made circular groove inside the edge of artificial defect, whose shape are very similar to those in short-term exposure specimens SP and TP.

On the other hand, there was hardly any corrosion
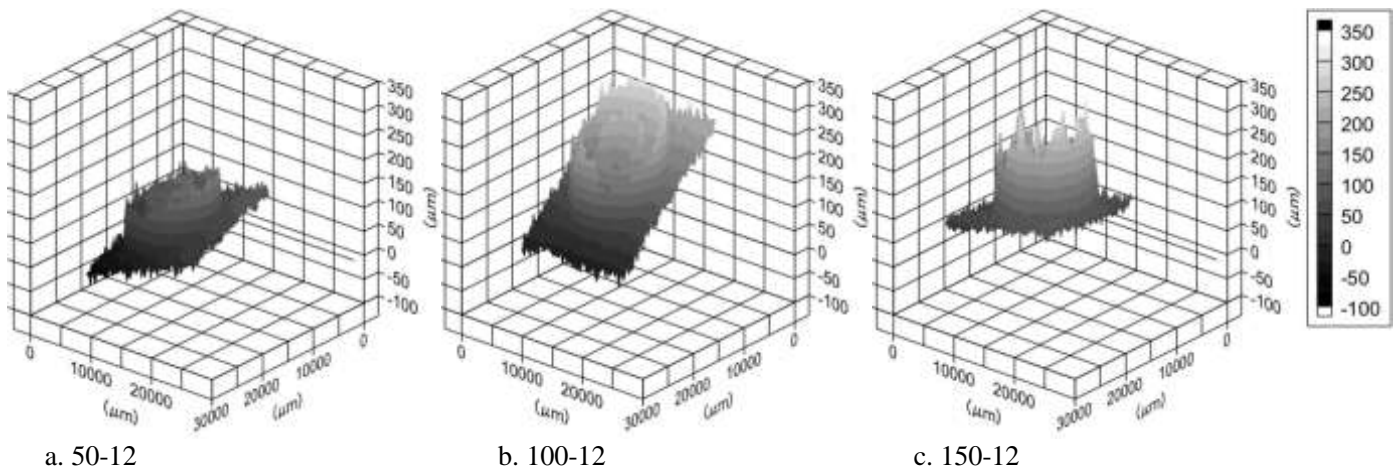

a. AP -12 (splash zone)   b. TP-12 (tidal zone)   c. SP-12 (submerged zone)

Figure 14. Shape of short-term exposure specimens around artificial defect of f12mm

a. 50-12   b. 100-12   c. 150-12

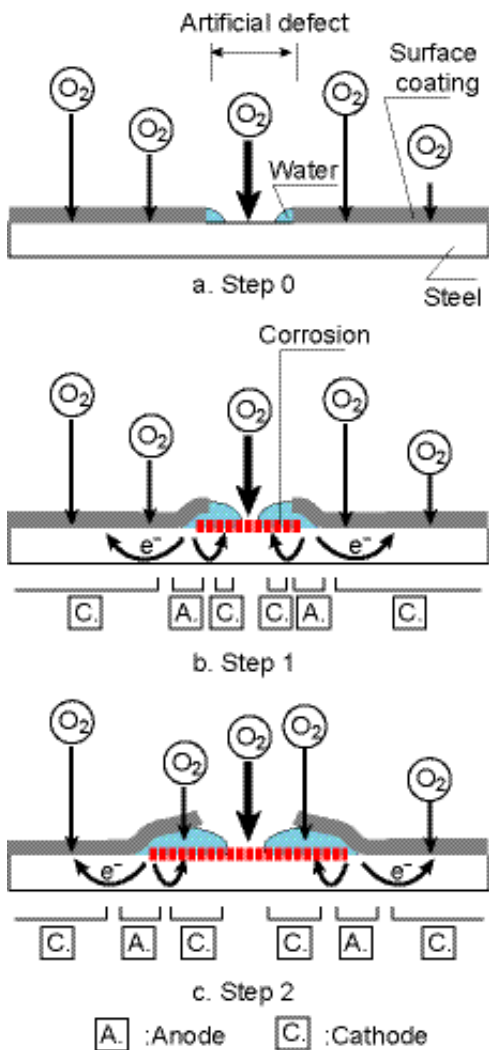Figure 15. Shape of laboratory test specimens around artificial defect of f12mm

Figure 16. Mechanism of corrosion progress around defect in the coating in splash zone

Figure 17. Mechanism of corrosion progress around defect in the coating in submerged zone

3.3.3 *Mechanism of the corrosion progress*

Figure 16 illustrates conceptual diagrams of how corrosion progresses from the surface coating defect in the splash zone.

Water tends to stay around the edge of defect (Fig. 16a). In this area, the edge of retained water is the most oxygen-rich part, which is substantially the center of the defect, and this part works as the cathode of a macro-cell corrosion circuit. Meanwhile, the peripheral parts covered with sound surface coating also work as the cathode because oxygen reaches the steel through the coating [Masuko 1981]. On the other hand, oxygen supply is relatively low around the circumference of the defect and here the anode is formed (Fig. 16b).

Once such a macro-cell corrosion circuit is formed, the surface coating near the anode starts to delaminate due to the cathode reaction of the steel under the coating [Funke 1981, Tsuru et al. 1988]. After that, the delaminated part
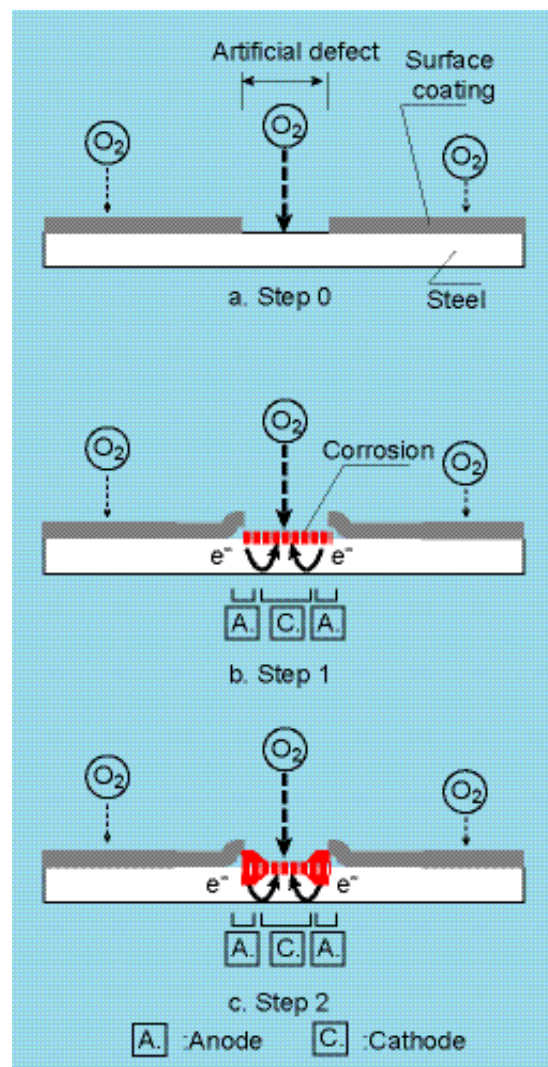
becomes a new anode of the macro-cell. In this way, the anode part of the macro-cell moves radially outward from the defect, (Fig. 16c), and as this process is repeated the delaminated area and corroded area are increased.

On the other hand, the amount of oxygen gas that reaches the steel through the sound coating of the submerged specimens is very small because of the low amount of dissolved oxygen in water (Fig. 17).

In this state, no cathode is formed in the steel under the coating (Fig. 17a). Therefore, a macro-cell circuit is formed only within the boundary of the defect in the coating, resulting in the corrosion occurring only within the defect area. Since the oxygen density is low around the edge of the defect, the anode is always formed here, and the corrosion reaction takes place at the circumference (Fig. 17b).

This is why a circular groove was formed by corrosion along the circumference of the defect in the specimens TP and SP, as shown in Figures 13 and 14 (Fig. 17c).
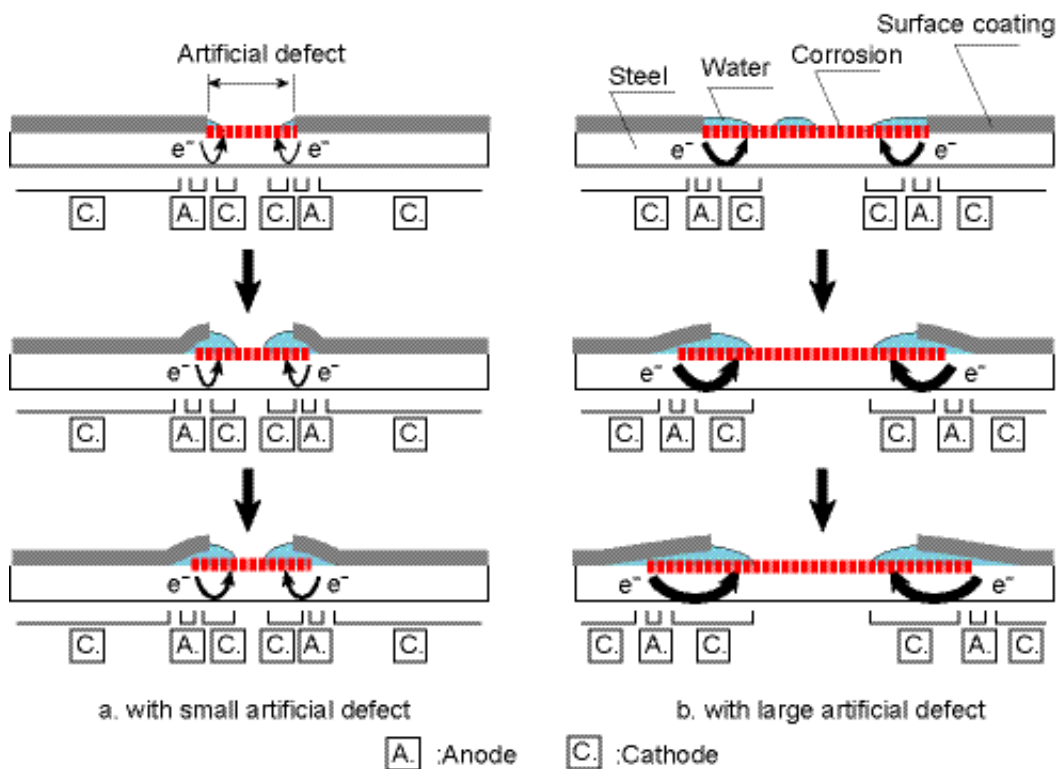
Figure 18. Mechanism of corrosion progress around defect in the coating in splash zone

The close relationship between the size of the artificial defect and the corrosion area can be explained by the fact that the defect size directly defines the cathode size (Fig. 18). In the early stages of deterioration of steel in the splash zone, as mentioned above, the anode is formed at the edge of the artificial defect, while the cathode is formed at the center of the defect and the peripheral parts under the sound surface coating. When the area of the artificial defect working as the cathode is large, corrosion progresses rapidly, resulting in accelerated surface coating delamination and corrosion area enlargement. As the steel under the delaminated coating works as the cathode, the corrosion is further accelerated by the enlarged cathode.

4   CONCLUSIONS

This study aimed at clarifying the corrosion mechanism of steel with surface coating in a marine environment. The corrosion progress of steel materials with tar-epoxy coatings that had been exposed in a marine environment for one and 19 years, respectively, and a steel material with a tar-epoxy coating that had been submerged in a chloride solution at 40°C for 1200 hours, were investigated. Some specimens were provided with artificial defects to investigate the effect of a coating defect on the progress of deterioration.

The results obtained in this study can be summarized as follows:

(1) After 19 years of exposure in a marine environment, the steel material with a surface coating corroded more severely in a tidal zone and a submerged zone than in a splash zone.

(2) The steel material with artificial defects in the surface coating deteriorated most severely in the splash zone after the one year exposure in the marine environment.

(3) Electric resistivity of steel measured by the AC impedance method is affected not only by the corrosion of steel but also by the deterioration of surface coating.

(4) The surface coating starts to deteriorate within one year in the tidal zone and the submerged zone.

(5) Corrosion of steel extends from the defect in a radial direction in the splash zone, and the speed of corrosion depends on the size of the defect.

(6) Corrosion of steel extends in a vertical direction at the edge of the defect and not in a radial direction in the tidal zone and the submerged zone.

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