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Technology

Corrosion Protection for Offshore Steel Structures Using a Metallic Sheathing Technology with Seawater-resistant Stainless Steel

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Abstract

Nippon Steel Engineering Co., Ltd. has developed a corrosion protection sheathing technology that uses highly reliable and economical seawater-resistant stainless steel. We have applied this technology to several offshore steel structures to minimize the life cycle cost in severe corrosive environments. So far, we have advanced corrosion protection technologies that consider long-term durability of sheathing materials and galvanic corrosion in the actual corrosive environment, and welding technologies to apply to actual structures. We explain these technologies and report the application records of some projects, the maintenance guidelines, and the inspection results after 10 years of service.

1. Introduction

Offshore steel structures such as wharfs, breakwaters, offshore airports, and tanker berths are important items of social capital and must last for a long time. They are welded structures of homogeneous and stable-quality steels and have many advantages such as a high freedom of design and a short period of construction. The seas are very corrosive environments for steels. Long-term use of offshore steel structures requires appropriate corrosion protection measures. Especially, exceptionally reliable corrosion protection methods must be applied to steel members used in splash and tidal zones that are severely corrosive environments. Nippon Steel Engineering Co., Ltd. developed a seawater resistant stainless steel sheathing method for the corrosion protection of offshore steel structures with an exceedingly long design service life of 30 to 100 years. This method is more advantageous than conventional organic coating corrosion protection when the maintenance cost for damage by the collision of driftage and aging of materials themselves are considered. It has been applied to many offshore steel structures, including the pier of runaway D at Haneda Airport (**Fig. 1**).

When applying seawater resistant stainless steel sheathings to offshore steel structures, we have endeavored to improve corrosion protection technology and sheathing technology at construction sites, such as welding. In this paper, we outline these advanced technologies and report the results of their application to offshore steel structures and the maintenance and control of offshore steel structures at 10 years after construction.

Fig. 1 Application of stainless steel sheathing to offshore steel structures

2. Application Range of Seawater Resistant Stainless Steel Sheathing

The corrosive environment in which a typical jacket-type off-

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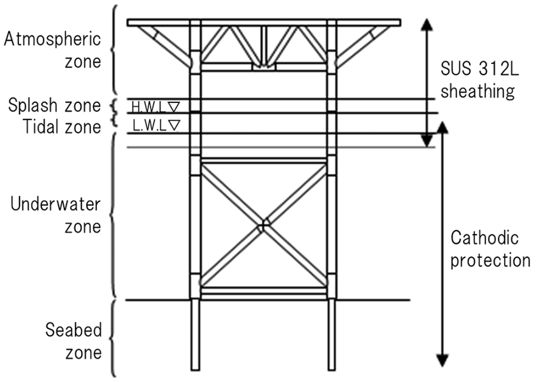

Fig. 2 Application of metallic sheathing to offshore steel structures

shore steel structure is placed is roughly divided into five zones from the top in the vertical direction: marine atmosphere zone, splash zone, tidal zone, underwater zone, and seabed zone, as shown in **Fig. 2**. The corrosion rate is highest in the splash and tidal zones where the oxygen and salt contents are high in the water film formed on the surface of the structural members.

Corrosion protection with seawater resistant stainless steel sheathing is applied in parts of the marine atmosphere, splash, and tidal zones to cover steel members with strong and highly corrosion resistant stainless steel sheets and to shield them from the corrosive environment. A very economical and reliable cathodic protection method is employed in the underwater and seabed zones.

To reduce the cost of the sheathing material and to ease the installation of the sheathing to steel members, it is necessary to attach as thin steel sheets as possible while ensuring necessary corrosion protection performance. Stainless steel sheets about 0.4 to 1.5 mm thick are used as sheathing material.

3. Corrosion Protection Performance of Seawater Resistant Stainless Steel Sheathing

3.1 Properties of sheathing material

The super stainless steel SUS 312L that exhibits excellent corrosion resistance to seawater is used as sheathing material. **Table 1** shows the specified and typical mechanical properties of the SUS 312L.[1] The SUS 312L has a 0.2% proof stress about 1.5 times higher than that of the SUS 304 and SUS 316 at room temperature. In addition, the hardness of the SUS 312L is high so that excellent impact resistance and wear resistance can be expected.

Table 1 Mechanical properties of SUS 312L[1]

	0.2% proof stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Hardness (HV)
JIS	≥300	≥650	≥35	≤230
Example t=1.2 mm	461	843	39	192

Table 2 shows the pitting corrosion resistance and crevice corrosion resistance of the SUS 312L evaluated according to the ASTM G48.[1] The critical crevice corrosion initiation temperature in Table 2 is said to approximately correspond to the upper limit temperature at which crevice corrosion does not occur in natural seawater. This suggests that the SUS 312L is negligibly susceptible to corrosion in normal temperature seawater.

Table 2 Corrosion resistance of SUS 312L[1]

	SUS 312L	SUS 316L
Critical pitting temperature (°C) (ASTM G48-E)	70–75	20
Critical crevice temperature (°C) (ASTM G48-F)	55	5

3.2 Evaluation of corrosion protection performance by simulating actual environment

Nippon Steel Engineering has conducted various exposure tests to evaluate the corrosion resistance of the sheathing material in actual marine environments. **Figure 3** shows the results of a four-year shower exposure test with actual seawater at a long-term exposure test site in Yokosuka City, Kanagawa Prefecture. The shower exposure test was conducted to simulate cyclic drying and wetting in the splash zone. The comparison materials SUS 304 and SUS 316 corroded, but the SUS 312L retained its metallic luster and was confirmed to have excellent corrosion resistance. As shown in **Fig. 4**, exposure tests have been performed on the SUS 312L since 1997 at a wharf in the Wakamatsu Plant of Nippon Steel Steel Structure Co., Ltd. The SUS 312L is confirmed to have long-term corrosion resistance in the marine environment.[2]

Fig. 3 Seawater shower exposure test[2]

Fig. 4 Exposure test in coastal area

3.3 Protection against galvanic corrosion

The SUS 312L shows a potential more noble than that of carbon steel in seawater. When the SUS 312L is in contact with the carbon steel, the potential difference causes electric current to flow from the carbon steel to the SUS 312L through the seawater and increases the corrosion rate of the carbon steel. (This is called galvanic corrosion.) The SUS 312L and carbon steel are in contact with each other at the stainless steel sheathing boundary. In the atmospheric zone, the carbon steel is painted and protected from exposure. Normally, there is usually no likelihood of galvanic corrosion. In the undersea zone, cathodic protection is provided with aluminum alloy anodes. Electric current flows in from the aluminum alloy anodes at the least noble potential and inhibits the corrosion of the carbon steel. The corrosion rate of the carbon steel had been evaluated by a 10.5-year exposure test by simulating the damage of the stainless steel sheathing by the collision of driftage. The results are shown in **Fig. 5**. The corrosion rate of the stainless steel sheathing in the splash zone is similar to that of the carbon steel. In the tidal zone to the undersea zone, the corrosion of the stainless steel sheathing is prevented by cathodic protection. No or little effect of galvanic corrosion is observed in the damaged portions. The possibility is confirmed of predicting the corrosion amount of the exposed portions of the carbon steel.[3)]

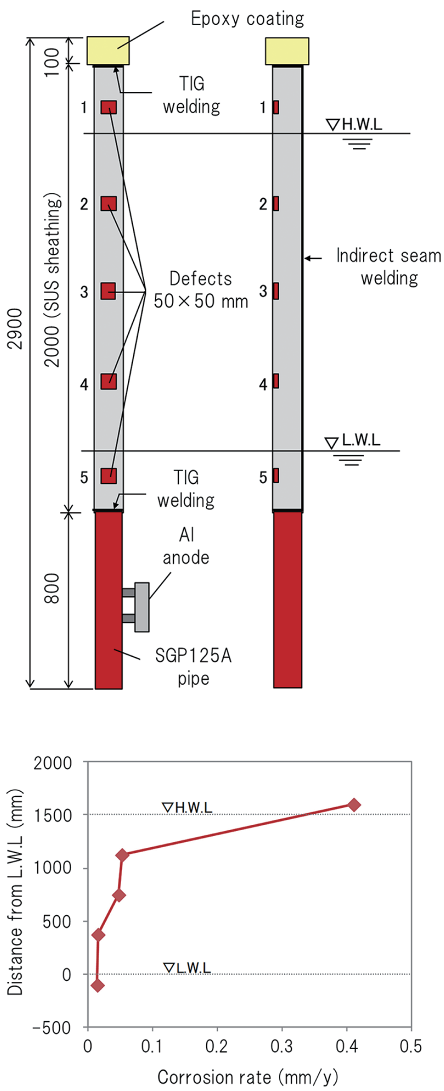

Fig. 5 Measurement of corrosion rate of steel at stainless steel damaged area[3)]

4. Welding Technology for Seawater Resistant Stainless Steel Sheathing

4.1 Automatic welding to steel pipes

The combined indirect seam-plasma welding process developed for automatically welding 0.4 mm thick SUS 312L sheets is applied to the steel pipe members that occupy the main parts of the sheathed areas of the steel structure. Indirect seam welding is an indirect conduction seam welding process in which two electrodes are applied to the sheathing sheets as shown in **Fig. 6**. In conventional indirect seam welding, back bars of copper or a similar metal are placed at the back of the sheets to stably obtain an electric current flow path to penetrate the sheets to be welded. For this indirect seam welding process, the current flow path is obtained through the steel pipe on the back side of the sheathing sheets. The thin SUS 312L sheets can be thus directly welded to the steel pipe.[4)]

The SUS 312L sheets can be joined to the steel pipes by indirect seam welding alone. The welded joint thus produced may become a crevice structure and may initiate crevice corrosion, depending on the use environment. For this reason, the sheathing sheets are joined to the steel pipe by indirect seam welding. At the same time, the plasma welding process is also applied to eliminate the crevice structure.[4)] The plasma welding process uses the Inconel 625 as the welding material. The combined indirect seam-plasma welding process is schematically illustrated in **Fig. 7**. The ends of the indirect seam welded joint are sealed by tungsten inert gas (TIG) welding to ensure watertightness. **Table 3** shows some of the combined welding conditions. A high welding speed of 80 cm/min is achieved with 0.4 mm thick SUS 312L sheets.[5)] **Figure 8** shows the combined indirect seam-plasma welding equipment.[4, 5)]

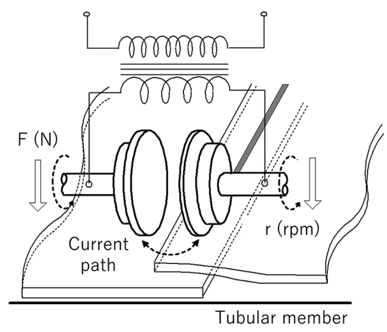

Fig. 6 Schematic illustration of indirect seam welding[4)]

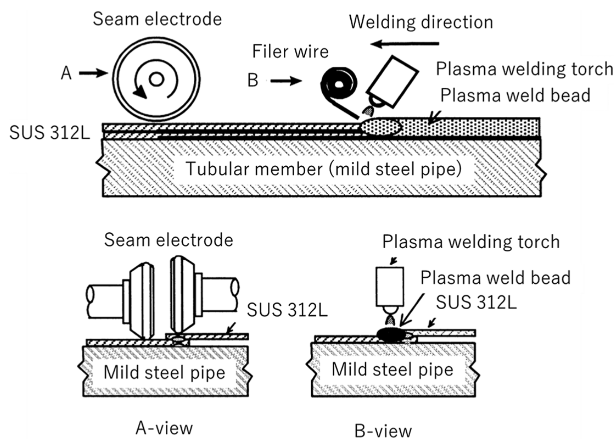

Fig. 7 Schematic illustration of combined welding[4)]

Table 3 Welding condition of combined welding[5)]

	Current (A)	Speed (cm/min)	Pressure (kN)	Shielding gas
Indirect seam welding	5 500–7 500	80	2–5	–
Plasma welding	80–120		–	Ar+7%H_2

Fig. 8 Equipment for automatic combined welding[4, 5)]

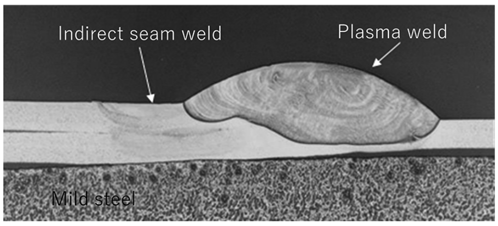

Fig. 9 Cross section of weld bead[4)]

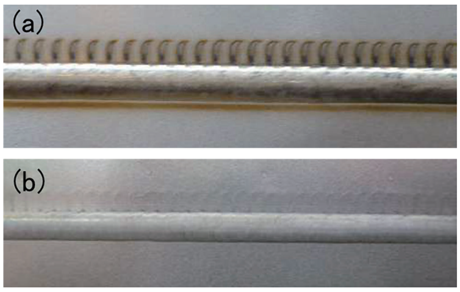

Fig. 10 Appearance of weld bead after electrolytic polishing
(a) Before polishing (b) After polishing

Figure 9 shows a cross-sectional photograph of a welded joint obtained with this welding process. The welded joint has no such burn-through and pinholing as encountered with plasma welding and is sound without a crevice structure.[4)]

High-temperature oxidation regions are formed in the welded joint and in the nearby regions under the effect of the welding heat as shown in **Fig. 10** (a). The corrosion resistance of the high-temperature oxidation regions may be lower than that of the stainless steel base metal. The high-temperature oxidation regions are thus removed by electrolytic polishing after welding. Figure 10 (b) shows the welded joint surface condition after electrolytic polishing. It can be seen that the high-temperature oxidation regions near the welded joint are completely removed by electrolytic polishing.

4.2 Welding to flat surface members

The combined indirect seam-plasma welding process restricts the welding position only to the downward position due to its equipment structure. The welding of the stainless steel sheathing to flat surface members in the marine atmosphere zone and other zones must be otherwise performed in the vertical or upward position. In this case, this welding is carried out by manual TIG welding with the Inconel 625 as the welding material. From the viewpoint of facilitating welding (preventing burn-through and pinholing), SUS 312L sheets, about 1.0 to 1.5 mm in thickness, are used for sheathing. **Figure 11** shows an example of welding SUS 312L sheathing sheets to a flat carbon steel plate. First, two SUS 312L sheathing sheets are welded to the flat carbon steel plate. Next, an SUS 312L band piece is welded to cover the gap between the SUS 312L sheathing sheets. The SUS 312L sheathing sheets and band piece are tack welded by spot TIG welding.

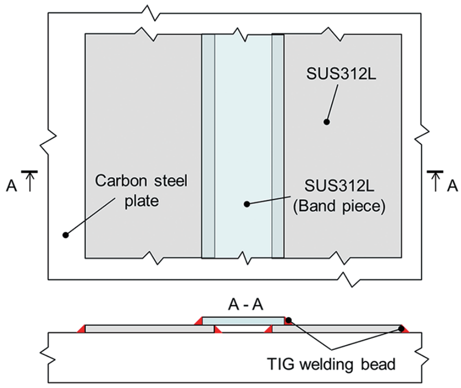

Fig. 11 Application of SUS 312L to a plane surface by TIG welding

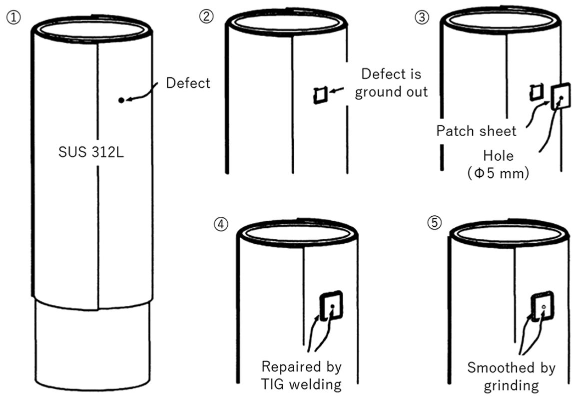

Fig. 12 Procedure of repair welding[4)]

4.3 Welding repair of damaged portions

A patch repair welding method is established by assuming that on-site repair may be required for sheathing sheet portions damaged by the collision of driftage. The repair welding procedure is shown in **Fig. 12**. As patches, 1.0 to 1.5 mm thick SUS 312L sheets are used. If seawater has entered the gap between the sheathing sheet and the steel pipe from the damaged portion, a 5 mmφ steam vent hole is drilled to remove the steam formed by the heat of welding from the water in the pipe. This steam vent hole is not required if the area around the repair portion is dry. The patch is lap fillet welded all around by TIG welding. The steam vent hole is then plugged by TIG welding. The Inconel 625 is used as the welding material. The welded patch is liquid penetrant tested. If no defects are found, the procedure is completed.[4)]

5. Application Results of Seawater Resistant Stainless Steel Sheathing

5.1 Introduction of application results

The seawater resistant stainless steel sheathing method has been applied to many harbor jacket structures, including runway D at Haneda Airport (Fig. 1).

Runway D at Haneda Airport was constructed offshore and put into operation in 2010. It is located near the mouth of the Tama River and about one-third of it is a pier structure to secure the flow of the river water. The pier structure is constructed of a grid-pattern steel girder superstructure to provide a large flat surface; 198 steel jackets constructed of truss substructures of legs and braces to support the superstructure; and 1 165 foundation piles to secure the jackets. **Figure 13** shows the appearance of the jacket structure before marine transport. At runway D at Haneda Airport, the stainless steel sheathing described here is applied to the surfaces of all of the 1 165 jacket legs (total area of 114 000 m^2) at the pier. The SUS 312L sheets for all of the stainless steel sheathings were bright annealed at the Yamaguchi Works of Nippon Steel Stainless Steel Corp., so that the oxide scale formed during the annealing of the SUS 312L sheets would not adversely affect the steel members of the pier structure of runway D with a design service life of 100 years. Since then, bright annealed SUS 312L sheets have been used for all of the sheathings installed by Nippon Steel Engineering, regardless of the length of the design service.

Table 4 shows some of the jacket structures with stainless steel sheathings applied by Nippon Steel Engineering in recent years. The stainless steel sheathing technology has been applied as an important corrosion protection technology to ensure the reliability of offshore structures in many harbor infrastructure projects that demand long-term durability in severely corrosive environments.

5.2 Maintenance and control of runway D at Haneda Airport

For runway D at Haneda Airport, a 100-year maintenance and control program was prepared at the time of design and construction.[6] The preventive maintenance philosophy is introduced to avoid the large-scale repairs of the steel jackets. **Table 5** outlines the maintenance and control procedures for the stainless steel sheathings.

A large factor in the stainless steel sheathing being damaged and losing its corrosion protection function is the collision of driftage. Runway D is located at the mouth of a large river where there are many pieces of driftage. Once a year, all legs are visually inspected from afar on a routine basis. **Table 6** shows the results of the most recent visual patrol inspection of 1 203 jacket legs of runway D about 10 years after service. Partial deformations, such as those caused by the collision of driftage, were observed in multiple positions of the stainless steel sheathings (233 positions judged c). There were no positions where the underlying steel pipes were damaged and corroded. These results demonstrated the excellent reliability of the stainless steel sheathings.

If damage to the stainless steel sheathing is found during future patrol visual inspections, it will be repaired in accordance with the procedures described in Section 4.3. Regarding on-site repairs, there is a case where the stainless steel sheathing was damaged by the collision of a workship during the construction work of runway D and was repaired. **Figure 14** shows the repair situation at that time. Approximately 10 years have passed since the repair, but the repair portion shows no corrosion and no other alteration. We have confirmed that if the sheathing is damaged and properly repaired on-

Fig. 13 Jacket structure

Table 4 Recent application records to jacket structures

Year	Project	Sheathing area (m^2)
2019	Tokuyama-Kudamatsu Port Kudamatsu Area Pier	3 561
2018, 2019	Fukuoka Island City	1 339
2018	Mizushima Port Tamashima Area	2 124
2018	Sasebo Port Uragashima Area	2 216
2016, 2018	Tokyo Port No. 13 Terminal	4 141
2016, 2017	Hakata Port Chuo Wharf Berth	1 725
2016, 2017	Kushiro Port	927

Table 5 Maintenance procedure

Action	Frequency
Annual patrol	Once a year
Emergency inspection	In case of emergency
Close-up visual inspection	After 5, 15, 30, 60, 90 years
Corrosion monitoring	After 5, 15, 30, 60, 90 years

Table 6 Inspection results after 10 years of service

Inspection items	Degree of deterioration*			
	a	b	c	d
Stainless steel sheathing: Deformation, damages, corrosion	0	0	233	970

*a: Protection performance has deteriorated and structural steel is corroded.
b: Protection performance is about to deteriorate because of corrosion and/or abrasion of stainless steel sheathing.
c: Protection performance has not deteriorated, but slight corrosion and/or deformation of stainless steel sheathing are identified.
d: No changes of stainless steel sheathing are identified.

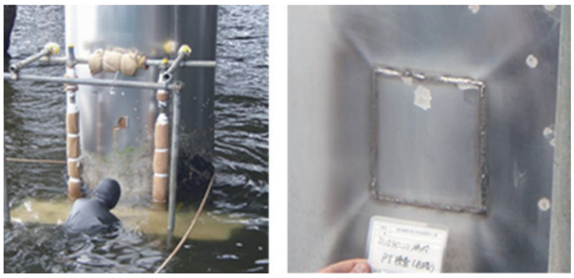

Fig. 14 On-site repair of damaged area

site, it can recover and maintain its corrosion protection function for a long period of time.

Based on the above results, we believe that the sheathing will be able to maintain its corrosion protection performance without requiring any major repair work even after 100 years, if properly maintained and controlled as done now. Concerning the maintenance and control of runway D, the items and frequency of inspection are planned to be reviewed based on the results of deterioration judgment and prediction. The maintenance control data are all stored in a database.

6. Conclusions

The seawater resistant stainless steel sheathing has been applied in many construction projects, including runway D at Haneda Airport, and has contributed to ensuring the reliability of offshore steel structures as a corrosion protection technology to provide both long-term durability and economy. Stainless steel sheathing construction technology such as welding has been improved day by day.

We will continue our technology development to expand the application range of the stainless steel sheathing and improve its construction efficiency. We will also work to improve the reliability and reduce the construction cost of offshore steel structures.

Acknowledgment

We would like to thank the late Masami Abe (the then Chief Researcher of the Port and Airport Research Institute) for his great cooperation in conducting various exposure tests in Yokosuka City, Kanagawa Prefecture.

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