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Development of Exclusive Welding Consumables for Corrosion-resistant Steel Plates

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Abstract

Launching new steel plates onto the market after completion of development also requires the development and delivery of welding consumables that match the new functions of the developed steel plates. This report introduces welding consumables exclusively developed for the recently developed corrosion-resistant steel plates. The first welding consumable is used exclusively in high corrosion-resistant steel for crude oil tankers (NSGP™-1 & 2). The second is used exclusively in coating cycle extension steel (CORSPACE™) that has superior atmospheric corrosion resistance in paint film defects. It was confirmed that the weldability and welding performance of these welding consumables were equivalent to those of an existing popular welding consumable.

1. Introduction

Many large-scale steel structures such as ships as well as high-rise buildings and steel bridges are constructed from steel plates (base metal) that are welded together using welding consumables. In order for steel plates to work appropriately in an entire structure, welds are expected to be equipped with the same function as that of the base metal. This is demonstrated by examples such as the heavy dependence of the mechanical behavior of a whole structure on the mechanical properties of welds, and/or the influence of poor weld metal corrosion resistance under servicing surroundings remarkably inferior to that of the base metal on the service life of a whole structure. Accordingly, when a steel plate equipped with new functions is developed and introduced to the market, the development of exclusive welding consumables is necessary in order for the welded joints to fully exert functions equivalent to those of the plate. Particularly, in the case of corrosion-resistant steel plates in which special attention to chemical compositions is required to secure corrosion resistance, designing of chemical compositions that enable the weld metal to be equipped with corrosion resistance equivalent to that of base metal is essential. As an example, **Table 1** shows a list of the main product lines of corrosion-resistant steel plates developed to date and the welding consumables used exclusively in them.

Nippon Steel & Sumitomo Metal Corporation (NSSMC) conducts continuous research and development on welding consumables and welding technologies that are best suited to the properties of the base metals it supplies in order for them to fully exploit their potential In addition, in close cooperation with Nippon Steel & Sumikin Welding Co., Ltd. (NSSW), an affiliate company of NSSMC, Nippon Steel & Sumitomo Metal promotes the commercialization of newly developed welding consumables, realizing prompt delivery to steel plate users.

This report introduces the results of development of welding consumables for exclusive use in innovative high corrosion-resistant steel plates for crude oil carriers (NSGP™-1 & 2) and the coating cycle extension steel plates (CORSPACE™).

2. Development of Exclusive Welding Consumables for High Corrosion-resistant Steel Plates in Crude Oil Carriers (NSGP-1, NSGP-2)

2.1 Outline of NSGP-1 and NSGP-2[1–3)]

High corrosion-resistant steel plates for crude oil carriers (NSGP-1 and NSGP-2) exhibit remarkable corrosion resistance un-

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Table 1 Example of welding consumables used exclusively for corrosion-resistant steel plates

Type of corrosion-resistant steels	Developed steel plates	Developed welding consumables: product names
High corrosion-resistant steel for crude oil tankers	NSGP™-1, NSGP™-2	FCAW: NSSW SF-1·GP, NSSW SM-1F·GP SAW: NSSW NSH-50M × NSSW NSH-1RM × NSSW Y-DL (3 electrodes)
Coating cycle extension steel	CORSPACE™	SMAW: NSSW L-55·PX, NSSW L-60·PX FCAW: NSSW SF-1·PX, NSSW SM-1F·PX FCAW: NSSW SF-60·PX, NSSW SM-60F·PX GMAW: NSSW YM-26·PX, NSSW YM-55C·PX, NSSW YM-60C·PX SAW: NSSW YF-15 × NSSW Y-D·PX, NSSW YF-800 × NSSW Y-D·PX SAW: NSSW YF-15B × NSSW Y-DM3·PX, NSSW NF-820 × NSSW Y-D·PX SAW: NSSW YF-15B × NSSW Y-DM·PX, NSSW NF-820 × NSSW Y-DM·PX
Sulfuric-acid/hydrochloric-acid dew-point resistant steel	S-TEN™ 1	SMAW: NSSW ST-16M FCAW: NSSW SF-1ST SAW: NSSW Y-1ST × NSSW NB-1ST
	S-TEN™ 2	SMAW: NSSW ST-16Cr FCAW: NSSW FC-23ST GMAW: NSSW FGC-55
Nickel-based high weather-resistant steel	NAW-TEN™ 15	SMAW: NSSW CT-50N, NSSW CT-60N GMAW: NSSW YM-3N FCAW: NSSW SF-50WN, NSSW SF-60WN SAW: NSSW NF-320M × NSSW Y-3NI
Seawater corrosion resistant (undersea) steel	MARILOY™	SMAW: NSSW RS-55 GMAW: NSSW YM-55RSA FCAW: NSSW SF-55RS

der corrosive environments specific to crude oil tankers.

Corrosion on the bottom differs from that on the ceiling in oil tankers. Pitting-like corrosion develops on the bottom (hereinafter referred to as pitting), and general corrosion develops on the ceiling. Since the pitting developed on the bottom is deep, and sometimes several hundred pittings exist in a tanker, a huge maintenance cost is incurred in periodical inspections and for repairing the pitting in tankers built from conventional steels.

Development of the pitting on the bottom of a tanker is attributed to the brine that permeates in crude oil, and decrease in the pH (of brine) along with the progress of corrosion further develops the growth of pitting cumulatively. Moreover, corrosion on the ceiling develops by exposure to an atmosphere containing H_2S derived from crude oil, and additionally, by the repetition of dry and wet environments on the ceiling surface due to day and night temperature changes in the hull.

Based on this corrosion mechanism, and by studying chemical compositions effective in the realization of corrosion resistance, as well as by optimizing steel-material production conditions, NSGP-1 for use in oil tanker bottom plates of crude oil carriers, and NSGP-2 for use in ceilings were developed, respectively. A comparison of the corrosion-resistance performance of the developed steel (NSGP-1) and conventional steel is shown in **Fig. 1** (corrosion conditions: 10% NaCl-HCl solution (pH 0.85), temperature 30°C immersion duration 72 h).

Excellent corrosion resistance performance was confirmed, and the steel was stipulated in the corrosion-protecting standard pertaining to oil tankers of crude oil carriers enacted in 2013 as an alternative corrosion-protection measure to painting (application of corrosion-resistant steel) for the first time in the marine vessel field. Hence, omission of painting of the inside of oil tankers is now possible, and the steel is making great contributions to the following: omission of painting of inside of oil tankers, enhancement of durability of oil tankers, reduction of painting cost in ship building, reduction of emission of volatile organic compounds (VOC) from painting, and reduction in maintenance cost after completion.

2.2 Development of exclusive welding consumables for NSGP-1 and NSGP-2

The compositional design of exclusive welding consumables was formulated based on the chemical compositions of NSGP-1 and NSGP-2. In the construction of oil tankers, in addition to butt welding, fillet welding for attaching stiffener plates is frequently used. Moreover, in addition to welding of NSGP-1 and NSGP-2, welding of NSGP-1 or NSGP-2 with conventional steel materials for shipbuilding is considered. Assuming jointing of various types of steel materials, the chemical compositions of welding consumables were designed so as to realize a corrosion resistance that secures corrosion resistance equivalent to that of the base metals of NSGP-1 and

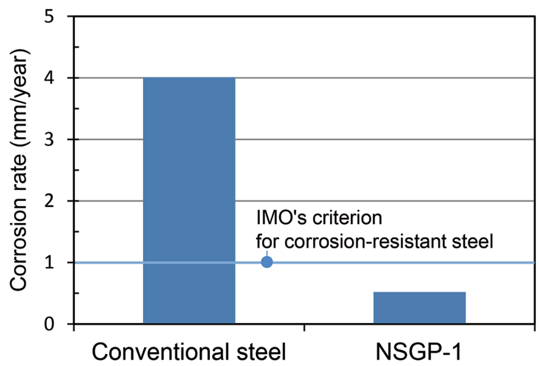

Fig. 1 Comparison of corrosion rate between developed steel (NSGP-1) and conventional steel plate

Table 2 Typical chemical compositions (principal elements) of deposited metal of exclusive welding consumables for NSGP-1 and NSGP-2

Welding method	Welding consumables	Chemical compositions (mass%)					C_{eq} (IIW)*
		C	Si	Mn	P	S	(mass%)
FCAW	NSSW SF-1·GP	0.05	0.42	1.16	0.017	0.006	0.305
	NSSW SM-1F·GP	0.04	0.45	1.46	0.018	0.013	0.347

* C_{eq} (IIW) = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5

Table 3 Typical mechanical properties of deposited metal of exclusive welding consumables for NSGP-1 and NSGP-2

Welding consumables	Plate thickness (mm)	Wire diameter (mm)	Heat input (kJ/mm)	Tensile test		Charpy impact test
				0.2% proof stress (N/mm^2)	Tensile strength (N/mm^2)	Charpy absorbed energy at 0°C vE_0 (J)
NSSW SF-1·GP	20	1.2	1.8	553	613	111
NSSW SM-1F·GP	20	1.2	1.7	524	598	66

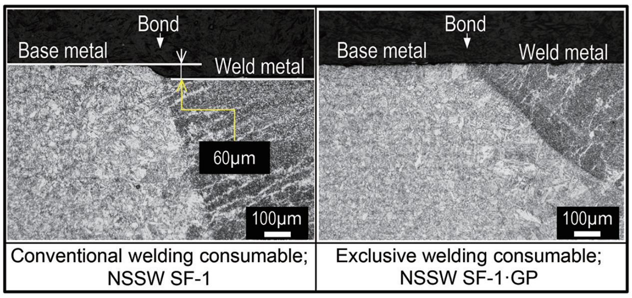

Fig. 2 Macrostructure of welds of NSGP-1 after corrosion test

NSGP-2 under oil tanker conditions. As a result, NSSW SF-1·GP was developed as flux cored wire for all position welding, and NSSW SM-1F·GP was developed as flux cored wire for horizontal fillet welding.

These exclusive welding consumables were developed based on the NSSW SF-1 and NSSW SM-1F of Nippon Steel & Sumikin Welding, both being flux cored wires (FCW) used for conventional steel with excellent welding workability, and the developed welding wires added with corrosion-resistant compositions also ensure equivalent high welding workability. Moreover, both of the developed welding wires are seamless type flux cored wires, which previously focused on the reduction of hydrogen in the welding consumables, and susceptibility to hydrogen cracking of the weld metal has been reduced accordingly.

Corrosion resistance performance of the developed exclusive welding consumables was compared with that of the existing welding consumables for conventional steel use. **Figure 2** shows the cross-sectional macrostructure at the boundary of the weld metal and the base metal on the corrosion test specimen (corrosion conditions: 6N-HCl 15 mL-1.93 mol NaCl-1L, diluted with pure water by 10 times (pH 2.1), temperature 30°C, immersion duration 168 h). For the left side test specimen, NSSW SF-1, a flux cored wire for conventional steel use, is used, and, for the right side test specimen, NSSW SF-1·GP, the developed exclusive welding consumable, is used. When the corrosion-induced thickness reduction of the weld metals is compared, as the weld metal of the exclusive welding consumable does not form a step at the boundary between the base metal and the weld metal, the corrosion-induced reduction in thickness is considered to be almost equivalent to that of the base metal.

Chemical compositions (principal elements) of the deposited metals are shown in **Table 2**. The principal elements of the chemical compositions and the carbon equivalents (C_{eq}) other than those related to corrosion resistance are the same level as those of the welding consumables for conventional steel, and ensure excellent weldability. The mechanical properties of the deposited metals are shown in **Table 3**. The deposited metals secure strength and toughness that sufficiently satisfy the strength specifications of NSGP-1, NSGP-2 and other tanker-use shipbuilding steel materials.

These exclusive welding consumables have been endorsed by shipbuilding associations (NK, ABS, LR) with classifications that are equivalent to those of NSSW SF-1 (for all position welding), FCW products for conventional steel use, and NSSW SM-1F (for horizontal fillet welding), on which the development was based. Therefore, at the jointing sections where different steel plates from among NSGP-1, NSGP-2 and conventional ship building steel plates have to be welded, the selection of welding consumables depending on the combination of steel is unnecessary, and the developed welding consumables contribute to securing the corrosion resistance of the entire oil tanker without hindering work efficiency.

3. Development of Welding Consumable for Exclusive Use in Coating Cycle Extension Steel (CORSPACE)

3.1 Outline of CORSPACE[4, 5]

The coating cycle extension steel (CORSPACE) is an innovative new type of corrosion-resistant steel plate that enables the extension of the repainting cycle by suppressing the propagation of corrosion from coating film defects in painted steel structures. With this steel, it is possible to significantly reduce the life cycle cost (hereinafter referred to as LCC) of steel structures. Many steel structures are used after being coated with corrosion-resistant paint. However, there are many cases in which corrosion develops by ageing where sufficient coating film thickness cannot be secured such as on the insides of structural members that are jointed at an acute angle, and/or in the coating defects that cannot be found during construction. In particular, under severe corrosive circumstances such as airborne salt in coastal areas, and/or antifreeze agents, corrosion progresses rapidly, and the progress of accumulative separation of coating film and reduction in plate thickness become matters of concern.

We clarified the fundamental mechanism of the progress of corrosion around coating defects, and found that a small amount of Sn added to steel material significantly suppresses the solution reaction of Fe into thin water film assumed to exist in coating film defects. Taking advantage of this suppressive reaction, we have developed

Table 4 List of exclusive welding consumables for CORSPACE

Tensile strength rank of CORSPACE	Covered electrodes	Solid wire	Flux cored wire		Submerged arc welding materials	
	All position		All position	Fillet	Butt	Fillet
SS400-CORSPACE SM400-CORSPACE SM490-CORSPACE SM490Y-CORSPACE SBHS400-CORSPACE	L-55·PX	YM-26·PX	SF-1·PX	SM-1F·PX	YF-15 × Y-D·PX	YF-800 × Y-D·PX
SM520-CORSPACE	—	YM-55C·PX	—	—	YF-15B × Y-DM3·PX	NF-820 × Y-D·PX
SM570-CORSPACE SBHS500-CORSPACE	L-60·PX	YM-60C·PX	SF-60·PX	SM-60F·PX	YF-15B × Y-DM·PX	NF-820 × Y-DM·PX

CORSPACE steel that suppresses coating film separation and corrosion in coating film defects, and enables extension of the repainting cycle.

3.2 Development of exclusive welding consumable for CORSPACE

We designed and developed exclusive welding consumables for CORSPACE, taking into consideration securing the amount of Sn in the weld metal that characterizes the corrosion-resistance of CORSPACE and the reduction of elements that promote corrosion in coating film defects. As a variety of application fields is assumed for CORSPACE, exclusive welding consumables were provided for almost all types of welding consumables (manual welding rod, FCW, solid wire, submerged arc welding (SAW) consumables). **Table 4** shows a list of the exclusively developed welding consumables corresponding to the strength grade of CORSPACE.

The welding consumables for exclusive use in CORSPACE were developed based on the welding material of Nippon Steel & Sumikin Welding that has excellent welding workability, and is used for conventional steel, and the developed products, which employ chemical compositions contrived to suppress coating film separation, secure equivalent excellent welding workability. Moreover, the developed FCW products are all seamless type flux cored wires, and the susceptibility to hydrogen cracking of the weld metal has been reduced.

As an example of corrosion resistance performance of the developed exclusive welding consumables, the result of the evaluation of the weld metal of NSSW SF-1·PX, an FCW product, is shown. For comparison, NSSW FCM-1F of existing FCW for conventional steel use was selected. The groove shape of the conventional steel weld for evaluating the properties of weld metal is shown in **Fig. 3**. A butt-weld test specimen was prepared, and a flat corrosion test specimen that includes the weld metal was taken from the weld test sample and corroded by the accelerated test of repeated drying and humidifying as per SAE J 2334[6] as shown in the block diagram in **Fig. 4**, and the thickness reduction of the weld metal was measured. **Figure 5** shows the corrosion resistance performance of the weld metal of developed NSSW SF-1·PX. As compared with the case of existing welding consumables for conventional steel, plate thickness is reduced to approximately 1/4.

Table 5 shows the major chemical compositions and the mechanical properties of deposited metals of welding consumables exclusively developed for CORSPACE. The carbon equivalent (C_{eq}) of principal elements other than those related to corrosion resistance is the same level as that of the weld metal of the welding consumables for conventional steel, and secures excellent weldability. Moreover, it is confirmed that no weld defects such as cracks are caused by the corrosion-resistant chemical compositions. These exclusive welding consumables secure sufficient strength and toughness that conform to corresponding CORSPACE specifications. JIS certification has been acquired for the manual welding rod, FCW and solid wire (regarding welding consumables for SAW, conformity to JIS has been confirmed).

Weld are not as flat and smooth as the base metal surface, and

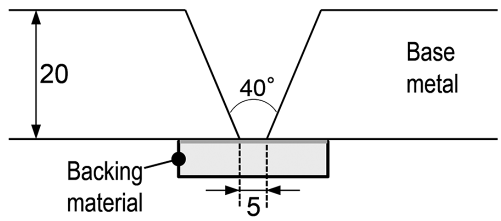

Fig. 3 Groove shape of welds

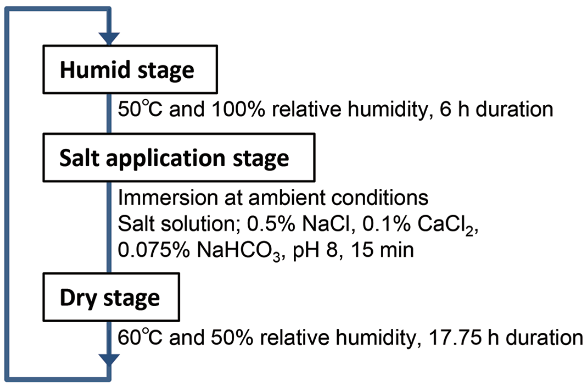

Fig. 4 Test cycle condition of SAE J 2334[6]

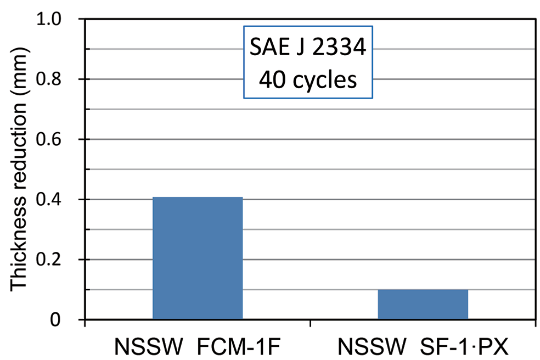

Fig. 5 Comparison of corrosion-resistance of weld metals

Table 5 Typical chemical compositions and mechanical properties of deposited metal of exclusive welding consumables for CORSPACE

Product names	JIS	Chemical compositions (mass%)								Tensile test		Charpy impact test	
		C	Si	Mn	P	S	Ni	Mo	Sn	0.2% proof stress (N/mm²)	Tensile strength (N/mm²)	Test temperarure T (°C)	Absorbed energy vE_T (J)
L-55·PX	Z 3211 E4916-U	0.07	0.61	1.10	0.012	0.003	—	—	Added	503	607	−30	145
L-60·PX	Z 3211 E57J16-N1M1U	0.07	0.56	1.07	0.010	0.006	0.70	0.24	Added	612	700	−20	126
YM-26·PX	Z 3312 YGW11	0.08	0.39	0.97	0.005	0.011	—	—	Added	483	571	0	133
YM-55C·PX	Z 3312 YGW18	0.06	0.46	1.02	0.004	0.010	—	0.22	Added	521	606	0	140
YM-60C·PX	Z 3312 G57JA1UC3M1T	0.05	0.48	1.06	0.004	0.010	—	0.23	Added	554	629	−5	127
SF-1·PX	Z 3313 T49J0T1-1CA-UH5	0.06	0.44	1.19	0.013	0.006	—	—	Added	539	612	0	136
SM-1F·PX	Z 3313 T49J0T1-0CA-UH5	0.05	0.54	1.46	0.018	0.014	—	—	Added	510	597	0	64
SF-60·PX	Z 3313 T57J1T1-1CA-N1-UH5	0.05	0.55	1.57	0.011	0.006	0.53	—	Added	595	665	−5	78
SM-60F·PX	Z 3313 T57J1T1-0CA-G-UH5	0.05	0.57	1.80	0.014	0.010	—	—	Added	567	642	−5	81
YF-15×Y-D·PX	Z 3183 S50J2-H (applicable)	0.07	0.45	1.54	0.016	0.006	—	—	Added	511	601	0	93
YF-800×Y-D·PX	Z 3183 S501-H (applicable)	0.04	0.68	1.55	0.009	0.011	—	—	Added	415	534	0	49
YF-15B×Y-DM3·PX	Z 3183 S532-H (applicable)	0.08	0.31	1.76	0.013	0.006	—	0.21	Added	553	648	0	108
NF-820×Y-D·PX	Z 3183 S532-H (applicable)	0.05	0.63	1.83	0.007	0.011	—	—	Added	478	588	0	81
YF-15B×Y-DM·PX	Z 3183 S624-H4 (applicable)	0.08	0.31	1.70	0.013	0.005	—	0.37	Added	595	699	−20	67
NF-820×Y-DM·PX	Z 3183 S582-H (applicable)	0.06	0.59	1.81	0.005	0.011	—	0.40	Added	564	662	−5	70

become undulated with excess metals. In the structures painted without removing such excess metals, the welds tend to become coating defects on account of such configuration irregularities. Accordingly, it is beneficial to furnish weld metals with corrosion resistance (coating film separation resistance) to prolong the coating cycles of structures.

Even today, the growing cost of repair and/or renewal of corroded steel structures including the cost of repainting is becoming a major problem, and in the future too, acquiring money for the maintenance and control of public infrastructures is expected to become even more challenging. Therefore, we believe that the application of CORSPACE contributes to the reduction of LCC of public infrastructures, and will be utilized as a new technology for prolonging the life thereof.

4. Conclusion

New functions required of steel plates including corrosion resistance performance are expected to become ever more sophisticated and stringent. Nippon Steel & Sumitomo Metal and Nippon Steel & Sumikin Welding cooperate to enhance and maximize the performance of steel plates, and further, to promote the expansion of the product line of welding consumable products. We are determined to continue promoting the research and development of new technologies so that our customers realize the great advantage of using a steel material with the relevant welding consumable as one package.

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