Technical Report

Activities by Nippon Steel Corporation and Group Companies for Offshore Wind Solutions

Hiroyuki KAWATA*
Takahiro KAMO
Michio KANEKO
Chika KOSUGI
Hiroyuki TAKEKAWA
Ryuichi HOMMA
Takayuki YONEZAWA
Kazumasa HISAZUMI
Motohiro OKUSHIMA

Abstract

Offshore wind power is expected to be a major renewable energy source in Japan. Offshore wind power is used in a wide range of industries, i.e. turbine, foundation structure, float, installation, operation & maintenance (O&M), power transmission, and the use of electricity. The steel industry will be able to contribute to offshore wind power in many ways. Nippon Steel Corporation and Nippon Steel group can contribute to offshore wind power with technologies acquired through demonstration research projects, and technologies established in different fields, such as maritime and civil engineering. In this manuscript, we present the technical activities conducted by Nippon Steel and Group Companies to provide solutions for offshore wind power.

1. Relationship of Steel Industry with Offshore Wind Power Generation

Fossil fuels (petroleum, coal, natural gas, etc.) that support modern society are extremely easy-to-handle energy integrations. However, their generation in the natural environment takes an inordinately long time, and they are virtually irreversible resources. Considering the history of humankind which has been hit by numerous natural disasters, it is desirable to conserve fossil fuels to the extent possible, and use them everlastingly in anticipation of the future.[1] In particular, Japan, which has scarce fossil fuel reserves, is expected to break free from her dependence on fossil fuels as an energy source from the perspective of energy security,[2] and it is imperative to increase the energy self-sufficiency rate with so-called “renewable energy”.[3]

However, to reduce the use of fossil fuels, the establishment of alternatives of power generation for which fossil fuels are now mainly used becomes a problem. Among the renewable energy resources, in Japan, solar energy and wind power are highly potential major sources of power.[3] Between these, solar power generation has already reached a 9.9% share of the entire electric power generation of 106 TWh in Japan (in 2022),[4] a large-scale amount taking prominence in the world. In the meantime, the actual result of the achievement of wind power generation is no more than 0.9%, 9 TWh, leaving a very big space for development as compared with the countries where wind power is the major source of power.[5, 6] Therefore, offshore wind power is “the key to making renewable energy a main source of power”[3]. Wind power generation is divided mainly into two categories of land type and offshore type, depending on its installation site. In Japan, there are many issues in developing land power generation since the land space suitable for wind power generation is limited, and large-scale forestry exploitation for installing multiple generators is required. Therefore, as a renewable energy which can become the new major power source, the development of “offshore wind power generation” is commissioning an industry in Japan.[7]

Steel materials are widely used in large quantities as structural and functional materials in a variety of areas. **Figure 1** shows the role of the steel industry in offshore wind power generation and in its peripheral region. Wind power is generated by running huge wind turbines, which each require robust steel structures to support themselves. In particular, offshore wind turbines are continuously increasing in size at present, taking advantage of the benefits of ma-

* Dr. Eng., Chief Researcher, High Function Steel Research Dept., High Toughness Steel Research Lab., Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

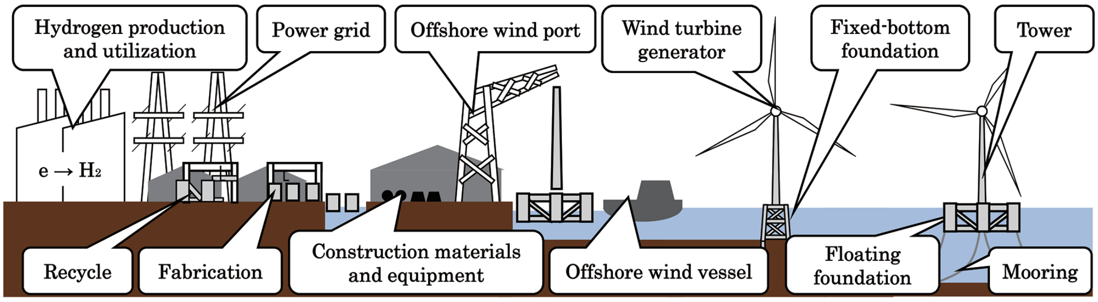

Fig. 1 Overview of offshore wind power considering the contribution of the steel industry

rine transportation, and in addition to the tower that supports the wind turbine itself, fixed-bottom type foundations such as that of the monopile type and/or of jacket type,[8] or the floating type foundation like the semisubmersible type[9] are becoming necessary, and a large amount of steel materials is used. For instance, in the case of the 10 MW rated wind turbine, it is presumed that about 4000 tons of steel are required for use in the tower and the floating body of the semisubmersible type.[10] In addition, the transition piece which connects the tower and the foundation section, and further in the case of the floating type, the chain used for the mooring system[11] are also made of steel. Furthermore, in the turbines supported by these steel structures, bearings and gears durable for long-term rotation are used.[12] (The foundation structure of the fixed-bottom type is explained in detail in another paper of No. 15[13] in this report.)

Installation and the operation of wind turbines and foundations are carried out by such vessels as the self-elevating platform (SEP) and service operation vessel (SOV),[14] the operations of which are centered on a base port[15]. Steel materials are utilized for port and port facilities themselves,[16, 17] vessels,[18] and the construction materials and equipment[19] like the stand used for works in ports. Furthermore, the steel industry has accumulated a great deal of knowledge not only about such towers and foundations, but also about the manufacturing processes like welding.

Furthermore, the relationship between offshore wind power generation and the peripheral region includes the contribution to power transmission and distribution facilities such as steel towers,[17] the recycling of used foundations by taking advantage of their excellent recyclability,[20] the application to hydrogen production and transportation facilities that produce hydrogen by taking advantage of the peak power generation, and the use of the produced hydrogen in steelmaking.[21] As described above, steel materials are related to the entire length of the offshore wind power generation business from the installation and operation to the utilization of the power generated in addition to the power generation facilities themselves (turbines + foundations), and upon the establishment of the offshore wind power generation market in Japan, the establishment of reciprocal relations is desired.

2. Relationship of Nippon Steel Group with Offshore Wind Power Generation

The Nippon Steel Group's participation in wind power generation started at the end of the 20th century when the company received an order for a tower from Denmark.[22] In 2003, at the dawn of the introduction of land wind turbines in Japan, a wind power generation project consisting of ten 1.5 MW generators was launched in Kitakyushu City. In 2011 and after, the company tackled the "Offshore Wind Power Generation System Proving Research (off the coast of Kitakyushu)"[23] and the "Fukushima Floating Offshore Wind Farm Demonstration (Fukushima FORWARD) Project"[24] with a view toward the full-scale introduction of offshore wind power generation. Therein, we conducted the detailed design of a fixed-bottom type foundation, and the jacket structure meeting the Japanese natural conditions was proposed.[25] Furthermore, for the latter, we promoted the study on the application of high-strength steel to the semisubmersible floating structure, peripheral technologies,[26] and mooring by chains.[27] In parallel with the development of these technologies, we have also supplied steel materials and steel structures to offshore wind power generation facilities in Japan and overseas.

Targeting the achievement of the 30 to 45 GW power generation capacity in the 2040s to make offshore wind power the major source of power in Japan, firstly the installation of the power generation facilities of the fixed-bottom type foundation was started, and the installation of the floating type for commercial purposes is scheduled in the 2030s.[28] The offshore wind power generation industry will expand rapidly on a tremendous scale and at a tremendous speed. The steel industry will utilize the technologies it has developed in this field, and those it has established in other fields such as ships, and civil and architectural engineering to rationally promote the establishment and expansion of the industry, and will contribute to the establishment of a new energy source that will become a new pillar that supports society. For such purpose, we consider that it is necessary to propose technologies which organically link materials, construction methods, and structures by not only simply supplying materials, but also by utilizing related knowledge and technologies.

This paper, entitled "offshore wind solutions," provides an overview of the group of technologies that Nippon Steel Corporation and the Nippon Steel Group possess for offshore wind power generation (**Table 1**).

3. Contribution through Steel Material

3.1 Steel material for offshore wind power generation (heavy plate)

The offshore wind power generation facilities are exposed to strong winds, and are required to have a long-term stabilized operation of longer than 20 years under the severe meteorological and oceanographic conditions. Furthermore, particularly in Japan, it is important to secure stability against natural disasters such as earthquakes, typhoons and tidal waves. Accordingly, a large amount of high-quality steel is required for the tower and the foundation which constitute the structure.[10, 29]

In the design of offshore wind turbines of the fixed-bottom type foundation with monopile and/or jacket, in Japan, the design must conform to the "Official Explanation of Technical Standards for

Table 1 The contribution of the Nippon Steel group's steel technology to the offshore wind power system

Wind farm	Wind turbine generator	Electrical steel sheet, Shaft, Bearing, Gear
	Tower	Steel plate (high strength), Flange, Bolt and nut
	Fixed and floating foundations, Transition piece	Steel plate (high strength, corrosion-resistant), High corrosion resistant materials (SUS, Titanium), PC steel wire, Bolts and nuts, Pipe and tube, Jacket structure, UIT (Peening)
	Mooring, Submarine cable	Chain, Cable, Anchor, Mooring system, Pipe and tube, Foundry pig iron
Port, Fabrication	Vessel	Steel plate (high strength, corrosion-resistant)
	Port	Steel sheet pile, Steel pipe pile, Coating, Steel slag
	Construction materials and equipment	Steel sheet, Steel plate, Bar and rod, Wire rope, Pipe and tube, Steel sheet pile, Steel pipe pile, Steel slag
	Fabrication	Welding technology, Welding consumable
Related field	Power grid	Transmission tower, Steel pipe pile, Overhead conductor, Electrical steel sheet
	Recycle	Steel scrap recycle
	Hydrogen production and utilization	Low-temperature steel plate, Pipe and tube, Electrical steel sheet, Hydrogen reduction steel making

Table 2 Typical heavy plate steel for fixed-bottom offshore wind steel structure[29] (Thickness ≤ 100 mm)

	Chemical composition (mass%)[a)]						
	C	Si	Mn	P	S	C_{eq} [b)]	P_{CM} [b)]
SM490C	≤0.18	≤0.55	≤1.65	≤0.035	≤0.035	(≤0.40)[c)]	(≤0.26)[c)]
SM520C	≤0.20	≤0.55	≤1.65	≤0.035	≤0.035	(≤0.42)[c)]	(≤0.27)[c)]

a) When necessary, alloying elements other than those shown in the table may be added.
b) Carbon equivalent, C_{eq}, and weld crack sensitivity, P_{CM}, are calculated for added elements using the following equations.
$C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$ (%) $P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B$ (%)

	Mechanical properties			
	Yield point or proof stress (MPa)	Tensile strength (MPa)	Elongation (%)	Charpy impact energy (J)
SM490C	≥295[c)]	490–610	≥21[d)]	≥47 (0°C)[e)]
SM520C	≥325[c)]	520–640	≥21[d)]	≥47 (0°C)[e)]

c) Thickness: 75–100 mm, d) Thickness > 40 mm, e) Rolling direction

Offshore Wind Power Facilities"[8] by the Ministry of Economy, Trade and Industry (METI) and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and either steel materials that meet the JIS standard conforming to the Building Standard Law or materials approved by MLIT are used.

In the meantime, the designs of the floating type offshore wind turbines are subject to the Electricity Business Act, Port and Harbor Law, and Ship Safety Law, and the facility is designed in accordance with the "Technical Standards for Floating Offshore Wind Power Generation Facilities"[9] formulated by MLIT based on these laws. The steel materials shall be those specified in the Ship Structure Rules (Ministry of Transport Ordinance No. 16, 1998), and for example, the rolled steel materials conforming to Class NK, Rules for the Survey and Construction of Steel Ships, Part K Materials, Chapter 3.1 Rolled Steels for Hull are used.

Steel with a tensile strength of 50 kg/mm^2 is mainly used for the fixed-bottom type foundation, which is being installed ahead of other types of foundations, and the plates thicker than those used for general ships, and many thick plates equal to or above in thickness to those used in marine structures or high-rise buildings are used. Especially for monopiles, ultra-thick steel plates over 100 mm in thickness are sometimes used. In general, the thicker a plate is, the higher the cleanliness should be, and the internal quality must be ensured, and high manufacturing technology and strict quality control are required to ensure a large and stable supply of such steel. **Table 2** shows the chemical compositions and the specified mechanical properties of SM490C and SM520C as examples of the rolled steel material applicable to the welded steel structure of the fixed-bottom type foundation.[30] The proof stress of these plates decreases as the plate thickness increases, and for example, the proof stress of SM520C is 325 MPa or higher at a plate thickness of 75 to 100 mm. The maximum tensile strength does not vary with plate thickness.

There is no limit on the carbon equivalent in these steels. However, the upper limit is specified when the steels are manufactured by controlled thermal processing, not by heat treatment. Since the 1980s, Japan has pioneered the practical application and the improvement of the TMCP (Thermo-Mechanical Control Process), mainly combining controlled rolling and accelerated cooling.[31] Compared to the products manufactured by normalizing and traditional controlled rolling processes, the steel plates manufactured by this process have an extremely fine metallurgical structure, and the strength can be increased by about 100 MPa with the same composition, i.e., the same carbon equivalent. In the TMCP steel, this increase in strength is utilized to reduce the carbon equivalent, resulting in high strength but with low carbon equivalent, thus reducing weld hardness and dramatically improving weldability (**Fig. 2**).[32]

TMCP technology is applied to steel materials for various uses

(**Fig. 3**). For example, a steel material for the marine structure having excellent weldability even in an extremely cold area below −40°C,[33] and a high strength line pipe steel material having high deformability even above the X80 class[34] have been developed. In addition to the aforementioned fixed-bottom type foundation, as the foundation of the floating type, pluralities of types represented by the semisubmersible type and spar buoy type are proposed, all of which are applied with the technologies cultivated for marine structures, ships, and architectural structures. To the steel materials used for such foundations, technology developed in the respective field is considered to be similarly applicable, and further expansion is expected.

3.2 Application of highly efficient welding technology

In establishing the offshore wind power generation as the major source of power, cost becomes a major factor, and the establishment of a mass production system of the tower and the foundation structure, and the reduction of the cost of operation and maintenance are required. In addition, offshore wind power generation facilities are large, and the steel materials used are thick, therefore, it is extremely important to ensure the toughness and the fatigue resistance properties of the welds and the heat-affected zone (HAZ) of the welds. To meet these needs, Nippon Steel has been developing high-quality steel materials, highly efficient welding technologies, and fatigue solutions (Section 4.1).

In the Fukushima Floating Offshore Wind Farm Demonstration (Fukushima FORWARD) Project,[24] a demonstration study of steel materials and welding technology[26, 35] was conducted on the assumption of a semisubmersible type floating structure. The steel materials used were KD36-TM (plate thickness 25 mm) and KE36-TM (plate thickness 40 mm and 50 mm) high-tensile TMCP steel for NK-class hulls. In particular, the HAZ toughness enhancing technology (HTUFF™)[36] was applied to KE36-TM, and as compared with KD36-TM, toughness was improved by refining the microstructure of HAZ (**Fig. 4**). **Figure 5** shows the relationship between the joint toughness and the weld heat input. The ductile-brittle transition temperature (vTrs) of KE36-TM with a fine HAZ microstructure is below −20°C even when highly efficient high heat input welding (maximum heat input of 31 kJ/mm) is applied, ensuring excellent toughness.

Figure 6 shows the change in arc time when a large heat input is applied, assuming and taking as the basis for comparison the submerged arc welding (SAW) of an X groove (plate thickness 60 mm) based on the case where a small heat input (3 kJ/mm) is applied which is similar to the welding technology used in Europe for steel materials for offshore structures. By increasing the heat input to 10 kJ/mm, the arc time can be reduced by 66%, and by 86% when the heat input is further increased to 20 kJ/mm. Therefore, it can be said that the entire welding process can be made much more efficient by using TMCP steel for large heat input welding with the HAZ toughness enhancing technology, and by adopting large heat input welding.

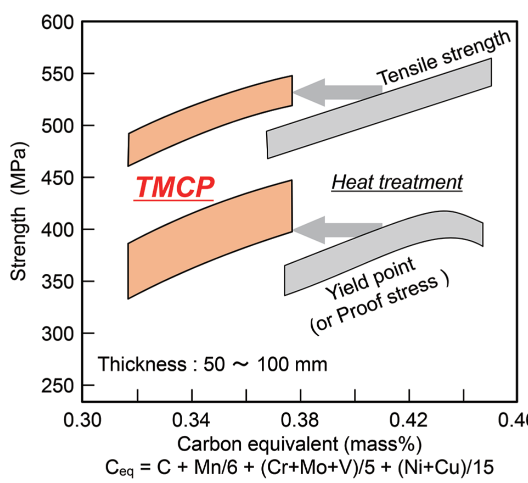

Fig. 2 Improving strength-weldability balance with TMCP[32]

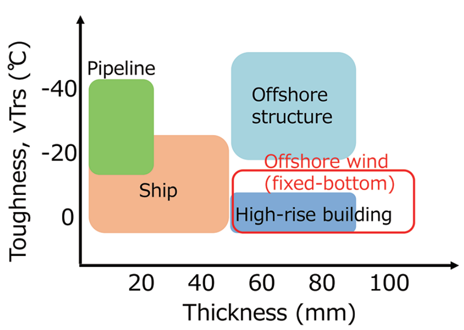

Fig. 3 Typical thickness and toughness of heavy plate steel for several industries[27]

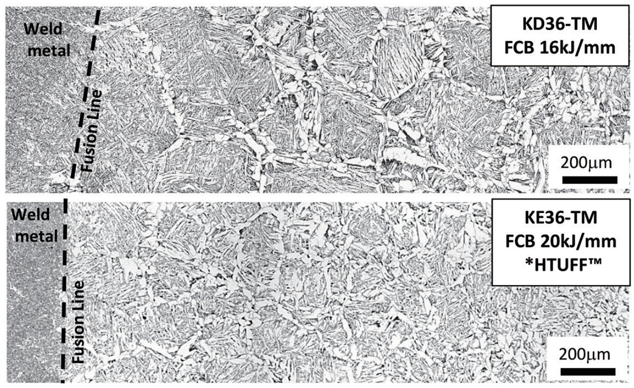

Fig. 4 Microstructures of welded joints[35]

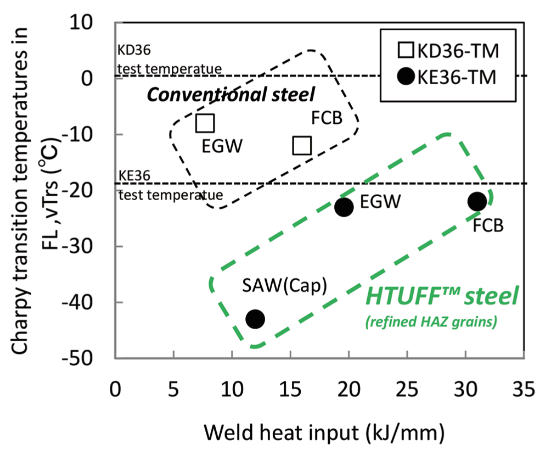

Fig. 5 Relationship between Charpy (vTrs) in fusion line (root) and weld heat input[35]

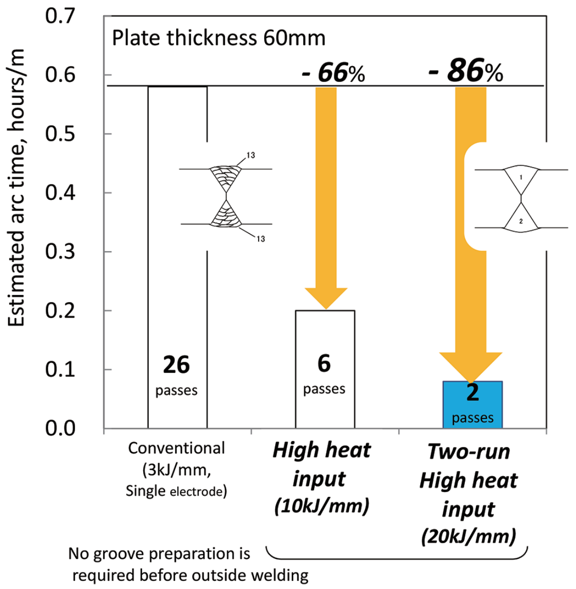

Fig. 6 Advantages of high heat input SAW in arc time[35]

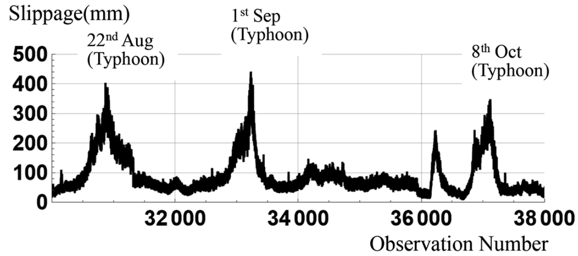

Fig. 7 Calculated sliding behavior of mooring chain link[38]

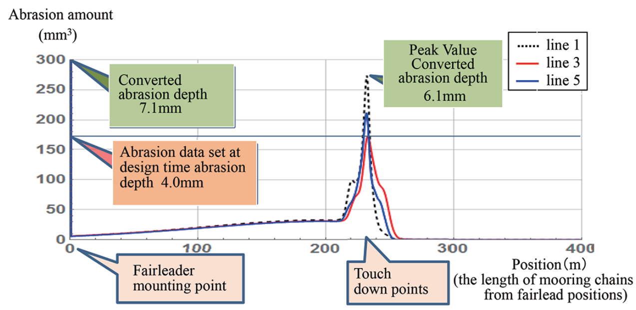

Fig. 8 Longitudinal distribution of wear on mooring chain[38]

3.3 Mooring system and offshore wind power generation facility parts steel (bar and wire)

For floating type offshore wind farms, the key technical issue is not only the floating structure itself, but also how to maintain the positions of many floating structures. Therein, in addition to the structure, sea conditions, and the seabed environment, it is necessary to consider the operability (inspection and maintenance) and the redundancy for the event of unexpected situations such as ship collision, etc., and a mooring system with economic rationality is required based on a comprehensive view of materials, design, construction, and maintenance. In the Fukushima Floating Offshore Wind Farm Demonstration (Fukushima FORWARD) Project,[24] a multi-point mooring system using chains was adopted, and Nippon Steel and Nippon Steel Engineering Co., Ltd. conducted research on the durability of the mooring chains.[37] First, we established a method for estimating the amount of wear of the chain links by the abrasion test in artificial seawater, and from the results and the amount of sliding that occurs in the contact area of the chain links (**Fig. 7**), which was calculated using data from the movement observation of floating wind turbines, we were able to estimate the wear situation (**Fig. 8**) and fatigue damage (**Fig. 9**) in the mooring chain. Based on these findings, we further continued our research, and proposed empirically in advance to the world that grasping the wear, accumulated fatigue damage, and the soundness of chain links, and estimating risk thereby is the risk management method wherein design, inspection, and maintenance are integrated.[38]

Furthermore, the selection of the mooring system requires study pertaining to such conditions as the floating substructure and the installation environment, and the mooring system using chains is not always appropriate. For example, Nippon Steel Engineering has proposed a mooring system using high-tensile steel cables (**Fig. 10** shows the schematic diagram).[39] This mooring system is the combination of a catenary mooring and a taut mooring,[40] and utilizes the buoyancy of the cylindrical member, rather than the weight of the chain (catenary mooring) or the elongation of the mooring cable (taut mooring), to provide soft mooring force characteristics even with a cable that is difficult to elongate. This mooring system allows

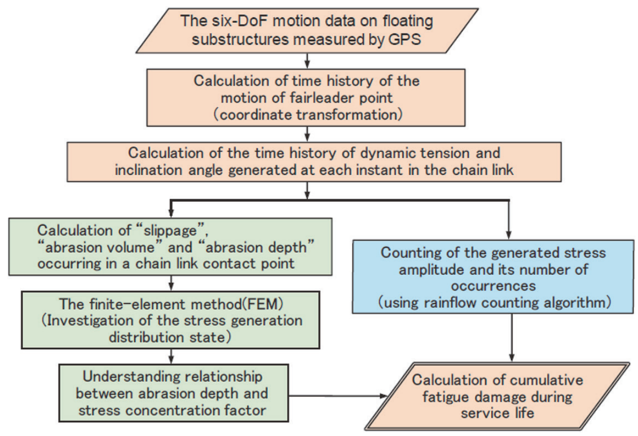

Fig. 9 Overall algorithm for fatigue damage evaluation of mooring chain[38]

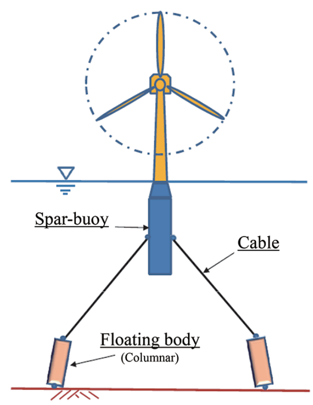

Fig. 10 Mooring system concept with high tensile parallel wire strand cable for floating offshore wind turbine[39]

the buoyancy of the cylindrical part to be adjusted to freely set the mooring characteristics, enabling moorings in a small occupation area in relatively shallow waters (shallower than 200 m) and/or in waters with restricted use. In addition, the use of lightweight and highly durable high-tensile marine steel cables can significantly improve work efficiency in installation, inspection, repair, and dismantling compared to chains.

In offshore wind power generation, the use of steel bars and wires is not limited only to mooring by chains and/or cables. For example, steel material is used for bearings, shafts, and gears inside the generator, and the foundation structure includes many bolts, all of which are required to have high durability. Furthermore, for steel bars and wire rods, technologies of combined use in a coexisting manner with other materials are required such as in the cases of the mooring system where chain and fiber wires are combined[41] and/or the steel wire that reinforces the concrete foundation structure.[8, 42] Nippon Steel wishes to contribute to the offshore wind power generation market through the stable supply of high-quality steel bars and wire rods, and the creation of value by combining "steel materials × methods" based on our understanding of materials and processing/utilization technology.[43]

4. LCC Improving Technology

4.1 Fatigue solution

In addition to the external forces caused by waves, fluctuating external forces such as wind and/or rotor vibration superimpose on the structure of offshore wind power generation, therefore fatigue durability is required for areas where stress concentrates like welded joints. Therefore, solution technologies to improve the fatigue strength of welded joints are required for increasing the scale of power generation facilities. This technology becomes especially important when high strength steel is used for the enlarged scale facilities because the fatigue strength of welded joints does not increase as much as the increase of the strength of steel.

Ultrasonic Impact Treatment (UIT) is a solution to improve the fatigue properties of welds. UIT can introduce compressive residual stress in addition to improving the shape of the weld toe, and it has been confirmed that the fatigue properties of the welded joint test specimens, and the welded structures such as ships and bridges can be dramatically improved.[44–51] Compressive residual stress introduced by UIT increases in high strength steels, therefore, higher fatigue strength can be expected by using UIT in combination with high strength steels.[52]

To date, in the Fukushima Floating Offshore Wind Farm Demonstration (Fukushima FORWARD) Project,[24] the effect of improving fatigue properties was confirmed by using a structural model test specimen, verifying the applicability of UIT to the floating structure.[53] In this demonstration test, a structural model test specimen (**Fig. 11**) was fabricated to simulate the corner boxing welding on the bracket end between the floating structure and the tower base, which is one of the most demanding areas in terms of required fatigue characteristics. The UIT was applied before the fatigue test was conducted. For UIT, ESONIX™ 27 UIS manufactured by Applied Ultrasonics Corporation was used. The fatigue test results are shown in **Fig. 12**. The test specimens after UIT exhibit fatigue strength higher than that of the as-welded specimens, and being compared at the 2×10^6 cycles, the fatigue strength after UIT is two times higher than that of the as-welded specimen. Thus, UIT is expected to significantly improve the fatigue strength of floating structures in addition to conventional structures of ships and bridges.

4.2 Corrosion resistant steel

Since the offshore steel structures are exposed to a severely corrosive environment, in general, the part below sea level is provided with cathodic protection, and the parts exposed to tideland, splash zone, and the atmosphere are provided with protective coating. Particularly, in the case of floating-type offshore power generation, in addition to a very severe corrosive environment, and due to difficulty in access higher than that of land-type power generation, mainte-

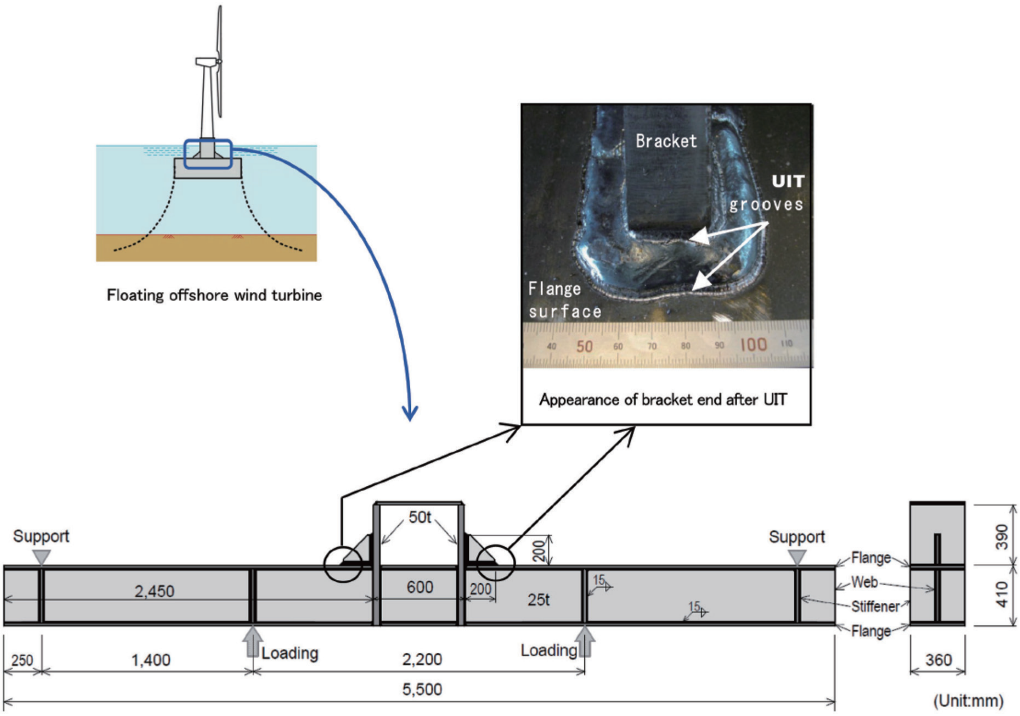

Fig. 11 Large-scale structural fatigue specimen[53]

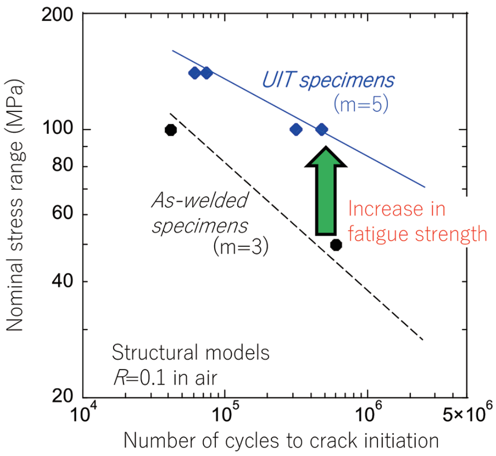

Fig. 12 Fatigue properties of large-scale structural specimens[53)]

nance and the management of corrosion protection of the steel structure become highly costly.

Nippon Steel has developed and put into practical application various low-alloy corrosion resistant steels corresponding to such corroding environments as those in acidic regions, neutral regions, and acid dew-point corrosion, atmospheric corrosion, and sea water corrosion.[54)] Low-alloy corrosion resistant steel is a steel material having both economic rationality and corrosion resistance compatibility by adding small amounts of corrosion resistant elements such as Cr, Cu, Ni, Sn, and so on in an optimal amount according to the corrosive environment, characterized by the fact that the weldability, processability, and the mechanical properties are almost the same as those of ordinary steel, and can be treated in the same way as ordinary steel. Low-alloy corrosion resistant steels can really be termed as low environmental load steel materials since they have long service periods, reduce the maintenance load, and thereby contribute to the reduction of life cycle cost (LCC), suppressing the consumption of valuable metal resources with excellent recyclability.

Furthermore, various types of facilities for offshore wind power generation are constructed near the base port, and near the coast where the power is received. However, the corrosive environment near the coast is more severe, and the corrosion-preventing coating deteriorates more quickly than inland. Nippon Steel has developed and commercialized CORSPACE™ (Corrosion Resistance Steel for Painting Cycle Extension) as a low-alloy corrosion resistant steel applicable in areas near the coast (**Fig. 13**).[55, 56)] CORSPACE™ is a low-alloy corrosion resistant steel developed for use in the bridge field, and features the addition of a small amount of Sn. **Figure 14** shows the exposure test results of CORSPACE™ (the coastal area of Okinawa Prefecture: corrosion categories C5 to CX in ISO 12944-2), which shows that the corrosion depth is reduced by half as compared to ordinary steel both in the air and under the eaves. **Figure 15** shows the result of the estimation of the repainting period (the period during which the peel-off area of the coating film reaches 15%) of CORSPACE™ vs. that of ordinary painted steel by using the accelerated corrosion test method (SAE J2334), and it is found that the repainting period of CORSPACE™ is two times longer compared with ordinary coated steel.

4.3 High corrosion resistant material

The corrosion rate of offshore structures varies greatly depending on the environment and the area of the structure. In the splash

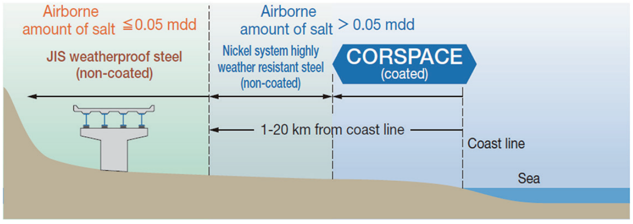

Fig. 13 Image of applying CORSPACE™ to a bridge[55)]

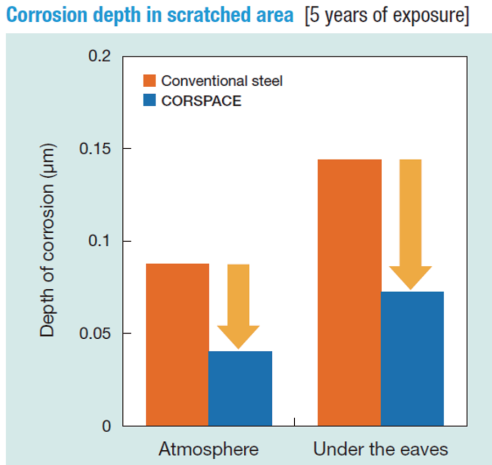

Fig. 14 Evaluation after outdoor exposure test (Okinawa)[55)]

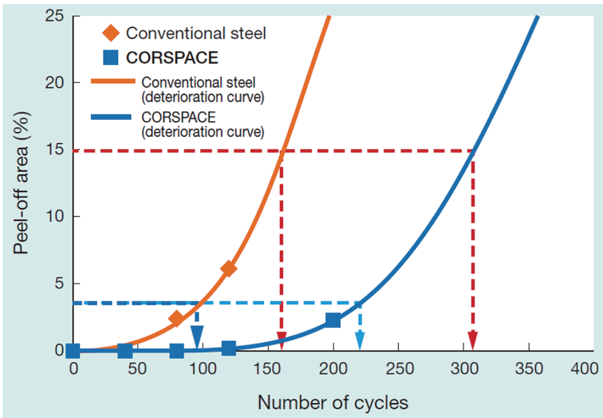

Fig. 15 Coating film peel-off area of CORSPACE™ and conventional steel[55)]

zone which is the most severely corroded area where electrolytic protection does not work, and corrosion protection using corrosion resistant steel or paint is also not sufficient, a corrosion protection method of covering the surface of a steel structure by using the high corrosion-resistant materials such as super stainless steel and/or titanium is sometimes used. For example, the jacket structure of Runway D at Tokyo International Airport (**Fig. 16**) which started operation in 2010 (Constructed by Nippon Steel Engineering) is provided with a seawater-resistant stainless steel covering the jacket legs (covering material: super stainless steel SUS312L).[57)] In addition, a panel-shaped “titanium cover plate” consisting of a thin titanium sheet and a coated steel sheet with an incombustible urethane core material sandwiched between them is installed on the underside and the sides of the runway pier to cover the steel girders above the jacket.[58)] These sufficiently reduce the possibility of the need for

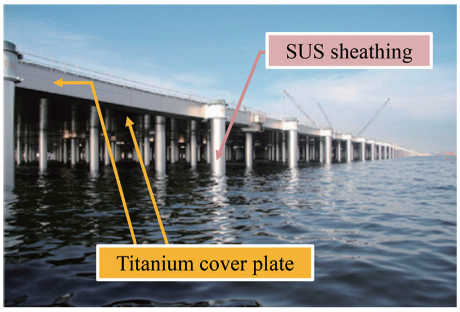

Fig. 16 Offshore steel structure of Runway D of Haneda, Tokyo International Airport[57)]

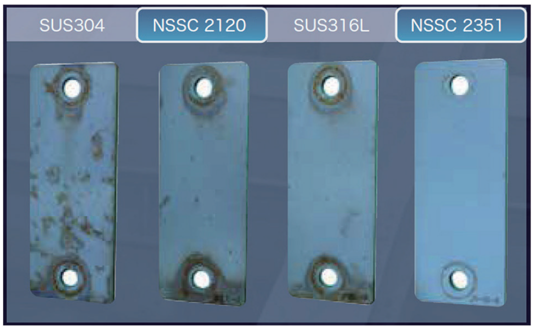

Fig. 17 Exposure test results of duplex stainless steels for 1year in Southeast Asia ocean[62)]

large-scale repair works within 100 years of the designed durable years, and have been employed with the aim of minimizing LCC.[59)]

Furthermore, the application of stainless steel itself to the parts where corrosion resistance is required is also considered. For example, the alloy-saving dual-phase stainless steel (NSSC2120™, NSSC™2351, Nippon Steel Stainless Steel Corporation)[60, 61)] is of the resource-saving type composition design, wherein the costly Ni and a part of Mo are replaced with Cr, Mn, and N, while maintaining the corrosion resistance serviceable in the atmosphere above the sea, and further high strength and excellent weldability are ensured. The exposure test results[62)] shown in **Fig. 17** indicate that the base metal corrosion resistance of NSSC2120™ and NSSC™2351 is equivalent or superior to that of SUS316L, a typical corrosion resistant material, and that the corrosion resistance of the welded parts is also comparable.

By comprehensively considering the environment, area, risk of corrosion progression, construction cost, and LCC, and by comparing these considerations with the pluralities of methods of using these highly corrosion-resistant materials with the addition of the aforementioned corrosion-resistant steel and coating, it is possible to propose a corrosion-resistant solution for offshore wind power generation that meets individual circumstances.

5. Peripheral Region, Consideration on Environment

5.1 Transmission network, base port preparation

In order for the offshore wind power to become the major power source, it is necessary to develop not only the maintenance of the power generation facilities themselves, but also the installation capability and the operation system after the start of operation. To the base port for the offshore wind power generation, a wharf that has a bearing capacity of ground and space sufficient enough to handle large-scale components, and a quay wall that can accommodate large vessels are required, and steel pipe sheet piles and steel pipe piles are indispensable for the preparation of such a port.[63)]

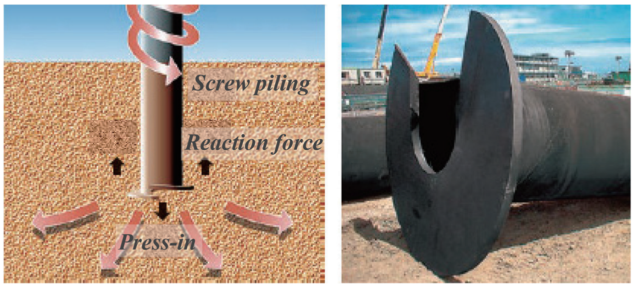

Fig. 18 Conceptual illustration and photograph of NS ECO-PILE™[63, 66)]

Furthermore, Nippon Steel does not limit itself only to providing products and technologies related to steel and construction materials, but is also capable of making a wide-ranging contribution to solving problems through its construction solution “ProStruct™”[64)] based on “steel material × application technology” in the field of civil engineering and architecture. For example, suitable locations for offshore wind power generation are in Hokkaido, Tohoku, and Kyushu, and the issue is to increase the power transmission capacity to the large consumption areas of the Tokyo metropolitan area and the Kansai area.[65)] Concrete piles are widely used for the foundations of power transmission towers, which are indispensable for power transmission. However, since the installation of such a tower requires carrying in of a large number of materials and equipment, and carrying out of the surplus soil, the construction load in mountainous areas becomes high. Then, ProStruct™ offers the “NS ECO-PILE™” (**Fig. 18**),[63, 66)] a rotary steel pipe piling method applicable to narrow areas in mountainous regions, transportable through narrow passages, and has excellent environmental load reduction features such as no earth removal, low vibration, and low noise. Furthermore, in the foundation pile applied with this piling method, a large pulling resistance capacity is maintained as the passive soil resistance, which acts on the blade part as propulsive force as the pile penetrates into the ground, and is wholly turned into pulling resistance.

5.2 Consideration on environment

Considerable amounts of steel materials are used for the offshore wind power generation facilities. Steel materials have high recyclability and low impact on environments.[20)] Furthermore, iron is a conventional element which widely exists on earth, and as ferrous ion in seawater, functions as an essential element for maintaining biological activity in organisms represented by human beings, and plants.[67)] Accordingly, in the sea area where iron is scarce, the growth of biology is considered to be suppressed. For example, in the coastal areas of Japan where sea desertification occurs, scarcity of not only the nutrient concentrations such as nitrogen and phosphorus which are necessary for seaweed growth, but also iron deficiency have been pointed out in some cases.[68)]

Steel slag, a byproduct of steel products, is widely used in construction work as a cement material, roadbed material, and civil engineering material, and is expected to be utilized in the development of “carbon-free ports”.[69)] In particular, among steel slags, the steelmaking slag obtained in the steelmaking process contains large amounts of silicon and phosphorus which are essential nutrients for seaweed in addition to divalent iron, and can be used as a nutrient supply source and substrate material to promote the development of seaweed beds in the coastal areas (**Fig. 19**).[70, 71] Nippon Steel has been investigating the use of steelmaking slag as a "material for the environment," and has so far developed seaweed bed materials (Vivary™ Unit, Vivary™ Bag, and Vivary™ Box) consisting of a mixture of carbonated steelmaking slag and humic substances, calcia modifier that uses steelmaking slag as a material to modify dredged sediment, and artificial stone materials (Vivary™ Rock and Vivary™ Block) using steelmaking slag as aggregate.

Nippon Steel has been verifying the effects of steel slag and elucidating its mechanism in experimental facilities that simulate the marine environment (**Fig. 20**),[71–73] and has conducted demonstration studies in various sea areas to confirm the effects of these materials. For example, in 2004, a seaweed bed creation project "Umi-no-Mori Zukuri (Seaweed Beds Creation)" was started in Mashike town, Hokkaido, using Vivary™ Units, etc. In the coastal area stretching about 300 m along the Betsukari coastline (**Fig. 21**) the project of which was started in 2014, a rich seaweed bed was formed that had extended 80 m offshore by 2022.[73] We will continue to study the creation of seaweed beds using steel slag-based materials and their environmental impact,[74] and will consider the application to offshore structures of wind farms as well as ports and coastal areas.

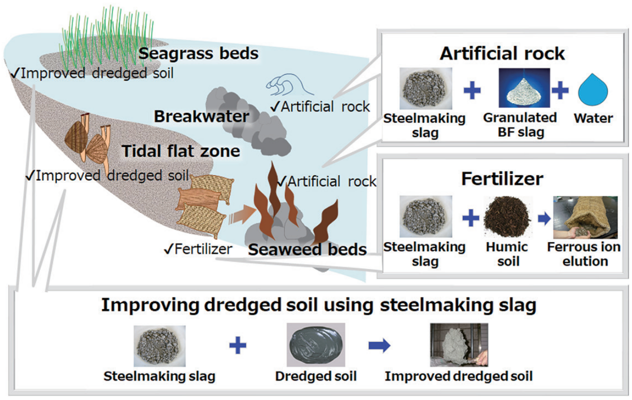

Fig. 19 Slag utilization for marine environmental restoration[71]

6. Conclusion

The shift to offshore wind power as the major power source must be achieved to reduce dependence on fossil fuels, and increase energy self-sufficiency. The precise specifications and the required characteristics of offshore wind power generation, especially of the floating type, will be determined from this point forward, and the manufacturing process and the operation system of the facilities are required to be established rationally in accordance with such specifications and required characteristics. The Nippon Steel Group will continue to contribute to the energy industry both in Japan and abroad through "offshore wind solutions" which will be developed from multiple perspectives not only in terms of materials, but also in terms of construction methods and structures while utilizing the technologies described in this paper.

References

1) e.g., Toichi, Ogawa, Sagawa: Energy and the Role of the State. Edited by the Japan Institute of Energy, Corona Publishing Co., Ltd., 2001, p.10–16
2) Agency of Natural Resources and Energy: Japan's Energy White Paper 2023. 2023, p.25–49
3) Ministry of Economy, Trade and Industry: The 6th Strategic Energy Plan. 2021, p.34
4) Institute for Sustainable Energy Policies (ISEP): 2022 Share of Electricity from Renewable Energy Sources in Japan (Preliminary), 2023/08/26 Refer to https://www.isep.or.jp/archives/library/14364
5) Department for Business, Energy & Industrial Strategy (UK): Energy Trends: March 2020, p.59–66
6) Nalley, S. et al.: Annual Energy Outlook 2022 (AEO2022), U.S. Energy Information Administration, 2022
7) Ministry of Economy, Trade and Industry: Selection of Operators for the Offshore Wind Power Generation Project off "Mitane Town and Oga City, Noshiro City, Akita Prefecture", "Yurihonjo City, Akita Prefecture" and "Choshi City, Chiba Prefecture". 2023/08/26 Refer to

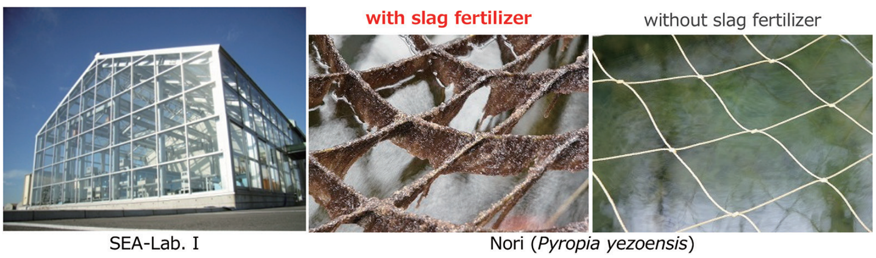

Fig. 20 Seaweeds grown in the experimental seawater tanks in SEA-Lab. I with/without slag fertilizer[72]

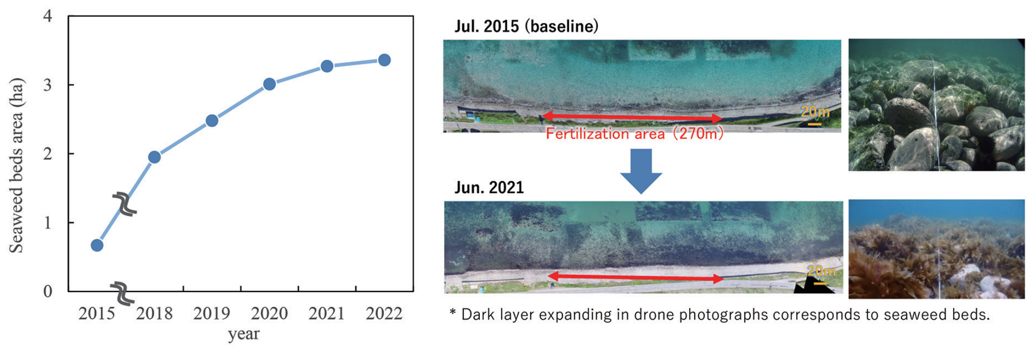

Fig. 21 Expansion of marine forest in the experimental field (Mashike town, Hokkaido) from 2015 to 2022[73]

https://www.meti.go.jp/press/2021/12/20211224006/20211224006.html
8) Committee on Study of Developing Offshore Wind Power Generation Facilities: Official Explanation of Technical Standards for Offshore Wind Power Facilities (revised edition). 2020
9) Ministry of Land, Infrastructure, Transport and Tourism: Technical Standards for Floating Offshore Wind Power Generation Facilities. 2020
10) Ministry of Land, Infrastructure, Transport and Tourism Ports and Harbors Bureau: Document 2 of Subcommittee for Promoting Offshore Wind Power Generation of Environment Section of Port and Harbor Break out Session of the 12th Council of Transport Policy. 2022
11) Utsunomiya, T. et al.: Journal of Japan Society of Civil Engineers, Ser. B3 (Ocean Engineering). 70 (2), I1–I6 (2014)
12) Special Steel Association of Japan: The Special Steel. 63 (4), 2–10 (2014)
13) Ootake, A. et al.: Nippon Steel Technical Report. (132), 86–96 (2025)
14) Matsunobu, T. et al.: Wind Energy. 44 (4), 595–599 (2020)
15) Ministry of Land, Infrastructure, Transport and Tourism Ports and Harbors Bureau: Document 1 of Subcommittee for Promoting Offshore Wind Power Generation of Environment Section of Port and Harbor Break out Session of the 22th Council of Transport Policy. 2023
16) Japan Dredging and Reclamation Engineering Association (JDREA): Document of the first Public-Private Council on Enhancement of Industrial Competitiveness for Offshore Wind Power Generation. 2020
17) Nippon Steel Corporation: Nippon Steel Quarterly magazine. 11, 32–33 (2022)
18) Ishida, R.: Bulletin of the Iron and Steel Institute of Japan. 27 (4), 184–187 (2022)
19) Ookawa, T. et al.: Report of the Coastal Development Institute of Technology. (15), 11–14 (2015)
20) Isohara, T.: Nippon Steel Technical Report. (127), 11–14 (2022)
21) Kamijo, C. et al.: Nippon Steel Technical Report. (127), 21–28 (2022)
22) Nippon Steel Corporation: Nippon Steel Monthly. 126, 1–8 (2003)
23) New Energy and Industrial Technology Development Organization (NEDO): Implementation Policy of Research and Development of Technologies Pertaining to Natural Energy Such as Wind Power in fiscal 2011. 2011
24) Fukushima Offshore Wind Consortium: website. 2023/08/26 Refer to http://www.fukushima-forward.jp/index.html
25) Inugai, T. et al.: Nippon Steel & Sumikin Engineering Co., Ltd. Technical Review. 4, 30–38 (2013)
26) Ishihara, T. et al.: Japanese Society of Steel Construction Journal of Steel Structures & Construction. (36), 17–18 (2019)
27) Ookubo, H. et al.: Nippon Steel Engineering Co., Ltd. Technical Review. 13, 20–38 (2022)
28) Public-Private Council on Enhancement of Industrial Competitiveness for Offshore Wind Power Generation: Vision for Offshore Wind Power Industry (1st). 2020
29) Homma, R. et al.: Japanese Society of Steel Construction Journal of Steel Structures & Construction. (50), 9–11 (2022)
30) JIS G 3106: 2020, Rolled Steels for Welded Structure
31) Nomiyama, Y. et al.: Nippon Steel & Sumitomo Metal Technical Report. (110), 8–16 (2015)
32) Nippon Steel Corporation: Nippon Steel Monthly. 169, 10 (2008)
33) Yoshida, Y. et al.: Proceedings of the 12th Int. Conf. OMAE, Glasgow, ASME, 1993
34) Hara, T. et al.: Proceedings of the International Pipeline Conference, Calgary, ASME, 2008
35) Homma, R. et al.: Bulletin of the Iron and Steel Institute of Japan. 27 (4). 188–192 (2022)
36) Kojima, A. et al.: Materia Japan. 42 (1). 67–69 (2003)
37) Agency of Natural Resources and Energy: Final report issued by Summarization Committee for Fukushima Floating Offshore Wind Farm Demonstration Project. 2022, p.25–26
38) Ookubo, H. et al.: Nippon Steel Engineering Co., Ltd. Technical Review. 13, 20–38 (2022)
39) Torii, T. et al.: Nippon Steel & Sumikin Engineering Co., Ltd. Technical Review. 6. 18–27 (2015)
40) Ministry of Land, Infrastructure, Transport and Tourism: Technical Standard Safety Guideline for Floating Type Offshore Wind Power Generation Facilities. 2020. p.1–9
41) Utsunomiya, T. et al.: Conference Proceedings the Japan Society of Naval Architects and Ocean Engineers. 21. 265–266 (2015)
42) Ministry of Land, Infrastructure, Transport and Tourism: (separate volume) Design and Construction Guideline for Concrete Floating Type Offshore Wind Power Generation Facilities. 2023
43) Nippon Steel Corporation: SteeLinC™ catalog
44) Statnikov, E.S.: IIW Doc. XII-1668-97, 1997
45) Haagensen, P.J. et al.: IIW Doc. XIII-1748-98, 1998
46) Shimanuki, H. et al.: Preprints of the National Meeting of JWS. 81, 342 (2007)
47) Nose, T. et al.: Transactions of the Japan Society of Mechanical Engineers Series A. 74 (737), 166–167 (2008)
48) Shimanuki, H. et al.: Welded Structure Symposium 2009 Lecture Proceedings. 479–482 (2009)
49) Mori, T. et al.: Welding in the World. 56, 141–149 (2012)
50) Okawa, T. et al.: Welding in the World. 57, 235–241 (2013)
51) Shimanuki, H. et al.: Nippon Steel & Sumitomo Metal Technical Report. (110), 97–104 (2015)
52) Yonezawa, T. et al.: Welding in the World. 64, 171–178 (2020)
53) Homma, R. et al.: Nippon Steel & Sumitomo Metal Technical Report. (110), 50–57 (2015)
54) Kojima, A. et al.: Nippon Steel & Sumitomo Metal Technical Report. (110), 3–7 (2015)
55) Nippon Steel Corporation: CORSPACE™ Corrosion Resistance Steel for Painting Cycle Extension catalog
56) Sugae, K. et al.: Nippon Steel & Sumitomo Metal Technical Report. (110), 77–83 (2015)
57) Matsunaga, S. et al.: Nippon Steel Technical Report. (126), 150–155 (2021)
58) Tokita, M. et al.: Nippon Steel & Sumitomo Metal Technical Report. (106), 9–15 (2014)
59) Sato, H.: The 64th Shiraishi Memorial Lecture. The Iron and Steel Institute of Japan, 2012
60) Oikawa, Y. et al.: Materia Japan. 55 (2), 70–72 (2016)
61) Oikawa, Y. et al.: Nippon Steel Technical Report. (126), 22–27 (2021)
62) Nippon Steel Stainless Steel Corporation: NSSC™Duplex Series catalog
63) Nippon Steel Corporation: Nippon Steel Quarterly magazine. 11, 32–33 (2022)
64) Hirata, H. et al.: Nippon Steel Technical Report. (130), 3–9 (2024)
65) Organization for Cross-regional Coordination of Transmission Operators, Japan: Long-run Policy of Wide-area System. 2023
66) Nippon Steel Corporation: Nippon Steel's Steel Pipe Pile and Steel Pipe Sheet Pile Construction Method catalog
67) Nippon Steel Corporation: Color Illustration A Book for Understanding Iron and Steel. Nippon Jitsugyo Publishing, 2004
68) Matsunaga, K. et al.: J. Exp. Mar. biol. Ecol. 241, 193 (1999)
69) The Ports & Harbours Association of Japan: Document of the first Public-Private Council on Enhancement of Industrial Competitiveness for Offshore Wind Power Generation. 2020
70) Kato, T. et al.: Nippon Steel & Sumitomo Metal Technical Report. (109), 79–84 (2015)
71) Kosugi, C. et al.: Nippon Steel Technical Report. (127), 50–59 (2022)
72) Kato, T. et al.: Nippon Steel & Sumitomo Metal Technical Report. (109), 85–89 (2015)
73) Nippon Steel Corporation: Nippon Steel Quarterly magazine. 15, 8–11 (2023)
74) Kato, T. et al.: Nippon Steel Technical Report. (127), 89–94 (2022)

Hiroyuki KAWATA
Dr. Eng., Chief Researcher
High Function Steel Research Dept.
High Toughness Steel Research Lab.
Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

Ryuichi HOMMA
Dr. Eng., Chief Manager, Head of Section
Plate, Shape, Pipe & Tube Research Section
Steel Products Research Dept.
East Nippon R & D Lab.

Takahiro KAMO
Chief Manager, Head of Dept.
Welding & Joining Metallurgy Research Dept.
Welding & Joining Research Lab.
Steel Research Laboratories

Takayuki YONEZAWA
Dr. Eng., Researcher
Applied Mechanics Research Dept.
Materials Reliability Research Lab.
Steel Research Laboratories

Michio KANEKO
Dr. Eng., Principal Researcher
Materials Reliability Research Lab.
Steel Research Laboratories

Kazumasa HISAZUMI
Dr. Eng., Chief Manager, Head of Section
Research Section-I
Steel Structures Research Dept.-I
Steel Structures Research Lab.
Steel Research Laboratories

Chika KOSUGI
Ph.D., Senior Manager, Head of Section
Research Section-I
Environmental Technology Research Dept.
Environment Research Lab.
Advanced Technology Research Laboratories

Motohiro OKUSHIMA
Chief Manager
Plate Technical Service & Solution Dept.
Plate Technology Div.
Plate & Construction Products Unit

Hiroyuki TAKEKAWA
Chief Manager, Head of Section
Project Development Section-I
Project Development Dept.
Project Development Div.