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Progress in This Decade and Future Prospects of Welding Technologies on Steel Plates and Pipes

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Abstract

Steel structures require various qualities such as strength, toughness, heat resistance, weldability, and anti-corrosion, and these requirements are becoming increasingly strict. Welding science, therefore, should be more sophisticated in many fields such as efficiency, quality, energy and cost savings. In this session, I review the progress of steel and welding technology throughout this decade and introduce some topics in shipbuilding, civil construction, bridge engineering, tanks, and renewable energy fields.

1. Introduction

Steel materials exert their social values only after they have been fabricated into structures through various processes. Welding is an essential technology for the manufacture of steel structures; therefore, the characteristics and reliability of steel structures depend on welding. Materials to be used for structures have various requirements to match the environments in which they are used. Welds are also often required to have characteristics equal to or higher than those of steel materials. Therefore, welding technologies that can make the most use of the characteristics of steel materials are very important. In addition, easier welding (weldability) of steel materials is required. Welding needs to be highly efficient and labor-saving.

This trend is becoming increasingly obvious compared to the past and the requirements are becoming stricter. Nippon Steel & Sumitomo Metal Corporation has developed high performance and high quality steel plates and pipes to satisfy these requirements and placed steel materials and welding solution technologies as a set onto the market in close cooperation with Nippon Steel & Sumikin Welding Co., Ltd., a group company. Furthermore, Nippon Steel & Sumitomo Metal has been supporting the customers through proposals that can solve their various problems with welding technologies and expand the design flexibility. This paper introduces some steel materials developed in the last approximately ten years and technologies for welding them along with their trends and future prospects.

2. Recent Trends of Welding Technologies

2.1 Shipbuilding

As the world economy grows, social needs for mass transportation are on the rise, so container ships have been increasing in size. Therefore, steel plates with a thickness of 50 mm or more have been used for sheer strakes and hatch side coamings. To weld such thick steel plates efficiently, the two-electrode electro gas welding method shown in **Fig. 1** was developed and that has been applied for container ships.[1, 2] The two-electrode welding increases the welding efficiency dramatically as shown in **Fig. 2** and this method can reduce weld defects at the same time.[3] To weld thicker steel plates, the four-electrode VEGA® welding method shown in **Fig. 3** was developed and that made vertical welding possible in a single path for plates with a thickness of 200 mm as shown in **Fig. 4**.[3]

Since 1990, marine pollution due to accidental oil spills from tankers has been a very big problem. The International Maritime Organization (IMO) has tightened the international rules for tankers. Typical examples are double hulls as a structural measure and the corrosion resistant standard (MSC.288(87)) for crude oil tanks (COTs) as an anti-corrosion measure.

Type of corrosion on the bottom plates of COTs is the pitting corrosion as shown in **Fig. 5**.[2] The depth reaches 10 mm at maximum. **Figure 6** illustrates a corrosion mechanism concluded through the investigation of actual ships and the results of study in our laboratories.[4] It has been observed that water indispensable for corrosion remains on COT bottom plates while ships are carrying crude oil. The water is neutral water (brine) containing highly-concentrated chlorides and it is possibly a deposit that the water contained in the crude oil is precipitated during transportation. On the other hand, a crude oil component called oil coating is adhered to the inner surface of COTs. The oil coating acts as barrier against corrosion. Therefore, corrosion may begin at a defect of the oil coating.[4]

When corrosion begins at a defect of the oil coating, the pH low-

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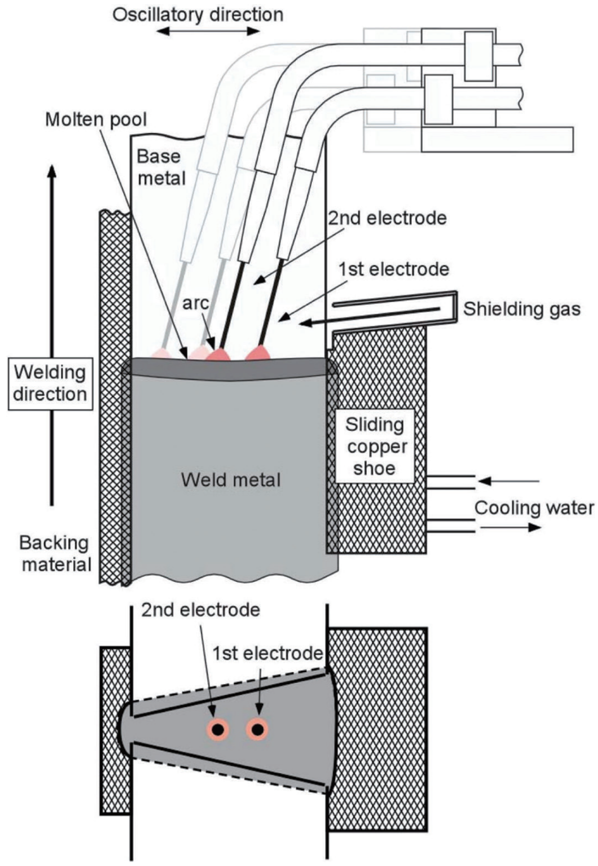


Fig. 1 Schematic diagram of two-electrode VEGA® welding process

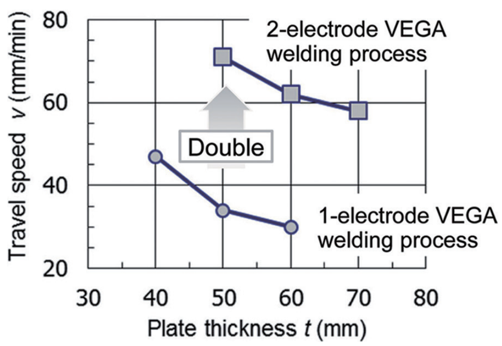


Fig. 2 Comparison of travel speed with single- and two-electrode VEGA®

ers due to hydrolysis reaction. Since highly-concentrated brine (10 mass%) remains on the bottom plate, the corroded section can be a highly acidic environment. Therefore, active dissolution possibly occurs in a pit and dome-like corrosion may be formed. When the actual pH in pits was measured, it was 1.5 or lower.[4)] Meanwhile, Ship Research Panel 242 (SR242) of the Shipbuilding Research Association of Japan reported that the progress of pits stopped at dock inspection.[5)] Thus, Nippon Steel & Sumitomo Metal has developed NSGP™-1 that reduces the corrosion rate significantly under environments such as those described above. Nippon Steel & Sumitomo Metal has also developed an exclusive welding material in cooperation with Nippon Steel & Sumikin Welding.

Photo 1 shows the results of corrosion tests of welds on NSGP™-1. Unified Interpretations UI SC258 of the International Association

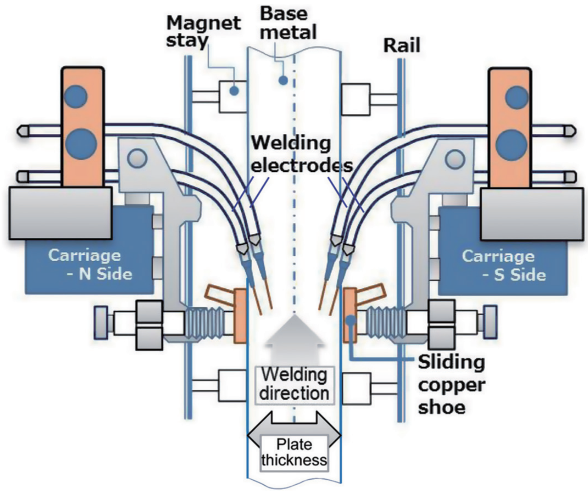


Fig. 3 Schematic diagram of four-electrode VEGA® welding process

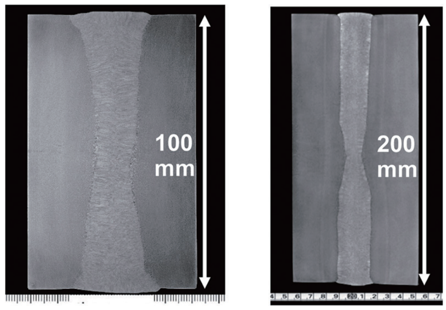


Fig. 4 Macrostructure of welds 100 mm and 200 mm thick with four-electrode VEGA® welding process

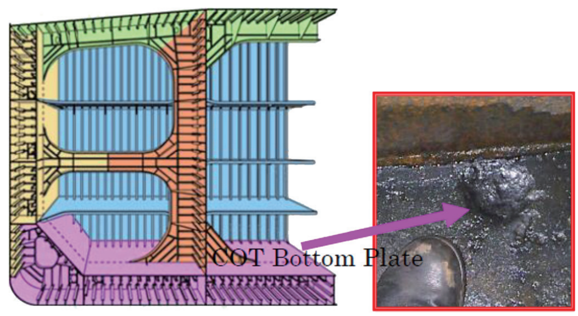


Fig. 5 Example of pit corrosion on COT (Crude Oil Tank)

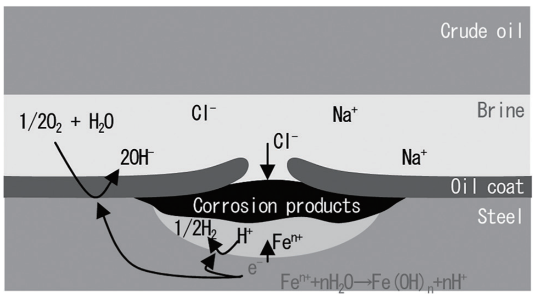


Fig. 6 Summarized process and mechanism of localized corrosion on COT bottom plate

of Classification Societies (IACS) stipulate that the step height between base metal and weld metal shall be 30 μm or less or the step height is 50 μm or less and the inclination at the boundary is 15° or less is acceptable.[4] When the conventional welding material was used, there was a clear step height of approximately 60 μm at the boundary between the base metal and weld metal and it did not satisfy the target value. When the newly developed special welding material was used, no step height was seen at the boundary between the base metal and weld metal and the weld satisfied the target value. In addition, **Table 1** shows the results of a Charpy impact test of a welded joint made by one-side submerged arc welding with a heat input of approximately 13 kJ/mm. It shows that the welded joint has excellent toughness.[4] NSGP™-1 has already been used for the COT bottom plates of more than ten very large crude oil carriers (VLCCs).

2.2 Civil construction

In the civil construction field, super high rise structures are highly demanded in urban areas to enable using the most efficient use of the land. TOKYO SKYTREE® and Abeno Harukas in Osaka are listed as typical such structures. This section introduces the welding technology used for TOKYO SKYTREE® as an example of welding technology for such structures. The steel pipe truss structure is used for TOKYO SKYTREE® as shown in **Photo 2**.[6–8] As shown in **Fig. 7**, horizontal welding (2G), diagonal circumferential welding (6G), and welding in other positions were required, so a welding material for which welding in all positions was possible was demanded. In addition, the yield strength of the steel material used was high at 400 MPa class and over-matching was required for welded joints. Therefore, Nippon Steel & Sumitomo Metal developed the new flux-cored wire SF-55 in cooperation with Nippon Steel & Sumikin Welding.

As shown in **Fig. 8**, the SF-55 wire is a seamless type, so the flux is not exposed to the air. Therefore, the flux can be annealed at high temperatures after being placed in a steel sheath. The water remaining in the wire can be reduced during the annealing. As a result of this, the quantity of diffusible hydrogen is 4 mL/100 g or less, which is very low for flux-cored wires[9]. The SF-55 contributed to more efficient welding through the reduction or omission of preheating. The flux of seamless type flux-cored wires does not absorb moisture during use, which also further enhances the reliability of construction management. **Table 2** lists examples of the mechanical properties of SF-55.

2.3 Bridges

In bridge engineering, the application of new steel material grade SBHS500, a JIS grade determined in 2008, has been promoted. Nippon Steel & Sumitomo Metal had taken the lead in the planning performance required for the steel material, putting together such requirements into standards, and putting them to practical use from the very early stage of the creation of the BHS grade that was a former grade of the SBHS500 grade. SBHS500 with excellent weldability can be applied for high heat input welding, contributing to higher efficiency of welding.[10] The world-first, full-welded large truss structure was adopted for the Tokyo Gate Bridge shown in **Photo 3**. Bolted connection was avoided as corrosion was a concern for the bridge over the sea and panel points of welded structures were used as shown in **Photo 4**, which made the bridge safer.

Another example for which high heat input welding was applied

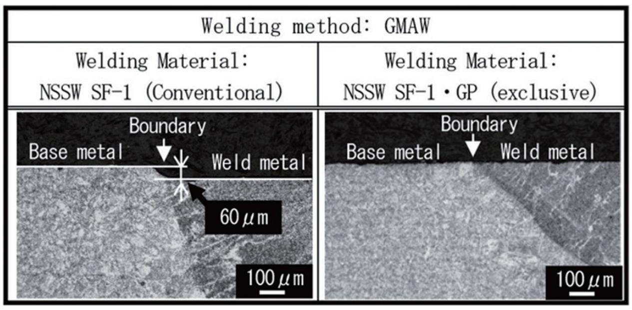


Photo 1 Cross section view of welded joints of NSGP™-1 after corrosion test

Table 1 Impact test results of welded joint (plate thickness: 20 mm)

Notch location	Weld metal	Fusion line	HAZ 1 mm	HAZ 3 mm	HAZ 5 mm
Absorbed energy at 0°C (J)	117	103	103	193	208

HAZ: Heat affected zone

Photo 2 Appearance of the TOKYO SKYTREE®

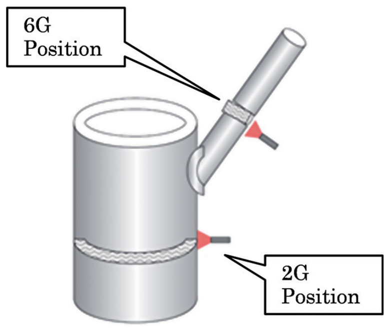


Fig. 7 Example of welding positions required in the TOKYO SKYTREE®

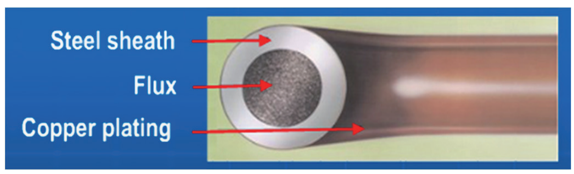


Fig. 8 Schematic image of cross section on seamless type flux cored wire

Table 2 Example of chemical compositions and mechanical properties of weld metal with the SF-55 flux cored wire

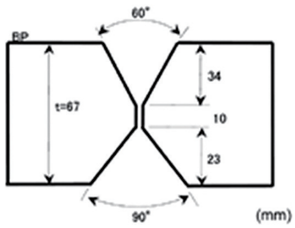
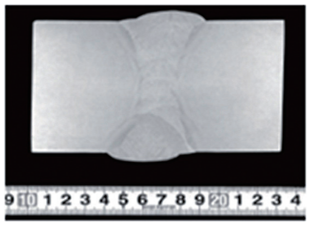
Brand name	Classification	Typical chemical composition of weld metal (mass%)					Mechanical properties			
		C	Si	Mn	Mo	Others	YP	TS	EL	Charpy absorbed energy
SF-55	JIS Z 3313 YFW-C55DR (T550T1-1CA-G-UH5)	0.06	0.4	1.28	0.15	—	560 MPa	629 MPa	25%	94 J at 0°C

YP: Yield point, TS: Tensile strength, EL: Elongation

Photo 3 Appearance of the Tokyo Gate Bridge

Photo 4 Example of the panel points on the Tokyo Gate Bridge

Table 3 Groove geometry and macro section of high arc energy SAW

Electrode	Y-DM (diameter: 4.8 mm)
Flux	NF-320M
Groove preparation	
Macroetch cross-section	

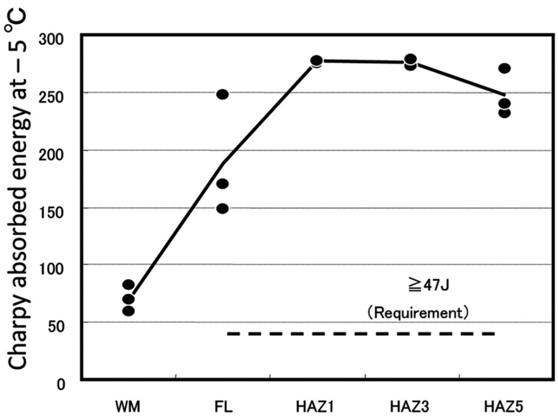


Fig. 9 Charpy impact test results of welded joints on SBHS500 steel by high arc energy SAW

is the Nagata Bridge in Tokyo.[10] SBHS500 with a thickness of 67 mm was used and high heat input welding of 10 kJ/mm (it was limited to 7 kJ/mm for conventional SM570) was applied along with the omission of pre-heating of on-site welding to reduce the construction period. **Table 3** shows an example of groove geometry and cross section macrograph of high heat input submerged arc welding (SAW). **Figure 9** shows an example of Charpy absorbed energy for joints welded by high heat input submerged arc welding. Even with high heat input welding of 11 kJ/mm, the toughness satisfies 47 J that is the required value for the joints on the Nagata Bridge.[10]

In addition, thicker SBHS500 plates for which the thickness exceeds 50 mm have been increasingly used near the panel points of bridges. Approximately half of the panels used for the Asakegawa Bridge on the Shin-Meishin Expressway and the Tsukiji Ohashi Bridge in Tokyo are thicker than 50 mm. The maximum thickness of the SBHS500 plates used is 86 mm for the Asakegawa Bridge and 80 mm for the Tsukiji Ohashi Bridge. Further application of SBHS500 is expected to reduce the weight of bridges and enhance the safety in the future.[10]

2.4 Tanks

With regard to tanks, this section introduces technologies for liquefied natural gas (LNG) tanks. Natural gas that does not damage the environment much when burned has been gaining attention as clean energy. In addition, due to the recent development of shale gas in North America, its importance as a primary energy source is further increasing. As the demand for LNG will increase around the world in the future, more ground type LNG tanks will probably be constructed. As a material for the inner tank of ground type LNG tanks, 9%Ni steel with excellent strength at very low temperatures and low-temperature toughness is used.

9%Ni steel developed by the International Nickel Company (INCO) in the U.S. has been used for more than half a century and its high level of safety is recognized. However, the price of Ni was high and highly variable, so reduction in the quantity of Ni to be used was demanded to reduce the construction costs of LNG tanks. Nippon Steel & Sumitomo Metal started the development of low Ni steel in the 1960s and this section introduces the development and

Table 4 Chemical compositions and production process

		Chemical compositions (mass%)						Production process
		C	Si	Mn	Ni	Cr	Mo	
Developed steel	Heat A (7.1%Ni-steel)	0.05	0.05	0.8	**7.1**	Added	Added	TMCP (DQ-L-T)
	Heat B (6.3%Ni-steel)	0.05	0.06	1.0	**6.3**	Added	Added	TMCP (DQ-L-T)
Conventional steel	9%Ni-steel	0.05	0.22	0.65	9.2	Tr.	Tr.	RQ-T

DQ: Direct quenching, RQ: Reheat quenching, L: Lamellarizing, T: Tempering

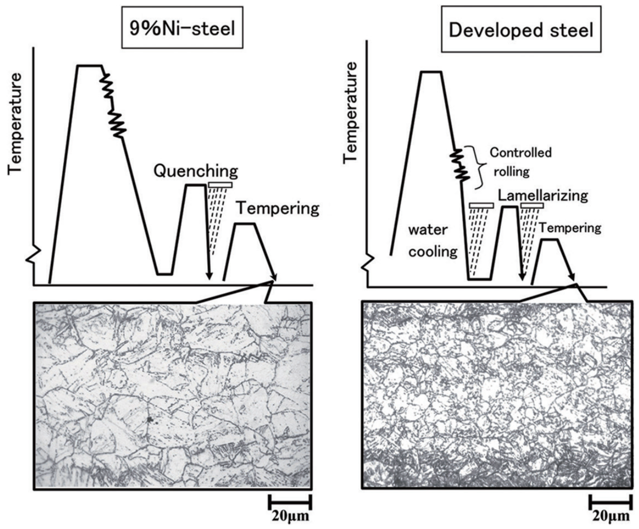


Fig. 10 Production process and microstructure

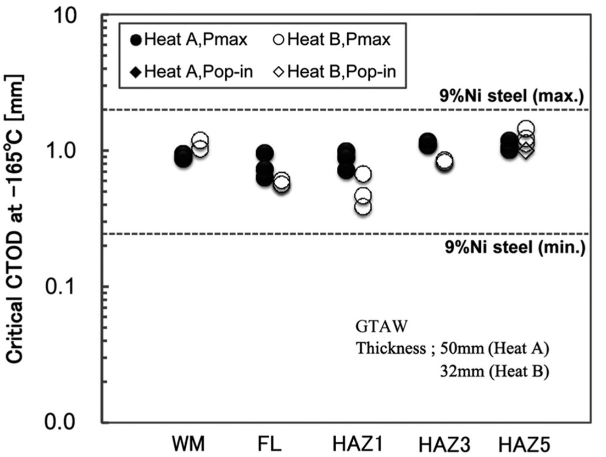


Fig. 11 CTOD test results of welded joints

application cases. **Table 4** shows an example of the chemical compositions of low Ni steel and 9%Ni steel for comparison. For low Ni steel, Ni was reduced to 6 to 7% and Mn was increased while Cr and Mo were added.[11)]

Figure 10 illustrates the production processes of 9%Ni steel and low Ni steel for comparison. The processes are reheat quenching-tempering (RQ-T) for 9%Ni steel while thermo mechanical control process-lamellarizing-tempering (TMCP-L-T) is used to manufacture low Ni steel. TMCP-L-T can make microstructure finer and can reduce the quantity of Ni to be added. **Figure 11** shows the crack tip opening displacement (CTOD) test results of welded joints using low Ni steel. The results are excellent, the same as those of 9%Ni

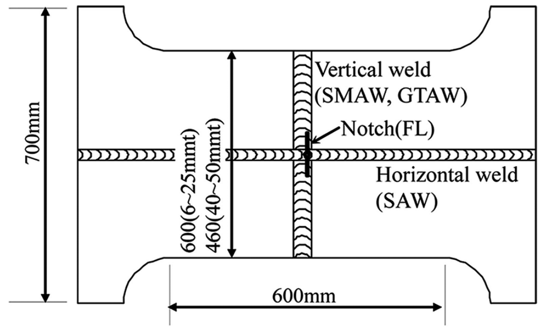


Fig. 12 Specimen of cross weld notch wide test

steel for both compositions of Heat A and Heat B shown in Table 4.[11)]

A cross weld notch wide plate test was carried out as a large-scale fracture test assuming actual welds on LNG tanks. **Figure 12** illustrates the form of the test piece. **Table 5** and **Fig. 13** show the test results. Penetrating notches with a length twice that of the plate thickness were made on the fusion lines (FLs) on gas tungsten arc welding (GTAW) joints in the vertical position and shielded metal arc welding (SMAW) joints. Fracture stress (σ_{net}) was measured at −165°C and all the values were very high (equal to or more than 750 MPa). Thus, the characteristics are almost the same levels as those of 9%Ni steel.[11)] In addition, for all the test pieces, the cracks starting from the ends of the notches escaped to the weld metals and ultimately resulted in general yielding. They broke through the maximum loads. The results above show that low Ni steel has brittle crack initiation suppressing properties at the base metals and welded joints equal to or higher than that of 9%Ni steel.[11)] Thanks to these properties, low Ni steel (Ni = 7.0 to 7.5%) was adopted for No. 5 LNG, the largest class in Japan, at Senboku Terminal 1 of Osaka Gas Co., Ltd. through discussion by the FY2010 committee for evaluating the technical standards conformity under the Gas Business Act.

2.5 Renewable energy

Wind power generation has been gaining attention as a promising power generation method of renewable energy to rank with photovoltaic power generation. Wind turbines are installed onshore and offshore. The wind velocity is high over the sea and turbulence is small, in general, so offshore wind turbines are particularly suitable for wind power generation. Japan does not have many coastal areas where the sea is shallow for some distance unlike Europe. Therefore, practical implementation of floating offshore wind turbines that can be used in deepwater areas has been discussed. Since FY2011, Nippon Steel & Sumitomo Metal has conducted the study of a floating offshore wind farm by forming and participating in a consortium consisting of ten companies with Marubeni Corporation (project integrator) and the University of Tokyo (technical adviser) as its center for such demonstration study project.

Table 5 Results of cross weld notch wide test

	Thickness (mm)	Width (mm)	Welding method	Notch		Temperature (°C)	Fracture stress (net) (MPa)
				Position	Length (mm)		
Heat A (7.1%Ni-steel)	6	600	SMAW	Fusion line	36	−166	822
	25	600	GTAW	Fusion line	50	−167 - −181	752
	25	600	SMAW	Fusion line	50	−168 - −185	756
	40	460	GTAW	Fusion line	80	−165 - −179	768
	40	460	SMAW	Fusion line	80	−166 - −179	812
	50	460	GTAW	Fusion line	100	−163 - −173	807
Heat B (6.3%Ni-steel)	6	600	SMAW	Fusion line	36	−165	1 002
	12	600	SMAW	Fusion line	24	−165	954
	12	600	GTAW	Fusion line	24	−165	983
	32	600	SMAW	Fusion line	64	−165	857
	32	600	GTAW	Fusion line	64	−165	851

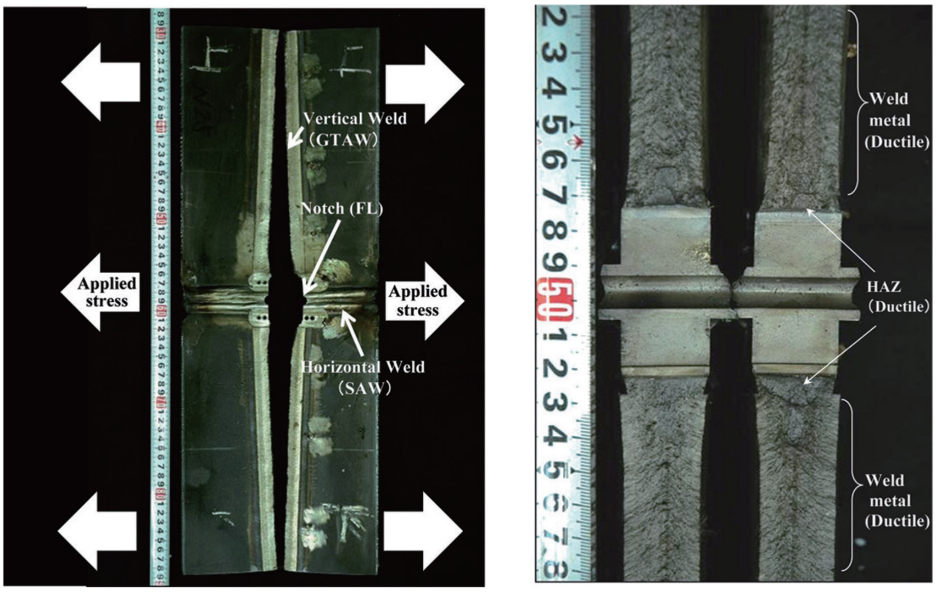


Fig. 13 Fracture path and fracture surface of cross weld notch wide test (Heat A, 25 mmt)

This project is a world first as a wind farm consisting of multiple floating offshore wind turbines and a floating offshore substation.[12) This section introduces a high heat input welding technology as an issue to be addressed for offshore wind power generation. When a large wind turbine is installed, thick plates are used for important structural sections in the floating structure as is the case with bottom-mounted wind turbines. Therefore, assuming that a large quantity of large wind turbines would be installed in the future, reducing the welding costs of thick plates, that is to say, improving the efficiency of welding is an important issue to be solved in order to expand offshore wind power generation. A case study of high heat input welding to solve this issue is shown below. High heat input welding can reduce the arc time significantly as shown in **Fig. 14**, making welding more efficient.[12)]

However, as the heat input increases, the toughness of the weld metal (WM) and heat affected zones (HAZs) tends to decrease in general, which may make it difficult to secure the toughness at low temperatures of 0 to −40°C that is required in the offshore wind power generation field. Nippon Steel & Sumitomo Metal has HTUFF™ (High HAZ Toughness Technology with Fine Micro-

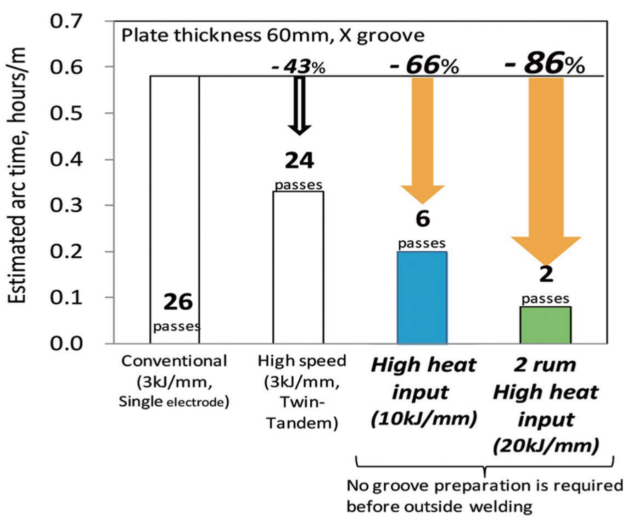


Fig. 14 Advantages of high heat input SAW in arc time

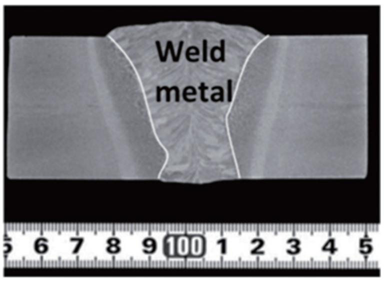


Fig. 15 Example of macro sections by high arc energy welding

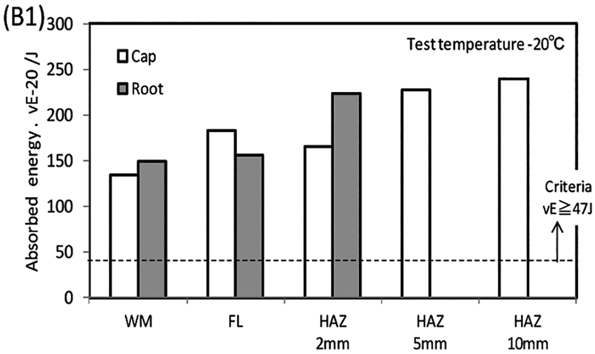


Fig. 16 Charpy impact test results of welded joints by high arc energy welding

structure Imparted by Fine Particles) steel that is a technology to prevent the coarsening of HAZ structure under such conditions by ultrafine nanoparticles that are thermally stable at high temperatures and a welding technology that can make the utmost use of the characteristics of the HTUFF™ steel, with Nippon Steel & Sumikin Welding, a group company. **Figure 15** shows the cross section macrograph of a joint welded by one-sided SAW with a heat input of 31 kJ/ mm. **Figure 16** shows the Charpy test results of the joint.[12] The absorbed energy observed is excellent at all the notch locations in Fig. 16, so the technologies are contributing to achieving high-efficient welding and securing safety.

2.6 Others

In addition to the materials introduced in this paper, high temperature materials with both excellent creep property and weldability have been developed, such as SAVE12AD[13] and HR6W[14] that are expected to be used for the next-generation USC boilers. The quality of electric resistance welded (ERW) steel pipes has been improved by reducing oxides at weldments by applying plasma shielding.[15] Regarding shale gas gaining attention recently, a new type of steel tube that can reduce coking at chemical plants in the downstream process has been developed and welding technologies for them are under consideration.[16] In addition, regarding hydrogen expected as new clean energy, weldable tube materials have been developed,[17] so study results have been realized progressively.

3. Conclusion

The welding technologies in the last approximately ten years were introduced in the sections above. A weld is a discontinuous section regarding all micro- structure, chemical components, and dynamic properties such as residual stress and thermal deformation. The safety and usable life of structures rely on how well welding is performed. Characteristics required for steel materials and welds are not simple: various characteristics such as strength, toughness, fatigue characteristics, and thermal resistance are required. Recently, they have become increasingly diversified and even stricter. Welding technologies need to be further advanced and deepened with such tendency taken into consideration. To manufacture highly reliable steel structures efficiently in the future, it will be increasingly important to understand the basic phenomena of welding more deeply to develop steel and welding materials. It will also become increasingly important to understand customer side technologies such as those for design, management, and construction correctly and satisfy such needs.

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