Welding Process and Welding Consumables for Offshore Wind Power Generation Facilities

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Abstract

Japan's domestic policy aimed to achieve carbon neutrality by 2050 has resulted in a growing interest in power generation methods that employ renewable energy sources with low CO_2 emissions. Among these methods, offshore wind power generation has garnered significant attention in recent years. Wind turbines in offshore facilities rely on foundations such as monopiles for support. With the increasing size of wind turbines, the monopiles have also grown gigantic in diameter and length, making it necessary to use extra-thick steel plates for their construction. Welding these plates requires an appropriate welding process and welding consumables. To meet these requirements, Kobe Steel has developed a new electroslag welding process for extra-thick plates, SESLA™, and welding consumables for narrow-groove submerged-arc welding(SAW), FAMILIARC™ US-29HK and TRUSTARC™ PF-H55LT-N.

Introduction

Since the Great East Japan Earthquake on March 11, 2011, the nation's energy policy has undergone scrutiny, with increasing anticipation for renewable energy as a new source. Among these, one renewable energy that is attracting particular attention is offshore wind power generation. In order to overcome the energy crisis that European countries are also facing, they are successively announcing plans for the large-scale introduction of offshore wind power generation. In Japan, Round 1 bidding in the offshore wind promotion area has concluded, with expectations for Rounds 2 and 3 bids in the future[1].

In offshore wind power generation, significant costs are associated with installation, mooring, grid connection, operation, and maintenance. Ensuring profitability requires a crucial focus on increasing power generation per windmill. Technology development to enhance output by upsizing rotor diameter is actively progressing and, as depicted in **Fig. 1**, the rated power output of wind turbines for wind power generation is increasing gradually. Recent years have seen the adoption of windmills with a rated power output of 5 to 8 MW in offshore wind power generation. The anticipation is for larger windmills exceeding 10 MW in rated power output in the future, reflecting the trend toward upsizing offshore wind power generation equipment[2].

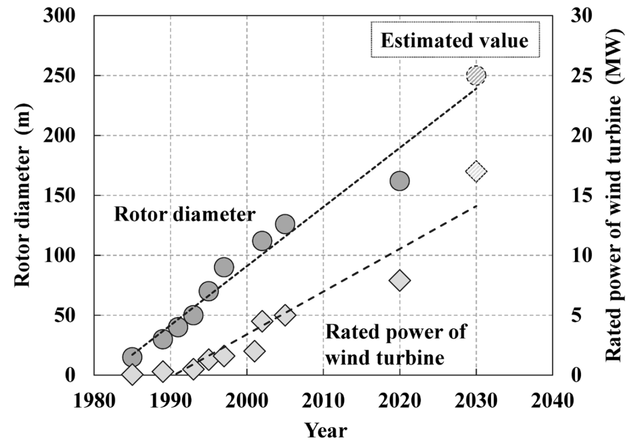


Fig. 1 Growth of rotor diameter of wind turbines and rated power for wind power generation[3)-5)]

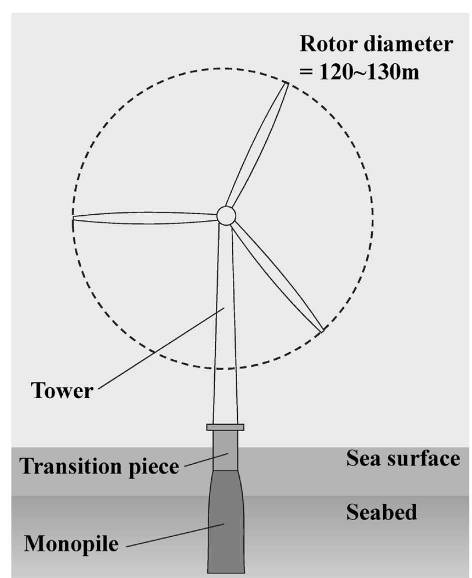


Fig. 2 Schematic image of a 5 MW-class offshore wind power generation facility

As illustrated in **Fig. 2**, offshore wind power generation equipment utilizes towers supporting windmills and monopiles beneath the sea surface as basic components. These are constructed by welding steel pipes made of extra-thick plates with a thickness exceeding 50 mm. For manufacturing single pipes and weld joints, both vertical and circumferential welding are indispensable, and an efficient welding process for extra-thick plates is being sought.

This paper introduces a new electro slag welding (hereinafter referred to as ESW)[6] process suitable for vertical welding (vertical seams) on extra-thick plates and welding consumables for narrow-groove SAW suitable for circumferential welding.

1. New ESW process, SESLA™

The new ESW process, SESLA™ (hereinafter referred to as SESLA™), is a high-efficiency vertical automatic welding process developed by Kobe Steel on the basis of the element technology of ESW. Unlike arc welding, ESW forms a slag bath, and welding progresses by melting the wire through resistive heating in this bath. This results in the significant advantage of minimal generation of spatter and fumes. Moreover, since the molten pool is protected by the slag bath, this welding process exhibits excellent wind resistance even without the use of shielding gas. The configuration of SESLA™ is illustrated in **Fig. 3**. The welding involves using a water-cooled copper sliding shoe on the front side of the groove and FAMILIARC™ KL-4 as a backing material on the back side. Similar to the process in conventional ESW, an arc is generated at the start of welding. The introduced flux is melted to form a slag bath. The electrical resistance heating of the molten slag bath serves as the heat source, melting the flux-cored wire. During this process, penetration is formed through the convection action of the slag bath, allowing welding to be completed in a single pass even in butt joints of thick plates.

1.1 SESLA™ dedicated welding consumables

Electrogas arc welding (hereinafter referred to as EGW) is widely applied in the shipbuilding sector and other industries as a high-efficiency vertical automatic welding process, similar to ESW. EGW uses an arc as the heat source and employs shielding gas, so it is necessary to consider the welding environment, including the risk of shield failure and fume generation. On the other hand, while ESW allows welding without the use of shielding gas, there is a limitation on the welding length due to the structure of the welding equipment.

SESLA™ is a new welding process developed to overcome the shortcomings of ESW. It utilizes a specific welding apparatus and dedicated welding consumables, namely the flux-cored wire FAMILIARC™ ES-X55E and the melting-type flux FAMILIARC™ EF-4. A study has been conducted using JIS G 3106 SM490A steel plates to investigate the impact of preheating on the mechanical properties of SESLA™ weld metal. The relationship between heat input and proof strength/tensile strength is shown in **Fig. 4**, and the relationship between heat input and -20℃ absorbed energy is shown in **Fig. 5**. The strength of SESLA™ weld metal decreases with an increase in heat input; however, it maintains excellent notch toughness.

1.2 Application to extra thick plates

The SESLA™ achieves excellent mechanical properties across a broad spectrum of heat inputs, and it has been verified that single-pass welding is viable for plate thicknesses up to 80 mm. **Table 1** outlines the conditions for testing and welding extra-thick plates with a thickness of 80 mm. JIS G 3106 SM490A was used as the base metal. **Fig. 6** displays

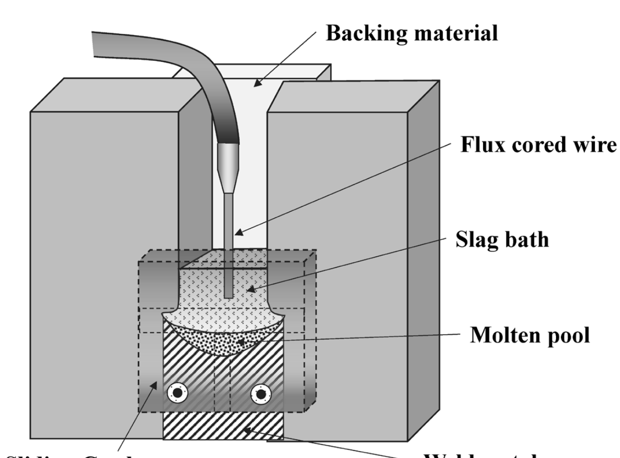


Fig. 3 Configuration of SESLA™

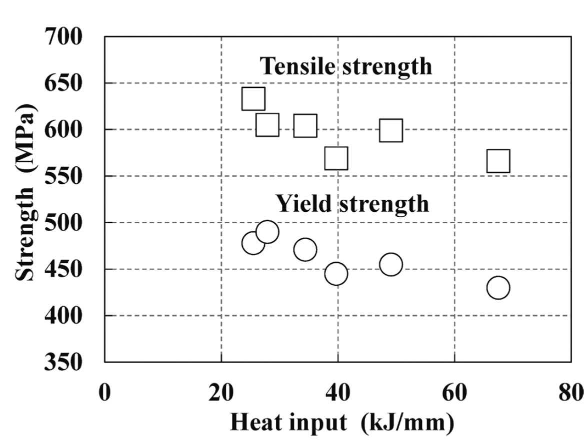


Fig. 4 Relationship between heat input and tensile strength of SESLA™

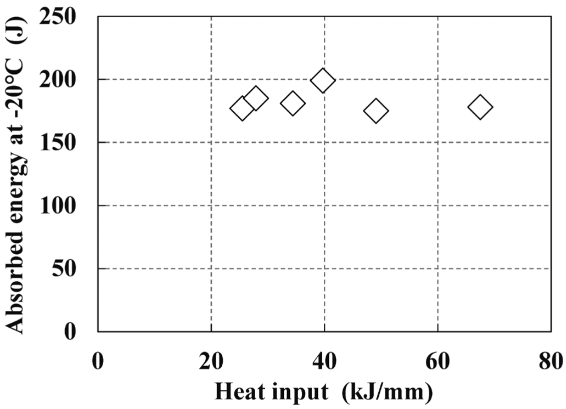
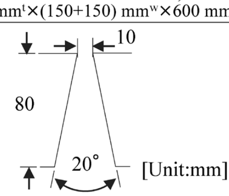


Fig. 5 Relationship between heat input and -20℃ absorbed energy in SESLA™

Table 1 Test condition of butt joint welding

Wire-flux combination	FAMILIARC™ ES-X55E／FAMILIARC™ EF-4
Base metal	JIS G 3106 SM490A, 80 mm^t×(150+150) mm^W×600 mm^L
Groove configuration	
Welding parameter	DCEP, 420 A-47 V-17 mm/min
Heat input	69.7 kJ/mm
Preheat	Room temp.
PWHT condition	As-welded

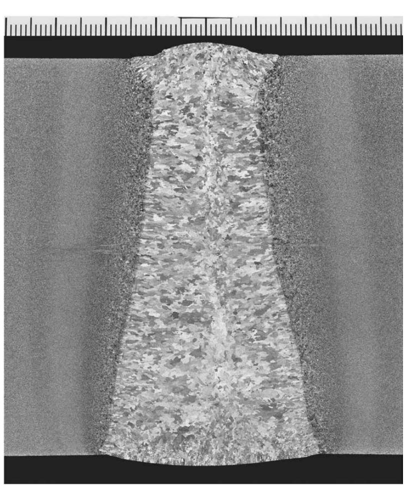


Fig. 6 Cross-sectional macrograph of weld joint

Table 2 Chemical composition of weld metal (mass%) *1

C	Si	Mn	P	S
0.06	0.20	1.22	0.010	0.004

*1 Location: Center of weld metal

Table 3 Mechanical properties of weld metal

Location	Tensile properties*1			Notch toughness*1			
	0.2%PS (MPa)	TS (MPa)	El. (%)	Absorbed energy (J)			
				【-40℃】		【-20℃】	
7 mm beneath the face side	435	561	24	168 169 153	Avg. 163	186 196 214	Avg. 199
40 mm beneath the face side	438	568	25	191 176 155	Avg. 174	191 202 207	Avg. 200
73 mm beneath the face side	446	577	23	162 159 163	Avg. 161	184 200 136	Avg. 173

*1 Tensile test specimen: round tensile specimen, Dia.=10 mm, G.L.=50 mm
Impact test specimen: 10×10 mm square shape, 2 mm V notch based on AWS B4.0

the macrostructure of the weld joint, while **Table 2** presents the chemical composition of the weld metal, and **Table 3** provides its mechanical properties. Satisfactory penetration is observed for a plate thickness of 80 mm. Despite the increased heat input of up to 69.7 kJ/mm, the weld metal maintains ample strength and exhibits excellent notch toughness at -40℃.

2. Consumables for narrow groove submerge arc welding

For welding extra-thick plates, the utilization of SAW with a high-deposition rate, is common. An effective approach to enhance its efficiency involves narrowing the groove. In response to narrow groove requirements in SAW, new SAW materials, namely FAMILIARC™ US-29HK and TRUSTARC™ PF-H55LT-N, have been developed. The following introduces the details:

FAMILIARC™ US-29HK is a solid wire for carbon steel, while TRUSTARC™ PF-H55LT-N is a fluoride-basic type bonded flux, adopting a flux design with enhanced basicity index. The advantages lie in the optimization of the flux design, ensuring excellent notch toughness and excellent slag removability in narrow grooves. Notably, these materials can be used with both direct current (DCEP) and alternating current (AC).

2.1 Performance of deposited metal

The investigation encompassed various performance characteristics of the deposited metals of FAMILIARC™ US-29HK and TRUSTARC™ PF-H55LT-N. **Table 4** presents the chemical composition of the deposited metal under both DCEP and AC. **Table 5** and **Fig. 7** present the as-deposited mechanical properties. It has been verified that a deposited metal with high strength (exceeding 550 MPa) and exceptional absorbed energy up to

Table 4 Chemical composition of deposited metal (mass%)*1, 2

	Polarity	C	Si	Mn	P	S
[F]US-29HK, [T]PF-H55LT-N*3	DCEP	0.07	0.29	1.85	0.013	0.002
	AC	0.08	0.27	1.73	0.013	0.002

*1 Location: Center of the deposited metal
*2 Welding condition: 550 A-30 V-420 mm/min; Ext.=30 mm; 4.0 mm wire dia.
*3 [F]: FAMILIARC™ welding consumables,
[T]: TRUSTARC™ welding consumables

Table 5 Mechanical properties of deposited metal*1, 2

	PWHT condition	Polarity	0.2 %PS (MPa)	TS (MPa)	El. (%)
[F]US-29HK, [T]PF-H55LT-N*3	As-welded	DCEP	514	603	28
		AC	534	618	29

*1 Size of impact test specimen is based on AWS B4.0
Tensile test specimen: round tensile specimen, Dia.=12.5 mm, G.L.=50 mm
Location: the same as analysis location for chemical composition
*2 Welding condition: 550 A-30 V-420 mm/min; Ext.=30 mm; 4.0 mm wire dia.
*3 [F]: FAMILIARC™ welding consumables,
[T]: TRUSTARC™ welding consumables

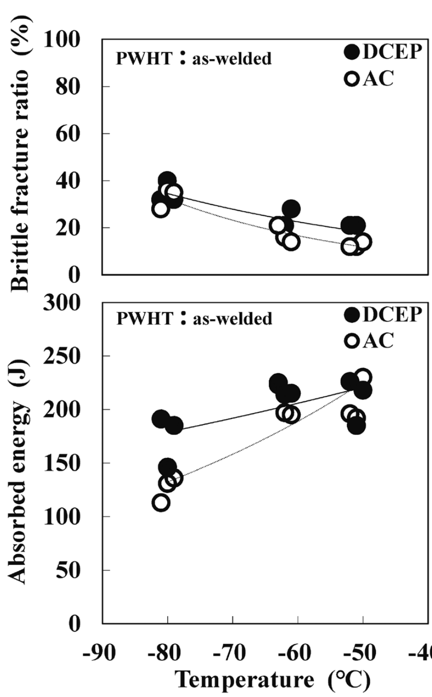


Fig. 7 Transition curves of notch toughness of deposited metal in as-welded condition*1, 2
*1 Size of impact test specimen is based on AWS B4.0 Impact test specimen: 10×10 mm square shape, 2 mm V notch Location: the same as analysis location for chemical composition
*2 Welding condition: 550 A-30 V-420 mm/min; Ext.=30 mm; 4.0 mm wire dia.

Table 6 Diffusible hydrogen test results*1

	Polarity	Diffusible hydrogen content (mL/100g)			
		N=1	N=2	N=3	Avg.
[F]US-29HK, [T]PF-H55LT-N	DCEP*2	3.2	3.3	3.3	3.3

*1 Test method: JIS Z3118, gas chromatography method
*2 Welding condition: 550 A-30 V-400 mm/min; Ext.=30 mm; 4.0 mm wire dia.
Redrying condition: 350°C×1 h, Welding atmosphere: 11°C×79 %RH

-60℃ can be obtained.

Table 6 displays the amount of diffusible hydrogen when welding with the combination of FAMILIARC™ US-29HK and TRUSTARC™ PF-H55LT-N under direct current (DCEP). Through the optimization of flux design, the amount of diffusible hydrogen has become as low as approximately 3 mL/100g.

2.2 Performance of weld joints

A test evaluating various performance characteristics of weld joints was performed using the combination of FAMILIARC™ US-29HK and TRUSTARC™ PF-H55LT-N in narrow gap SAW. **Table 7** outlines the test conditions, **Table 8** details the welding conditions, and **Fig. 8** illustrates the groove shape and welding procedure. Tandem welding aimed at achieving high efficiency was executed with a bipolar trailing electrode of 2.4 mm. The electrode arrangement for tandem welding is depicted in **Fig. 9**. **Fig.10** presents a cross-sectional macrograph of the weld joint, while **Table 9** details the chemical composition of the weld metal, and **Table 10** provides its mechanical properties. In the

Table 7 Test condition of both side butt joint welding

Electrode	FAMILIARC™US-29HK, Leading electrode(L):4.0 mm dia. Trailing electrode(T):2.4 mm dia.×2 wires
Flux	TRUSTARC™PF-H55LT-N
Base metal	JIS G 3106 SM490A, 80 mm^t×(150+150) mm^w×800 mm^L

Table 8 Welding parameters for both side butt joint welding

	No. of passes	Welding parameter*1	Heat input (kJ/mm)
1st side	1	Single, DCEP, 600 A-30 V-600 mm/min	1.8
	2	Single, DCEP, 650 A-30 V-600 mm/min	2.0
	3-8	Tandem, L: DCEP, 650 A-30 V T: AC, 600 A-32 V-700 mm/min	3.3
2nd side	1	Single, DCEP, 600 A-30 V-600 mm/min	1.8
	2-21	Tandem, L: DCEP, 650 A-30 V T: AC, 600 A-32 V-700 mm/min	3.3

*1 Preheat and inter pass temperature.:100～147°C

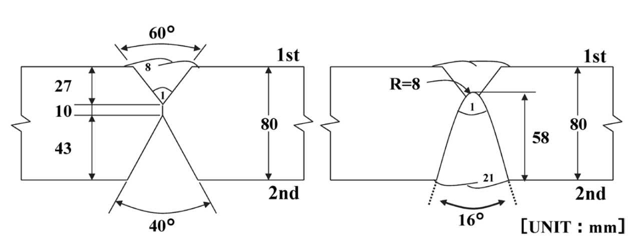


Fig. 8 Groove configuration and pass sequences

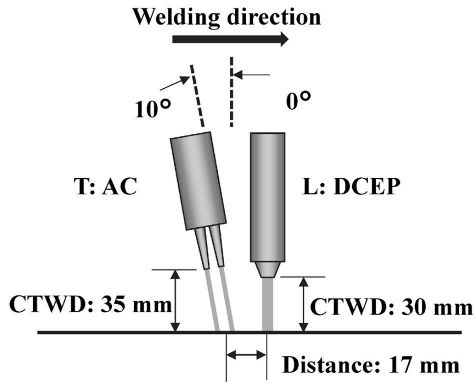


Fig. 9 Electrode configuration of tandem welding

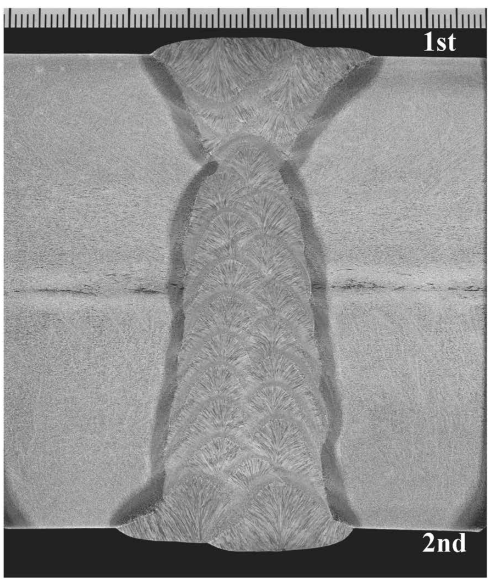


Fig.10 Cross-sectional macrograph of both side butt joint welding

Table 9 Chemical composition of weld metal (mass%)*1

C	Si	Mn	P	S
0.09	0.30	1.78	0.014	0.003

*1 Location: Center of weld metal

weld joint, excellent impact performance at -60℃ is ensured while maintaining strength[7)].

Conclusions

In recent years, there has been a growing expectation for the sustainable utilization of wind power generation as a renewable energy source. Particularly, offshore wind power generation is expanding globally, with significant growth observed in Europe. In Japan, the Cabinet has resolved to introduce offshore wind power generation on a large scale as a key strategy for the substantial integration of renewable energy into the main power supply. This decision is outlined in the 6th Next Energy Basic Plan (2021)[8)].

This paper has introduced SESLA™, a suitable welding process for the extra-thick plates used in the fabrication of components like giant monopiles in offshore wind power generation facilities, as well as consumables for narrow gap SAW, namely "FAMILIARC™ US-29HK / TRUSTARC™ PF-H55LT-N." These contribute to the high-efficiency welding of extra-thick plates, allowing the weld metal to attain excellent mechanical properties, including the necessary strength and low-temperature notch toughness required for large steel structures used offshore. This is anticipated to result in a broad application spectrum in the offshore wind power sector, focusing not only on the integrity and reliability of weld joints but also on the demand for upsizing and mass production of power generation facilities.

Table 10 Mechanical properties of weld metal*1

Location	Tensile properties*2			Notch toughness*2			
	0.2 %PS (MPa)	TS (MPa)	El. (%)	Absorbed energy (J)			
				【-60℃】		【-40℃】	
7 mm beneath 2nd side	496	618	33	112 123 127	Avg. 121	161 156 147	Avg. 155
40 mm beneath 2nd side	580	634	28	162 181 152	Avg. 165	194 196 196	Avg. 195
73 mm beneath 2nd side	591	664	28	128 130 179	Avg. 146	184 185 183	Avg. 184

*1 PWHT condition: as-welded
*2 Tensile test specimen: round tensile specimen, Dia.=6.0 mm, G.L.=24 mm
Impact test specimen: 10×10 mm square shape, 2 mm V notch based on AWS B4.0

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