Recent Development of High-strength and Tough Welding Consumables for Offshore Structures

Dr. Yoshihiko KITAGAWA[*1], Hiroyuki KAWASAKI[*1]

[*1] Welding Process Dept., Technical Center, Welding Business

As the exploration fields for oil and gas resources expand into deeper and colder seas, higher strength and greater toughness are required for the structural materials, including welding materials, used in offshore structures. Recent offshore structures require structural materials having sufficient CTOD properties, including a yield strength of 460MPa or higher and good impact toughness down to -60℃. To meet such requirements, we have developed advanced welding consumables for shielded metal arc welding (SMAW), submerged arc welding (SAW) and flux-cored arc welding (FCAW). For SMAW and SAW consumables, the basicity of the flux was adjusted to reduce the oxygen content in the weld metal, thereby achieving good impact toughness down to -60℃, a high yield strength of over 500MPa, and a high CTOD value down to -40℃. The FCAW consumable has been improved with optimized deoxidizers and the appropriate addition of Ni and Mn to produce a weld metal having a very fine microstructure, thus achieving both a yield strength of over 690MPa and good impact toughness down to -60℃.

Introduction

Recently, oil and natural gas are being more actively developed throughout the world to cope with the increasing energy demand. A rapidly growing number of offshore structures are being built, for example, in Southeast Asia, Korea and China. As the resource exploration area is expanded into deeper areas of the sea and low temperature oceans, the steel used for offshore structures is required to be stronger and tougher. To achieve such high strength, steels having a 0.2% yield strength (YS) of 500MPa to 690MPa are increasingly being used these days instead of the conventional steels of YS460MPa or less. As to the aspect of toughness, recent welded joints are required to have brittle fracture prevention characteristics, in addition to the Charpy impact energy absorption at temperatures from -40℃ to -60℃. Therefore, the critical crack tip opening displacement (CTOD) value, as described later, is more often included in the specification requirements for fracture toughness.

This paper describes the recent trend of offshore structures that are built in deeper areas of the ocean, and the high-quality welding consumables developed for the purpose.

1. Types of offshore structures

Offshore structures for oil and natural gas are roughly classified into a fixed, bottom-seated type that is directly supported by the ocean floor, and a floating type that is indirectly supported. The bottom-seated type includes a jacket with legs fixed to the ocean floor and an upper structure, including excavating equipment, mounted on the legs, a jack-up drilling rig consisting of fixed legs and an upper structure that is designed to move up and down, and a compliant tower (CT) with flexible legs. The floating type includes a semi-submergible rig (SSR), a tension-leg platform (TLP), a floating production, storage and offloading facility (FPSO) and a SPAR platform. A SPAR platform is a moored type, comprising a lower structure with a hollow cylindrical float and storage capacity. Since the floating type equipment can perform drilling and production in water deeper than the fixed type can, the number of such types has been increasing in recent years as the resources are sought in deeper areas of the ocean. **Table 1** shows the types of major offshore structures, their operating depths in the water and the strength grades of steel used.[1), 2)] As the structure becomes larger, high-strength steels of the YS460 -690MPa classes are increasingly used for weight reduction.

Table 1 Type, operating water depth, and steel grade of offshore structures

Type	Operating water depth[1),2)]	Steel grade
Jacket	<450 m	～YS500
Jack-up rig	30-200 m	～YS690
CT	300-700 m	～YS460
SSR	70->2000 m	～YS690
TLP	300-1500 m	～YS460
FPSO	50->2000 m	～YS460
Spar	300->2000 m	～YS460

2. Design concept of offshore structures

The capsizing of Alexander Kielland in 1980[3)] triggered the introduction in the 1980s of elasto-plastic fracture mechanics to the design concept in order to improve structural safety. This has raised the need of brittle-crack propagation arrest characteristics for steel plates and brittle-fracture prevention characteristics for welded joints. More

Table 2 Welding consumables for offshore structures requiring low temperature toughness

Welding process	Welding Consumable[*1]	Minimum applicable strength (MPa)[*2]		Applicable temperature (℃)[*2]		Chemical composition of weld metal (mass%)							Polarity or shielding gas
				vE	CTOD (δ)								
		0.2%YS (MPa)	TS (MPa)	≧47J	≧0.25mm or ≧0.10mm※	C	Si	Mn	Ni	Mo	Ti	B	
SMAW	[T] LB-7018-1	400/390[*3]	520/490[*3]	-40	0	0.06	0.4	1.5	-	-	0.03	0.004	AC/DCEP[*4]
	[T] LB-52NS	400/390[*3]	520/490[*3]	-60	-30	0.08	0.4	1.4	0.5	-	0.02	0.002	
	[T] NB-1SJ	460/400[*3]	550/520[*3]	-60	-40	0.08	0.3	1.3	1.3	-	0.02	0.002	
	[T] LB-55NS	470/460[*3]	570/550[*3]	-60	-	0.06	0.3	1.5	0.9	0.1	0.01	0.003	
	[T] LB-62L	530/460[*3]	620/550[*3]	-60	-10	0.07	0.3	1.0	2.1	0.1	0.02	0.002	
	[T] LB-67L	530	620	-60	-20	0.06	0.3	1.1	2.6	-	0.01	0.002	DCEP
	[T] LB-67LJ	530	620	-60	-40 ※	0.07	0.4	1.1	2.6	-	0.02	0.002	
	[T] LB-88LT	690	770	-60	-	0.04	0.6	1.8	2.6	0.7	-	-	AC
	[T] LB-80L	690	770	-60	-	0.04	0.5	1.4	3.0	0.8	-	-	DCEP
SAW	[T] PF-H55LT/ [F] US-36	400	520	-60	-50	0.08	0.2	1.4	-	-	0.02	0.004	AC
	[T] PF-H55LT/ [T] US-36J	465	550	-60	-20	0.09	0.3	1.7	-	-	0.02	0.004	
	[T] PF-H55S/ [T] US-2N	530	620	-60	-20	0.08	0.3	1.3	2.3	0.2	-	-	
	[T] PF-H80AK/ [T] US-80LT	690	770	-60	-	0.08	0.3	1.7	2.5	0.7	-	-	
	[T] PF-H55AS/ [T] US-36J	400	520	-60	-20	0.07	0.2	1.4	-	-	0.02	0.004	DCEP
	[T] PF-H62AS/ [T] US-2N	530	620	-60	-20	0.05	0.3	1.3	2.5	0.2	0.01	-	
	[T] PF-H80AS/ [T] US-80LT	690	770	-60	-	0.06	0.5	1.6	2.4	0.7	-	-	
GMAW (Solid)	[T] MG-S50LT	400	520	-60	-30	0.09	0.4	1.9	-	-	0.08	0.006	80%Ar-20%CO_2
	[T] MG-S88A	690	770	-60	-	0.06	0.5	1.6	3.6	0.8	-	-	
GMAW (FCW)	[T] DW-55L	400	520	-60	0	0.04	0.4	1.3	1.4	-	0.05	0.003	CO_2
	[T] DW-55LSR	420	550	-60	-10	0.06	0.3	1.2	1.5	-	0.05	0.004	
	[T] DW-62L	500	610	-60	-40 ※	0.06	0.3	1.2	2.5	-	0.06	0.004	
	[T] DW-A81Ni1	420	550	-60	-10	0.05	0.3	1.3	0.9	-	0.04	0.005	80%Ar-20%CO_2
	[T] DW-A55L	460	550	-60	-20	0.06	0.3	1.2	1.4	-	0.06	0.003	
	[T] DW-A55LSR	420	550	-60	-20	0.05	0.3	1.3	0.9	-	0.04	0.003	
	[T] DW-A62L	500	610	-60	-40 ※	0.07	0.3	1.3	2.1	-	0.04	0.003	
	[T] DW-A80L	690	770	-40	-	0.07	0.3	1.9	2.5	0.2	0.07	-	

*1 [F]: FAMILIARC™ welding consumables, [T]: TRUSTARC™ welding consumables
*2 For as-welded state (no post weld heat treatment)
*3 The left value is for AC (alternate current) welding and the right value is for DCEP (direct current electrode positive) welding.
*4 Chemical compositions of LB-52NS, NB-1SJ and LB-62L weld metals are for AC current, others are for DCEP current.

specifically, critical CTOD values were additionally required as fracture toughness criteria, especially for offshore structures.

The CTOD testing involves a specimen with a fatigue precrack, in which the precrack is opened by bending or tension to measure the crack opening displacement at the time when unstable fracture begins. The critical CTOD value indicates the opening displacement at the crack tip when the unstable fracture begins, or, when no unstable fracture occurs, indicates the crack tip opening displacement at the maximum load. In general, an offshore structure requires a critical CTOD value of 0.10mm to 0.25mm or even greater at temperatures from 0 to -10℃; however, lately more stringent requirements at temperatures from -30 to -40℃ are being seen.

3. Welding consumables for offshore structures

For the welding of offshore structures, welding consumables of various strength classes are used for steel grades of the YS320 - 420MPa class, the YS460 - 500MPa class and the YS690MPa class. These welding consumables include the materials approved by classification societies for general shipbuilding; however, qualities other than those approved are often required to satisfy the design requirements unique to offshore structures, such as applications in intensely cold sea, thicker structural members and the use of high-strength steel. In particular, the stringent requirement for low temperature toughness has led to having the offshore structures welded using consumables designed for steel used at low temperatures.

Table 2 shows typical welding consumables manufactured by Kobe Steel for the low-temperature specifications of offshore structures. The majority of materials in this table satisfy the Charpy impact performance requirements down to approximately -60℃. With the exception of the materials for YS690MPa class steel and a few others, they also satisfy the CTOD requirements down to temperatures of -10℃ or lower.

4. Design guidelines for weld metal with high toughness

4.1 Techniques for improving the toughness of weld metal

The following measures are effective in improving the toughness of weld metals: ① toughening the ferrite, ② refining the microstructure by lowering the transformation temperature, and ③ forming a fine needle-like microstructure consisting of acicular ferrite by introducing intragranular nucleation sites such as oxide. These are common

Table 3 Method to improve toughness of weld metal

Aim	Method	
	≦YS500	≧YS600
Toughening matrix	Addition of Ni	Increase of Ni
Refinement of microstructure	Addition of Mo Reduction of O	Reduction of O
Formation of acicular ferrite	Addition of Ti and B	Introduction of nucleation site (Ti oxide, etc.)

approaches for increasing toughness regardless of the strength.

Meanwhile, regarding the microstructures of weld metals, the weld metal of YS500MPa or lower has a microstructure mainly consisting of ferrite + pearlite, while the weld metal of YS600MPa or higher has a microstructure mainly consisting of bainite + martensite. Therefore, in order to design welding consumables for low-temperature specifications, taking account of toughness, the basic composition design of the weld metal should be fairly different below and above the strength boundary of YS500 - 600MPa. **Table 3** shows the method for improving toughness in accordance with strength. Currently, Ti and B are added in combination to the weld metal in the strength class of YS500MPa or lower to suppress the grain boundary ferrite while promoting the formation of acicular ferrite. On the other hand, an increased amount of Ni is mainly added to the weld metal of YS600MPa or higher to toughen the ferrite and refine the microstructure. Another common approach is to reduce the oxygen in the weld metal.

4.2 CTOD design technique

When developing welding consumables, it is not practical to conduct a CTOD test on each and every trial material, due to the long time and high cost of testing. So, a technique was devised for predicting the results of CTOD testing from a simple Charpy impact test, using the relationship depicted in **Fig. 1**. The horizontal axis represents the ratio of the area occupied by brittle fracture surface after the Charpy impact test, while the vertical axis represents the occurrence probability of different fracture modes in the CTOD test. It should be noted that the testing temperature for the Charpy impact test contemplates the temperature shift (ΔT) caused by the thickness effect.[4] Each plot represents values measured by the Charpy impact test and the CTOD test for various thicknesses and heat inputs, while each curve is an approximation of relevant measured values. This figure indicates that, in order to avoid unstable fracture (c-mode) and to achieve either perfectly ductile fracture (m-mode), or unstable fracture after stable and ductile crack propagation (u-mode), the brittle fracture surface ratio after the Charpy impact test must be approximately 40% or smaller.

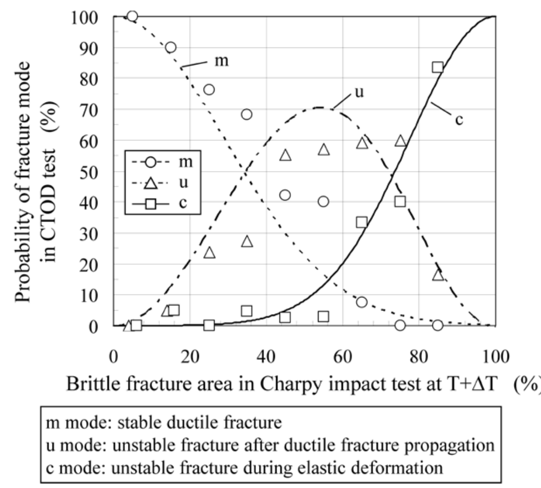


Fig. 1 Relationship between brittle fracture area in Charpy impact test and probability of occurrence of fracture mode in CTOD test

5. Development of covered electrode for YS500MPa class steel[5]

In response to the need for improved toughness of the weld metal for YS500MPa class steel, an electrode has been developed for shielded metal arc welding (SMAW) that satisfies the CTOD value at -40℃.

5.1 Development concept

The target specifications of the development have been set to include a yield strength of 500MPa or higher, a plate thickness of 50 - 60mm and a critical CTOD value at a testing temperature of -40℃ of 0.10mm or higher. To estimate the CTOD value at -40℃, the test temperature of the Charpy impact testing was set to be -74℃, contemplating the temperature shift of -34℃ for the plate thickness of 50mm.

High toughness was ensured mainly by the reduction of oxygen content in the weld metal. In the case of SMAW materials, the oxygen content in the weld metal can be controlled by adjusting the basicity (BL) of the covering material. **Fig. 2** shows the relationship between the oxygen content in weld metals, prepared with adjusted basicity, and the brittle fracture surface ratio at the testing temperature of -74℃. As shown, the oxygen content in the weld metal must be kept at 200ppm or lower to reliably satisfy the brittle fracture surface ratio of 40% or lower.

In addition to the above basicity adjustment, the Si content in the weld metal has been optimized to decrease the brittle fracture surface ratio. **Fig. 3** shows the relationship between the Si content in the weld metal and the brittle fracture surface ratio at -74℃. The values inside this figure represent the oxygen content in the weld metal. When the Si content is 0.4% or higher, solid-solute Si embrittles the matrix, increasing the brittle fracture surface ratio; whereas, when the Si content is 0.4% or lower, the oxygen content is increased as a result of the lowered deoxidation effect of Si, which results in an increase in the brittle fracture surface ratio. Therefore, the developed material is adjusted such that the Si content in the weld metal reaches the optimum value of approximately 0.4%.

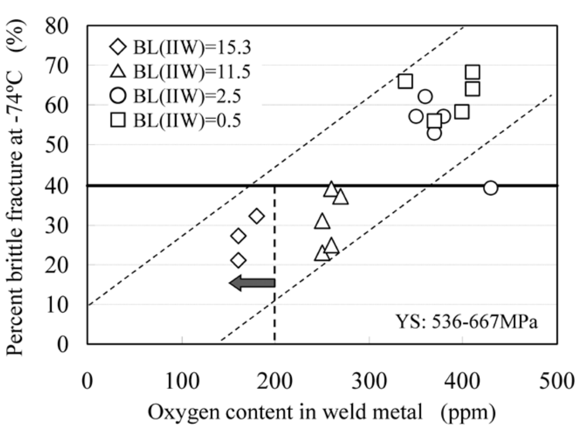


Fig. 2 Relationship between oxygen content in weld metal and percentage of brittle fracture at −74℃ for Charpy impact test (SMAW)

5.2 Mechanical properties of weld metal

The newly developed wire, "LB-67LJ," was used to prepare a welded joint, and the weld metal was subjected to tensile and Charpy impact tests. The results are shown in **Table 4**. Similar joints were used to evaluate the relationship between the welding heat input and the critical CTOD value at the test temperature of -40℃. The results are shown in **Fig. 4**. The both-side welding was done

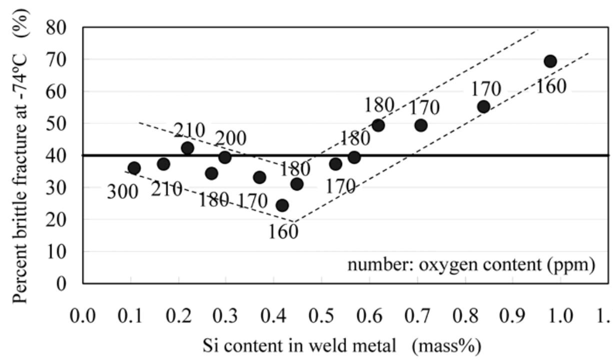


Fig. 3 Relationship between Si content in weld metal and percentage of brittle fracture at −74℃ for Charpy impact test (SMAW)

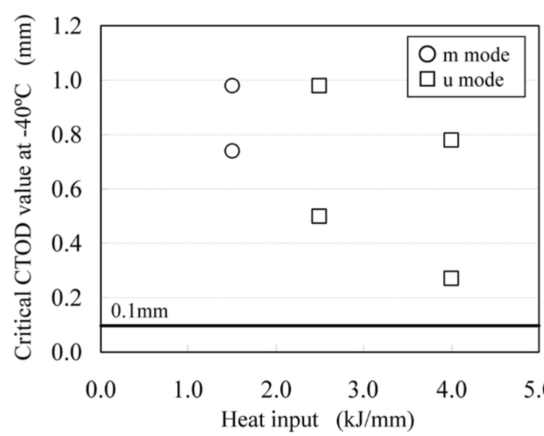


Fig. 4 Relationship between heat input and critical CTOD value at −40℃ of welded joint with LB-67LJ

Table 4 Mechanical properties of welded joint with LB-67LJ

Plate thickness	Welding position	Heat input (kJ/mm)	Location*3	Tensile properties*1			Notch toughness*2			
				0.2%YS (MPa)	TS (MPa)	El. (%)	Absorbed energy: J (Brittle fracture: %) -80ºC	-60ºC	-40ºC	FATT (ºC)
60mm	Horizontal (2G)	1.5	F	627	687	22	172 (15)	189 (3)	192 (1)	<-80
			B	640	708	25	146 (17)	186 (7)	197 (0)	<-80
	Flat (1G)	2.5	F	578	669	27	130 (18)	146 (13)	170 (5)	<-80
			B	550	650	28	82 (33)	152 (18)	160 (6)	<-80
	Vertical upward (3G)	4.0	F	576	668	23	107 (25)	141 (14)	153 (5)	<-80
			B	573	696	26	85 (38)	149 (7)	163 (4)	<-80

*1 JIS Z 3111 No.A2 specimen (dia.=6.0mm, G.L.=24mm)
*2 Charpy impact test specimen: 10mm×10mm, 2mm V-notch
*3 F: 7mm from 2nd side surface, B: 7mm from 1st side surface

on a 60mm thick plate with a double-V groove. The strength of the weld metal satisfies YS≧500MPa with its Charpy absorption energy being sufficiently high compared with the value, 50J, required for this strength class by ship classification societies. In addition, a critical CTOD value of 0.25mm or higher was obtained even at the welding heat input of approximately 4.0kJ/mm with all the fractures occurring in either m-mode or u-mode.

6. Submerged arc welding material for YS500MPa class steel [6)]

A submerged arc welding (SAW) material has been developed using bonded flux as a base with the targets of a yield strength of 500MPa or higher and a critical CTOD value at -40℃ of 0.10mm or greater.

6.1 Development concept

As in the case of the SMAW material described in the previous section, the reduction of oxygen content in the weld metal is mainly used as a technique to achieve high toughness in the weld metal. Several test materials with various flux compositions were prepared to investigate the oxygen content in the weld metal and the brittle fracture surface ratio at the test temperature of -74℃ (**Fig. 5**). The weld metal of SAW material has an oxygen content of approximately 300ppm or lower and has achieved a brittle fracture surface ratio of 40% or lower at -74℃. In the case of SAW, however, the decreased content of oxygen in the weld metal tends to cause the deterioration of the bead shape. The oxygen content has therefore been adjusted to approximately 280ppm to balance the welding workability and toughness.

6.2 Mechanical properties of weld metal

The newly developed SAW material was used to prepare a welded joint and the weld metal was subjected to tensile and Charpy impact tests. The results are shown in **Table 5**. The relationship between the welding heat input and the critical CTOD value at the test temperature of -40℃ is shown in **Fig. 6**. The joint is a double-V groove made of the plates of 60mm thick. Similar to the test

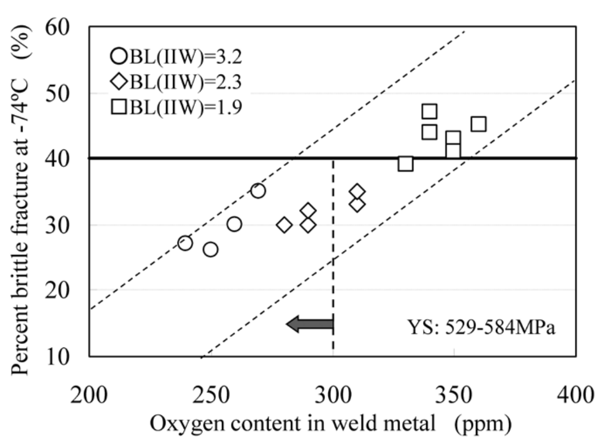


Fig. 5 Relationship between oxygen content in weld metal and percentage of brittle fracture at −74℃ for Charpy impact test (SAW)

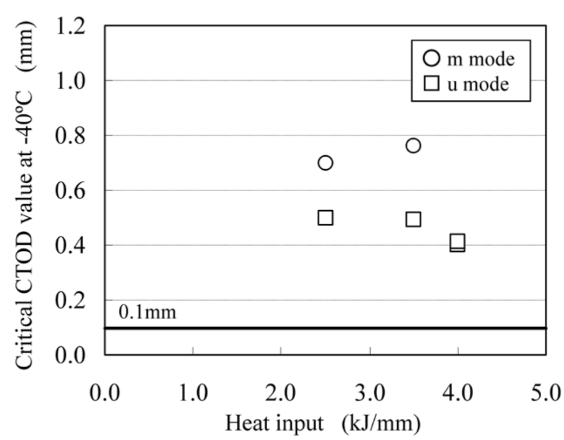


Fig. 6 Relationship between heat input and critical CTOD value at −40℃ of welded joint with developed SAW consumable

Table 5 Mechanical properties of welded joint with developed SAW consumable

Plate thickness	Welding position	Heat input (kJ/mm)	Location*3	Tensile properties*1			Notch toughness*2			
				0.2%YS (MPa)	TS (MPa)	El. (%)	Absorbed energy: J (Brittle fracture: %)			FATT (ºC)
							-80ºC	-60ºC	-40ºC	
60mm	Flat (1G)	2.5	F	557	662	32	66 (38)	108 (25)	166 (8)	<-80
			B	547	649	31	60 (44)	104 (24)	137 (11)	<-80
		3.5	F	532	674	30	51 (45)	83 (25)	137 (12)	<-80
			B	568	656	30	55 (44)	112 (24)	158 (6)	<-80
		4.0	F	532	674	30	51 (45)	83 (25)	137 (12)	<-80
			B	568	656	30	55 (44)	112 (24)	158 (6)	<-80

*1 JIS Z 3111 No.A2 specimen (dia.=6.0mm, G.L.=24mm)
*2 Charpy impact test specimen: 10mm × 10mm, 2mm V-notch
*3 F: 7mm from 2nd side surface, B: 7mm from 1st side surface

results for the SMAW material, the strength of the weld metal satisfies YS≧500MPa, with its Charpy absorption energy greatly exceeding 50J down to -60℃. The critical CTOD value at -40℃ is as high as 0.40mm or greater at the heat input of 4.0kJ/mm, with all the fractures occurring in either m-mode or u-mode.

7. Development of flux-cored wire for YS690MPa class steel [7)]

Conventionally, SMAW materials have mainly been used for the all-position welding of high-strength steel; however, there is an increasing demand for the use of flux-cored wire (FCW) in order to improve the efficiency of welding work and to deskill the work. We have therefore developed an FCW for all-position welding, applicable to the YS690MPa class steel that is often used for offshore structures such as jack-up rigs. As described above, increasingly stringent toughness requirements are being imposed on the welding consumables used in offshore structures. The major issue in developing welding consumables for high-strength steel, such as the YS690MPa class, is to achieve both strength and toughness simultaneously.

7.1 Development concept

Reducing the oxygen content in weld metal works well in improving toughness in the case of FCWs, too. Titania-based FCWs are mainly used for the all-position welding of steels of the YS500MPa class or lower. The FCWs designed for high-strength steel up to the YS690MPa class are likely to yield favorable welding workability. However, the weld metal formed of titania-based FCW tends to exhibit high oxygen content, making it difficult to achieve favorable toughness as the strength increases. Meanwhile, the FCW suffers from the fact that welding workability in the vertical position is deteriorated if the basicity of the flux is increased in order to reduce the oxygen content, as is done for SMAW and SAW materials, which makes the FCW inapplicable to all-position welding.

Fig. 7 shows the relationship between the number density of oxide in the weld metal of the FCW for high-tensile steel (YS550MPa class) and upper shelf energy (vE-Shelf) measured by the Charpy impact test. As shown, the vE-Shelf value tends to decrease with the increasing number density of oxide. **Fig. 8** shows the relationship between the bainite grain size of weld metal and fracture appearance transition temperature (FATT) measured by the Charpy impact test. As shown, the refining

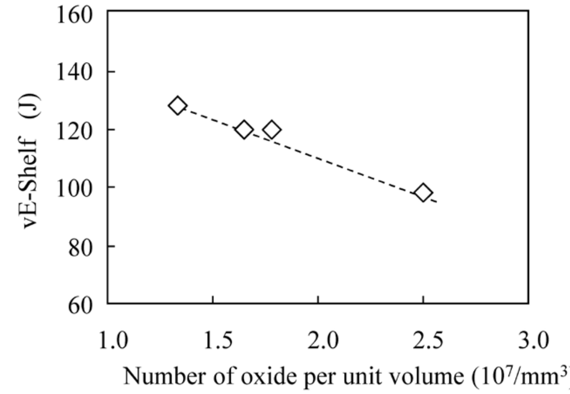


Fig. 7 Relationship between number density of oxide and upper shelf energy (vE-Shelf)

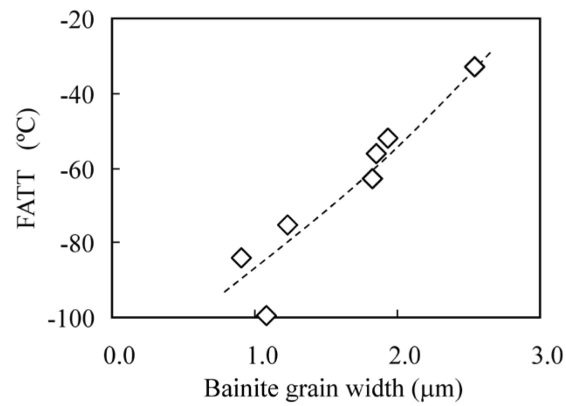
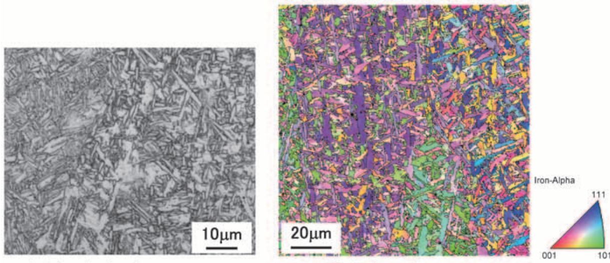


Fig. 8 Relationship between grain size of bainite and fracture appearance transition temperature (FATT)

bainite grain is effective in decreasing the FATT. In other words, in the case of FCW weld metal for high-tensile steel, suppressing the number density of oxide and promoting intragranular bainite transformation to refine the microstructure is considered to provide favorable toughness. In the case of the newly developed wire, the toughness is improved by optimized deoxidizer, which suppresses the amount and number density of oxide in the weld metal, and the addition of mainly Ni and Mn, which lowers the bainite transformation temperature and thus refines the microstructure.

7.2 Microstructure morphology

Fig. 9 shows the microstructure (left) of the weld metal made of a newly developed wire, DW-A80L, and the orientation map (right) obtained by electron backscatter diffraction (EBSD) analysis. Intragranular bainite is observed across the entire surface, forming an extremely fine microstructure. The microstructure size measured on the basis of the orientation map is approximately 1.66μm. **Fig.10** is the result of optical microscopic observation of oxide in the weld metal made of DW-A80L. The number



(a) Optical microstructure (b) Orientation map

Fig. 9 Microstructure of weld metal and EBSD orientation map

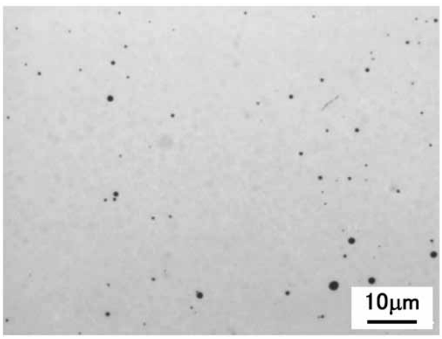


Fig.10 Optical micrograph of oxide in weld metal

density of oxide, obtained by image processing, is approximately 1.3×10^7/mm^3.

7.3 Mechanical properties of weld metal

Table 6 shows the results of tensile and Charpy impact tests of weld metal made by using DW-A80L. The welding was done on both sides of 50mm thick plate with a double-V groove. The strength of the weld metal satisfies the specification required for the YS690MPa class, and the refined microstructure keeps the fracture appearance transition temperature (FATT), as measured by the Charpy impact test, at a temperature of -60℃ or lower, suppressing the reduction in absorption energy.

7.4 Cold cracking resistance of weld metal

The welding of high-tensile steel, such as the YS690MPa class, often poses problems with cold cracking caused by hydrogen entering the molten metal during welding; so the cold cracking resistance of the weld metal made from the newly developed wire has been evaluated. The evaluation was conducted by a window-type, restrained weld cracking test on a Y groove joint with a plate thickness of 50mm. This test involves fixing the test plate by all-around, multi-layer fillet welding on a constraint plate (thickness 100mm) to ensure a high constraint force, and subsequently welding in the groove, such that the severely constrained state of actual structures is reproduced.

Table 7 shows the welding conditions and cracking test results. The existence of crack was checked by an ultrasonic test (UT) on the weld metal and a magnetic-particle test (MT), the latter test being conducted intermittently while cutting the weld metal. The lowest preheat and interpass temperature to prevent cold cracking is determined to be 50℃ or lower for the welding heat input of 1.7kJ/mm, and 75℃ for the welding heat input of 1.0kJ/mm. This wire is designed for reduced hydrogen to realize a favorable cold cracking resistance.

Table 6 Mechanical properties of welded joint with DW-A80L

Plate thickness	Welding position	Heat input (kJ/mm)	Location*3	Tensile properties*1			Notch toughness*2			
				0.2%YS (MPa)	TS (MPa)	El. (%)	Absorbed energy: J (Brittle fracture: %) -60ºC	-40ºC	-20ºC	FATT (ºC)
50mm	Horizontal (2G)	0.9	F	784	825	20	67 (14)	74 (6)	75 (4)	<-60
			B	818	848	22	66 (14)	73 (9)	77 (7)	<-60
	Vertical upward (3G)	1.7	F	736	811	23	52 (39)	68 (32)	79 (22)	<-60
			B	738	817	24	62 (29)	72 (22)	83 (18)	<-60

*1 JIS Z 3111 No.A2 specimen (dia.=6.0mm, G.L.=24mm)
*2 Charpy impact test specimen: 10mm × 10mm, 2mm V-notch
*3 F: 7mm from 2nd side surface, B: 7mm from 1st side surface

Table 7 Results of window type restrained weld cracking test

Plate thickness	Welding position	Welding current (A)	Arc voltage (V)	Heat input (kJ/mm)	Minimum preheat and interpass temp. to prevent cold cracking
50mm	Flat (1G)	280	29	1.7	≦50ºC
	Horizontal (2G)	280	29	1.0	75ºC

Conclusions

This paper has described the recent trend of offshore structures, upsized and used in deeper areas of the ocean, and the development of high-strength, high-toughness welding consumables to satisfy the needs of these structures. Currently, Kobe Steel has a line-up of welding consumables to satisfy most needs. We are committed to respond to requirements for even higher strength, toughness and efficiency. We will strive to develop new welding technologies, on the basis of various approaches, and welding consumables based on the new technologies.

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