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Research on Automatic TIG Root Welding of Low Temperature Carbon Steel and Stainless Steel Pipeline for LNG Module Construction

Chunrun Li [1,2], Tianli Zhang [1,2] and Yazhang He[1,2]

[1] CNPC Key Laboratory of Offshore Engineering, Tianjin 300451, China

[2] CNPC Engineering Technology Research Company Limited, Tianjin 300451, China

E-mail Address: zhangtl@cnpc.com.cn （Tianli Zhang）

Abstract. We investigated the application of automatic TIG welding for LNG process pipeline in Yamal LNG module construction project. The study achieved efficient automatic TIG welding of low temperature carbon steel and stainless steel pipeline in root welding and hot welding. The properties of the weld meet the requirements of project technical specification and standard ASME B31.3. Welding efficiency increases 2 times compared with conventional manual TIG welding in root welding and hot welding. Therefore, the construction quality and progress of the project are improved.

1. Introduction

China National Petroleum Offshore Engineering Co., Ltd contracted Russia Yamal LNG project, which is located on the Yamal peninsula in the Russian Arctic Circle. There are nine months of ice age each year and the lowest temperature reaches -52 ℃. The project includes 168 modules. The steel structure weighs more than 50,000 tons and the process pipelines reach a length of 190,000 meters. Process pipeline size ranges from 0.5 to 72 inches and the welding workload is 237,000 dyne. The main work of the project is to prefabricate the process pipes to 20~44 meters. The pipelines need deep cold insulation for the operating temperature of -169 ℃. The project adopts the construction mode of prefabricate in Qingdao and assemble in Russia. The process pipelines include low-temperature carbon steel pipelines and austenitic stainless steel pipelines. The representative materials of process pipelines are low temperature carbon steel ASTM A333 Gr.6 (design temperature of -50 ℃) and austenitic stainless steel ASTM A312/A358 TP304/304L (design temperature of -196 ℃).

The welding technical specification requires that the root welding of pipelines must be performed by TIG welding [1]. Manual TIG welding is usually used in root welding and hot welding. However, it has the characteristics of low efficiency and high operational skill requirement in pipeline welding. In order to improve the quality and efficiency of the pipeline welding, the construction of pipeline is divided into workshop prefabrication and site installation. Automatic TIG welding is adopted in workshop prefabrication.

2. Automatic TIG welding method

Characteristics. Automatic TIG welding is achieved by automatically filling the wire, swing the torch and rotating the workpiece in welding process. In theory, the process of welding could provide high welding speed and quality without human intervention.

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Welding system. The automatic TIG welding system is composed of power source, welding torch, cantilever welding machine (including cross slide, welding torch clamping mechanism, swinging mechanism and control box), wire feeding system, cooling circulation system and chuck type pipe driver.

Main functions.

(1) Arc-length control. The workpiece itself has ovality and groove processing error. Therefore, the distance between the workpiece and the tungsten electrode varies during the automatic welding. The change of arc length makes the arc unstable or even short-circuits.

(2) Oscillation Control. When the weld width exceeds a certain value, it is impossible to fuse the base metal on the side of the groove by simply increasing the current. Therefore, the tungsten must oscillate in the vertical direction of weld during the process of welding torch walking or workpiece rotation. The tungsten must stay on each side of the groove for a certain amount of time to ensure that the weld is fused completely with the base metal.

(3) Wire feeding system. The wire must be fed into the arc automatically in the automatic TIG welding system. The arc melts the wire to form the welding bead. The wire feeding point is located in the front or rear (inverse wire feeding) of the weld pool. The distance between the feeding point and the arc is one third of the pool length. Wire feeding angle is also an important factor affecting the wire feeding effect. Too great angle makes wire feeding unstable. Too small angle makes the distance between the welding wire and tungsten difficult to control. Weld back forming will also be affected.

3. Weldability analysis for piping material

The materials of low temperature pipelines in Yamal LNG module are mainly low-temperature carbon steel ASTM A333 Gr.6 and stainless steel ASTM A312/A358 TP304/304L/316/316L.

ASTM A333 Gr.6 is mainly used in low-temperature environment about -50℃. A major problem in the steel welding is how to ensure the low temperature toughness of the joint [2]. The material itself has good toughness and appropriate plasticity for its low carbon content. However, during the welding process, the grains grow up due to the reheating process. The toughness and plasticity of the welded joint become much lower than the base metal. In order to transport low temperature medium, the pipelines need higher toughness [3]. The impact value of the welded joints should not be less than 27J at -50 °C. Therefore, we must make a reasonable choice on welding method, welding materials, welding process and heat input.

The impact toughness of austenitic stainless steel ASTM A312/A358 TP304/304L decreases slowly with temperature reducing and there is no brittle transition temperature. So it can be used for cryogenic conditions up to -196 ℃. Ferrite-formation elements are often added into the weld metal to prevent hot crack. But the formation of ferrite will reduce the low temperature impact toughness. Therefore, the content of ferrite should not exceed 7 FN. There will be a small amount of carbide precipitation in the HAZ at the temperature of 600-800℃ [4], which reduces the resistance to intergranular corrosion. So it is necessary to strictly control the welding heat input and reduce the residence time in the temperature range of 600-800 ℃.

It is necessary to study the replacement of manual TIG welding by automatic TIG welding according to the welding characteristics of low temperature carbon steel and austenitic stainless steel. The heat input must be strictly controlled in order to ensure the low temperature impact toughness and corrosion resistance of welded joints.

4. Welding procedure qualification

4.1 Welding process

In the workshop welding process, root welding and hot welding adopt automatic TIG, while filling welding and cover welding adopt pulse MIG, automatic FCAW or SAW. The current of automatic TIG welding is larger than manual TIG welding. Therefore, the thickness of each weld bead is about 1mm larger than that of manual welding. SAW can be conducted directly after root welding and hot welding without filling welding. In the case of manual TIG welding, it is necessary to carry out two filling welding before SAW. Therefore, there is an obvious advantage to use automatic TIG in root and hot welding.

Welding Equipment. Miller XMT 450MPa is selected for automatic TIG welding and two wire feeders are equipped for MIG, FCAW and SAW, as shown in Fig.1.

(a) Welding equipment (b) Control box
Fig.1 Equipment matching

4.2 Base metal in WPQ

The welding work of LNG project is carried out according to the standards ASME B31.3 and ASME IX. The WPQ of carbon steel pipe select ASTM A333 Gr.6 (Group No.1) and ASTM A350 LF2 CL1 (Group No.2) as material. The results can be suitable for the welding of Group No.1 materials and Group No.2 materials. The WPQ of stainless steel pipe select 304L as material. The results can be suitable for the welding of TP304 (304L) and TP316 (316L).Chemical composition of the materials is shown in Table 1 and mechanical properties is shown in Table 2.

Table 1 Chemical composition (mass fraction %)

Steel Grade	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Cb	V
A333 Gr.6	0.3	0.29-1.06	0.025	0.025	0.10 Min.						
A350 LF2 CL1	0.3	0.60-1.35	0.035	0.04	0.15-0.40	0.4	0.3	0.12	0.4	0.02	0.08
304L	0.035	2.0	0.045	0.030	1.0	8-13	18-20				

Table 2 Mechanical properties

Steel Grade	Yield Strength /MPa	Tensile Strength /MPa	Elongation after Fracture /%	Impact Energy Ave /J (-45 ℃)
A333 Gr.6	214 Min.	415 Min.	30	18.5
A350 LF2 CL1	240 Min.	415-585	30	17.6
304L	170 Min.	485 Min.	35	27.0

4.3 Welding process design

WPQ of low temperature carbon steel pipelines. Alloy steel welding wire was adopted in carbon steel pipeline welding, considering the design temperature of -50 ℃. KM-80Ni1 (ER80S-Ni1) and KFX-81K2(E81T1-K2) were used for the process of TIG and FCAW. KM-80Ni1 (ER80S-Ni1), PREMIER WELD Ni1K and flux PREMIER 8500 were used for the process of TIG and SAW. Both processes met the requirement that the impact value reached at least 27 J at -60 ℃.WPQ requirements and welding parameters are shown in table 3 and table 4, respectively.

Table 3 Welding process qualification design for low temperature carbon steel

PQR No.	Wall Thickness	Groove Type	Welding Method	Welding Materials	Shielding Gas	Heat Treatment
CS-PIP-01/18	11.6/5.8mm	V	TIG/ FCAW	ER80S-Ni1/ E81T1-K2C	100%Ar/ 100%CO2	/
CS-PIP-02	11.6mm	V	TIG/ SAW	ER80S-Ni1/ ENi1K-Ni1	100%Ar/ --	/
CS-PIP-03	12.7mm	V	TIG/ SAW	ER80S-Ni1/ ENi1K-Ni1	100%Ar/ --	PWHT

Table 4 Welding parameters

PQR No.	Welding Bead	Welding Method	Welding Materials	Wire DIA (mm)	Polarity	Current (A)	Voltage(V)	Speed (mm/min)	Gas Flow （L/min)
CS-PIP-01/18	Root welding	TIG	ER80S-Ni1	1.2	DCEN	160-180	11-12	75-120	12-15
	Hot welding	FCAW	E81T1-K2C	1.2	DCEP	160-190	24-26	160-200	20-25
	Fill & Cover	FCAW	E81T1-K2C	1.2	DCEP	165-185	24-26	200-220	20-25
CS-PIP-02/03	Root welding	TIG	ER80S-Ni1	1.2	DCEN	176	13	72-110	12-15
	Hot welding	TIG	ER80S-Ni1	1.2	DCEN	191	13	91-93	12-15
	Fill & Cover	SAW	ENi1K-Ni1	2.4	DCEP	270-300	28-29	280-290	--

WPQ of stainless steel pipelines. The design temperatures for stainless steel pipelines were -50 °C, -104 °C and -196 °C in the project. Therefore, the temperature of impact test was selected as -196 °C. Filling material was KT-308 L / KM-308L (ER308L). The welding wire must have a lateral expansion of more than 0.38 mm and a ferrite content of not more than 7 FN. WPQ requirements and welding parameters are shown in Table 5 and Table 6, respectively.

Table 5 Welding process qualification design for austenitic stainless steel 304L

PQR No.	Wall Thickness	Groove Type	Welding Method	Welding Materials	Shielding Gas
SS-PIP-01	10.31mm	V	TIG/GMAW	ER308L	100%Ar
SS-PIP-18	19.05mm	V	TIG/SAW	ER308L	100%Ar

Table 6 Welding parameters

PQR No.	Welding Bead	Welding Method	Welding Material	Wire DIA (mm)	Polarity	Current (A)	Voltage (V)	Speed (mm/min)	Gas Flow （L/min)
SS-PIP-01	Root & Hot	TIG	ER308L	1.2	DCEN	171-180	12-13	75-130	12-18
	Fill & Cover	GMAW	ER308L	1.2	DCEP	180-190	25-28	125-133	20-25
SS-PIP-18	Root & Hot	TIG	ER308L	1.2	DCEN	142-198	11-14	78-120	15-20
	Fill & Cover	SAW	ER308L	2.4	DCEP	270-330	27-32	320-404	--

Set the welding parameters on the device according to PWPS. The main welding parameters are welding current, wire feeding speed, welding speed, swing frequency, swing width and sidewall residence time. Data setting is shown in Fig.2. The position of the welding torch is shown in Fig.3.

Fig.2 Data setting

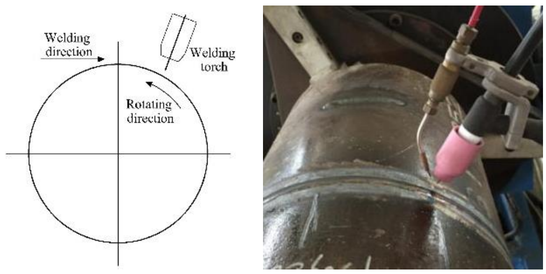

Fig.3 Position of the welding torch

4.4 Mechanical property tests

Test results of low temperature carbon steel pipeline are shown in Table 7. Test results of 304L stainless steel pipeline are shown in Table 8.

Table 7 Low temperature carbon steel pipeline tests

PQR No.	Tensile Strength /MPa	Bending Test	Impact Test				
			Sample Size (mm)	Test Temperature (℃)	Impact Value /J Weld Center	Pipe HAZ	Forging HAZ
					104	127	84
CS-PIP-01	637/540	Qualified	8*10*55	-50	81	162	94
					145	155	79
					30	19	22
CS-PIP-18	591/611	Qualified	4*10*55	-66.7	33	27	25
					58	26	22
					94	104	114
CS-PIP-02	585/590	Qualified	8*10*55	-50	104	149	75
					130	120	82
					89,	126	117
CS-PIP-03	538/539	Qualified	8*10*55	-50	115,	122	106
					135	149	114

Table 8 304L stainless steel pipeline tests

PQR No.	Tensile Strength /MPa	Bending Test	Impact Test				lateral Expansion		Ferrite (FN)
			Sample Size (mm)	Test Temperature (℃)	Impact Value /J Weld Center	HAZ	Weld Center (mm)	HAZ (mm)	
					77	176	1.00	1.65	
SS-PIP-01	626/631	Qualified	8*10*55	-196	74	87	1.00	1.475	4.3
					79	117	0.875	1.725	
					34	78	0.45	1.10	
SS-PIP-18	633/630	Qualified	10*10*55	-196	39	100	0.45	1.35	6.3
					38	78	0.55	0.95	

4.5 Analysis of welding results

Appearance of welded joints. The appearance of welded joints was smooth and uniform, especially the back of the weld bead. The weld fused well with the base metal on both sides of the groove, as shown in Fig.4 and Fig.5. X-ray inspection and magnetic particle inspection found no root incomplete fusions or surface defects.

(a) Back of root welding (b) Inside groove

Fig.4 Welded joints of stainless steel

(a) Back of root welding (b) Inside groove

Fig.5 Welded joints of low temperature carbon steel

Analysis of welding results.

1) Tensile strength, bending performance and impact toughness of the low temperature carbon steel welded joints meet the requirements of the Yamal project. The impact toughness of the weld are significantly improved after post weld annealing.

2) Tensile strength, bend performance and impact toughness of the stainless steel welded joints meet the requirements of the Yamal project. The lateral expansion of impact specimen is greater than 0.38 mm at -196 °C.

Microstructure analysis. Ferrite content of Stainless steel welded joint is less than 7 FN, which meet the requirements of the project in ferrite control. Therefore, the impact toughness of austenitic stainless steel in cryogenic conditions can be guaranteed.

4.6 Welding advantages

Appearance. The welded joints achieve satisfactory result of one side welding both sides formation. The stainless steel welded joints have an obvious advantage on formation. Comparison of back forming effect of stainless steel root welding is shown in Fig.6. The appearance of automatic welding is smooth because the welding speed is stable and the swing is uniform. The resistance of the liquid in the pipe can be reduced when in service.

(a) Automatic welding (b) Manual welding

Fig.6 Comparison of back forming

Welding efficiency. For root welding, the automatic welding speed is greater than 70 mm/min, while the manual welding speed is 30-45 mm/min. For hot welding, the automatic welding speed is greater than 110 mm/min, while the manual welding speed is about 70 mm/min. The total thickness of root and hot welding is 5 mm in automatic welding and 3.5-4mm in manual welding. If SAW is adopted after the root and hot welding, the thickness of 4 mm can't meet the requirement. Another TIG welding is required in the case of welding leakage. In general, the welding efficiency of automatic welding is about three times that of manual welding. Automatic welding has an obvious advantage in welding efficiency.

Weld Properties. With automatic TIG welding, the welding speed is approximately double that of manual welding. Although the welding current is increased compared with manual welding, the heat input is basically unchanged. The low temperature impact toughness has reached the requirement of more than 27J. For welded joints of austenitic stainless steel, there is no reduction in resistance to intergranular corrosion.

5. Conclusions

1) Automatic TIG welding achieved excellent formation in root and hot welding for stainless steel pipelines and low temperature carbon steel pipelines. The efficiency of automatic TIG welding is two times higher than that of manual TIG welding.

2) Automatic TIG welding achieved good formation at the back of the weld bead, which is helpful to reduce the internal fluid resistance of the process pipeline and improve the flow velocity.

3) Automatic TIG welding guarantees the low temperature impact toughness of low temperature carbon steel and stainless steel, and also the ability of austenitic stainless steel to resist intergranular corrosion.

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