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TECHNICAL RESEARCH ON APPLICATIONS OF X80 LINEPIPE GIRTH WELD FOR THE SECOND WEST-EAST GAS PIPELINE PROJECT (2nd WEPP)

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Abstract

The comprehensive requirements for the Second West-East Gas Pipeline Project, such as strength level, pipe diameter, wall thickness, transporting pressure and distance, transportation capacity, and tight construction period, represent the highest level in pipeline construction in China. With regard to the technical difficulties of welding in the project, several major problems were solved by comprehensive and systematic research on weldability, welding materials, welding process, especially the welding under low ambient-temperature conditions (down to -25 ^{o}C) of actual X80 pipe and strain-based designed X80 large deformation pipe. The whole research program paved the way for the onset and completion of the project on schedule.

Introduction

The Second West-East Gas Pipeline, as shown in Figure 1, runs across 15 provinces and municipalities from Xinjiang's Horgos in the West to Shanghai in the East, and then to the South at Guangzhou and Hong Kong. Designed with an annual transportation capacity of 30 billion cubic meters, the pipeline is connected to the Central Asia-China Gas Pipeline at Horgos in order to introduce overseas gas resources.

Construction of the Second West-East Gas Pipeline project started in February 2008. The total length of the pipeline is 8,704 kilometers, consisting of one trunk line and eight branches. The trunk line is divided into Western and Eastern segments at Zhongwei County of Ningxia Hui Autonomous Region. On June 30 this year, the Eastern section of the Second West-East Gas pipeline went into operation, marking the full completion and operation of the 4,978 km-long trunk line. The project involved extremely arduous construction conditions of various geologies and landscapes, including snowy mountains, deserts, swamps, as well as more than 60 hills and 190 rivers.

In order to realize the annual transporting capacity with a single pipe and with a tight construction time, the whole trunk line exclusively employs X80 grade with a pipe diameter of 1219 mm. In the Western part, the wall thickness ranges from 18.4 mm to 33 mm with a design pressure of 12 MPa. In the Eastern section, the wall thickness ranges from 15.3 mm to 26.4 mm with a design pressure of 10 MPa. One of the most important features is that X80 spiral pipe with a size of Φ 1219 x 18.4 mm was widely employed on a large scale in the Western section.

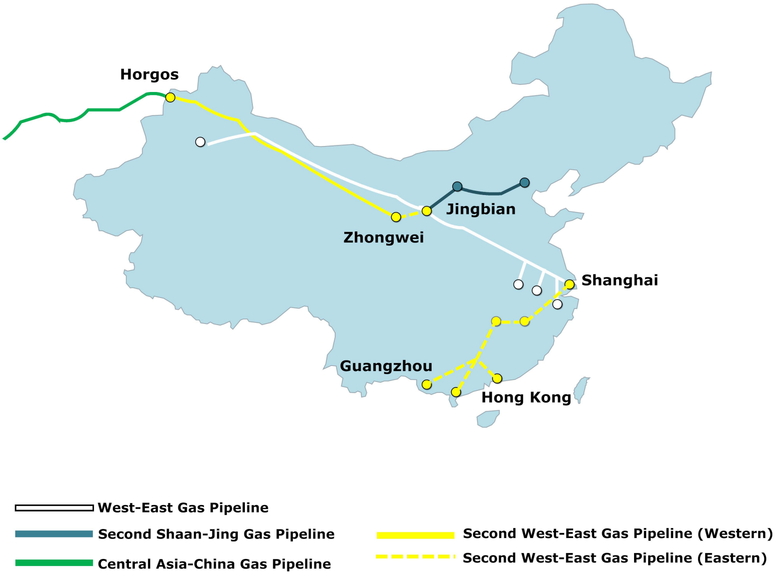

Figure 1. Route map of the Second West-East Pipeline.

Welding Technical Specifications

In 2004, China's first X80 pipeline was constructed as a demonstration in the Jining Cross-link Line of the First West-East Gas Pipeline, of which the whole length is 7,719 km, with a diameter of 1016 mm (40'') and design pressure of 10 MPa. The construction of a demonstration section provided important theoretical and technological support for the Second West-East Gas Pipeline Project.

It was the first time that X80 line pipe was employed on such a large scale, so relevant research work including development and application of X80 pipeline steel was necessary before construction. Some major research institutes and contractors set up a series of technical standards through a large amount of production and welding tests, of which there are two standards corresponding to welding [1, 2]. The required properties are shown in Table I.

Table I. Target Properties of Girth Weld Joints in X80 Linepipe

Performance	Girth weld joint in X80 linepipe	Girth weld joint in strain-based designed X80 linepipe
Tensile strength (MPa)	TS ≥ 625 MPa	TS ≥ 625 MPa
Requirement of fracture position	-	Base metal
All weld metal tensile test	-	610 MPa ≤ YS ≤ 750 MPa
Charpy Impact Energy (J) at -10 °C	Single Value ≥ 60 J Average Value ≥ 80 J	Single Value ≥ 60 J Average Value ≥ 80 J
HV10 hardness	≤ 300	≤ 300

Welding Construction Difficulties

For the gas pipeline project with such a large diameter, heavy thickness and high pressure, welding technology is one of the most important factors that affects construction quality and efficiency. The main difficulties of the project include the following aspects [3]:

Weldability Analysis and Evaluation for X80-Grade Pipes

This was the first time that API Grade X-80 linepipe was used in China on such a large scale. Pipes were manufactured by many domestic and foreign steel producers. Therefore, it was crucial to perform analysis of cold cracking sensitivity of X80 pipe and evaluate the weldability of pipes provided by different manufacturers.

Procedure Qualification Record (PQR)

To adapt to different cultural and geological environments, climate, and technical capacity of different contractors, welding processes for the pipeline construction were diverse and the welding materials even more varied. Therefore, the Procedure Qualification Record (PQR) became very difficult and the workloads were huge and demanding.

Welding Technology in Earthquake Areas

The trunk line crosses about 20 earthquake areas with potential earthquake magnitude of eight or higher, so the concept of strain-based design was introduced in these areas, which considers deformation resulting from ground movement as well as the stresses from the inner pressure of the pipelines. In this case, the X80 pipes are required to have high deformation resistance and the girth weld must have good toughness and higher strength than the pipe base metal. This ensures that the deformation occurs in the pipes rather than in the welds. This results in higher requirements on the selection of welding materials and welding process.

Welding in Low Temperature Environments

Because of the tight schedule, it was inevitable to conduct welding during winter. This involved the issue of guarantee of the weld quality in low temperature environments.

Welding Technology Features

Low Hydrogen Materials Used for Root Pass

The majority of the X80 line pipe used in the Second West-East Gas Pipeline Project was manufactured using the TMCP practice, which employs molybdenum as one of the major microalloying elements, together with certain amounts of other micro alloying elements such as niobium, vanadium and titanium, to optimize its performance. Due to the very strict requirements, Bao Steel, Shougang, Anshan Steel, Shagang and other steel manufacturers have been involved in making the Φ 1219 mm X80 pipeline steel. After analyzing the pipes from each manufacturer, we found that they all had similar chemical compositions, crack sensitivity coefficient (Pcm) and weldability [4, 5]. Table II shows the typical chemical composition of the X80 line pipe used in the Second West-East Gas Pipeline Project.

Table II. Typical Chemical Composition of X80 Linepipe Used in the Second West-East Gas Pipeline Project (weight percent)

C	Si	Mn	P	S	Mo	Ni	Nb	V	Ti	Al	Ceq	Pcm
0.046	0.22	1.85	0.010	0.002	0.09	0.23	0.090	0.007	0.013	0.031	0.45	0.18

Although X80 linepipe has low carbon content and Pcm, the tendency for weld cold cracking will certainly grow with the increase in strength. To ensure project safety, Y-groove cracking tests were carried out to evaluate the cold cracking sensitivity of X80 steel. The specimen adopted was an X80 steel plate with a thickness of 18.4 mm. Table III shows the test conditions of the Y-groove weld cracking test [4].

Table III. Test Conditions of Y-Groove Weld Cracking Test

Welding material	Cellulosic electrode	Low-hydrogen electrode	Solid wire	Metal powder-cored wire
Welding process	SMAW	SMAW	GMAW-STT	GMAW-RMD
Wire diameter (mm)	4.0	3.2	1.2	1.2
Welding current (A)	85 – 90	95 – 100	Base value 53 Peak value 430	Base value 53 Peak value 430
Welding voltage (V)	30 – 32	20 – 22	16 – 18	16 – 18
Welding speed (mm/min)	105	85	215	226
Wire feed speed (in/min)	-	-	150	150
Shielding gas	-	-	100% CO_2	75% Ar ＋ 25% CO_2
Welding environment	Temperature 5 ^{o}C, relative humidity 50% RH			

Four kinds of welding materials were employed in the test, with preheat temperature varying from 20v^{o}C to 150v^{o}C. The welded specimens were held for 48 hours after welding, five cross-sections of each specimen were inspected and the crack ratio of the cross-sections (CS) was calculated, Table IV. Figure 2 shows an example of the cross-section of a Y-groove weld.

Table IV. Test result (CS, %) of Y-Groove Weld Cracking Test

Preheat temperature	20 ℃	100 ℃	150 ℃
Cellulosic electrode	100	12.9	2.8
Low-hydrogen electrode	0	0	0
Solid wire	0	0	0
Metal powder-cored wire	0	0	0

Based on the oblique Y-groove cracking test, welding thermal simulation tests and implant tests were conducted to further evaluate the cold cracking resistance of the welds. The comprehensive testing results show that the preheat temperature must be higher than 150 ^{o}C if the cellulosic electrode is used to make the root pass while 100 ^{o}C is sufficient if the low-hydrogen electrode or wire are used. The following three factors suggested that the cellulosic electrode should not be used for the root pass in the project: 1) It is very difficult to achieve 150 ^{o}C preheat temperature in construction sites; 2) High preheat temperature will seriously affect the efficiency of field welding construction; 3) Reducing hydrogen content is very helpful to avoid the risk of hydrogen cracking.

Figure 2. Cross-section of oblique Y-groove welded seam.

The suggestion has been supported by the manufacturers and contractors. Through strict training of welders, the contractors gradually adapted themselves to the method of applying a low-hydrogen electrode for the root pass. During the whole construction period, two semi-automatic welding methods, using solid wire (STT) and metal power-cored wire (RMD), were applied as the major ways to lay the root pass because of their high deposition efficiency. Because of low productivity, the low-hydrogen electrode (SMAW) was only used for the root pass of tie-ins and full wall thickness repairs.

Various Welding Processes

To adapt to the diverse geography, climatic conditions and cultural characteristics, automatic welding and self-shielded flux-cored wire semi-automatic welding methods dominated in the Second West-East Pipeline Project. The former method took up 10 percent and the latter 90 percent of the whole line. Table V shows the major welding process list for the Second West–East Gas Pipeline project; Figure 3 shows automatic welding and Figure 4 shows self-shielded flux-cored wire semi-automatic welding.

Figure 3. Automatic welding PQR.

Figure 4. Self-shielded flux-cored wire semi-automatic welding PQR.

To fully understand the weldability of X80 linepipe, a welding thermal simulator was used to develop continuous cooling transformation curves for the HAZ (SH-CCT chart), see Figure 5. This provides support for setting welding parameters and obtaining satisfactory microstructures and mechanical properties of the weld joint [6].

Table V. Major Welding Processes in the Second West–East Gas Pipeline Project

No.	Welding method	Welding process	Root pass materials	Fill & cap materials
1	Automatic welding	GMAW (root pass by inner machine + fill and cap pass by dual-torch machine)	AWS A5.18 ER70S-G Φ0.9 mm	AWS A5.28 ER90S-G Φ1.0 mm
				AWS A5.28 ER80S-G Φ1.0 mm
				AWS A5.28 ER80S-Ni1 Φ1.0 mm
2		GMAW (root pass by RMD or STT) + FCAW-G (fill and cap pass by single-torch)	AWS A5.18 E70C-6M Φ1.2 mm	AWS A5.29 E101T1-GM Φ1.2 mm
				AWS A5.29 E91T1-K2 Φ1.2 mm
			AWS A5.18 E80C-Ni1 Φ1.2 mm	AWS A5.29 E81T1-Ni1 Φ1.2 mm
3	Semi-automatic welding	SMAW + FCAW-S	AWS A5.1 E7016-1 Φ3.2 mm	AWS A 5.29 E81T8-Ni2 Φ2.0 mm
				AWS A5.29 E81T8-G Φ2.0 mm
4		GMAW + FCAW-S	AWS A 5.18 ER70S-G Φ1.2 mm	AWS A5.29 E81T8-Ni2 Φ2.0 mm
				AWS A 5.29 E81T8-G Φ2.0 mm
5			AWS A 5.18 E80C-Ni1 Φ1.2 mm	AWS A5.29 E81T8-Ni2 Φ2.0 mm
				AWS A5.29 E81T8-G Φ2.0 mm

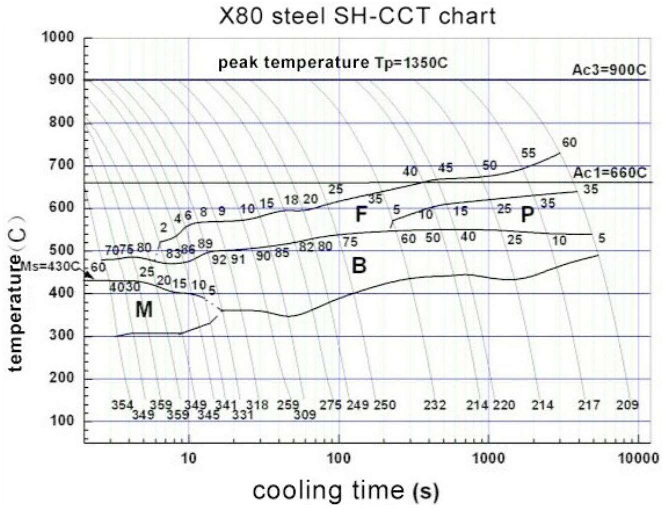

Figure 5. X80 line pipe SH-CCT chart for the Second West–East Pipeline Project.

<u>Overmatching Welding Process Suitable for Strain-Based Designed Pipe</u>

To meet the design requirements in earthquake areas, high strain-tolerant X80 line pipe based on strain based design concepts was used for the first time. To ensure the field safety of girth weld joints, overmatching of girth welded joints is required, and the tensile test specimens must not break in the weld joint. Because of limitations imposed by the various terrains in earthquake areas, only shielded metal arc welding and self-shielded or gas-shielded semi-automatic welding could be used. The welding processes in Table VI were performed in the test. For SMAW, 2/3 of the transverse tensile specimens failed in base metal, and 1/3 failed at the intersection of the HAZ of the cap bead and root bead. For Gas-shielded FCAW, half of the tensile specimens failed in base metal, and the balance failed at the intersection of the HAZ of the cap bead and root bead, as shows in Figure 6.

Table VI. Welding Processes for High Strain Tolerant Pipe

No	Welding process	Root pass materials	Fill & cap materials
1	SMAW	AWS A5.1 E7016-1 Φ3.2 mm	AWS A5.5 E11018-GH4R Φ3.2 mm
			AWS A5.5 E11018M-H4 Φ3.2 mm
2	SMAW + FCAW-G	AWS A5.1 E7016-1 Φ3.2 mm	AWS A5.29 E111T1-GMH4 Φ1.2 mm
			AWS A5.29 E111T1-K3MJH4 Φ1.2 mm

Figure 6. Welded joint tensile fractures in the HAZ area.

An analysis showed that during the welding process, because the post-weld cooling rate was slower than that after rolling, grains in the HAZ grew, and micro-alloying elements dissolved and second phase particles grew, which resulted in the HAZ having a reduced strength. Therefore, based on the geometric reinforcement method, as shown in Figure 7, the shape and direction of the HAZ softened area was changed by increasing the width and height of the cap bead, thereby overmatching of the welded joints was achieved. Figures 7 & 8 show one of the geometric reinforcement examples.

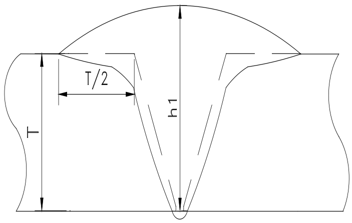

Figure 7. Geometric reinforcement weld design

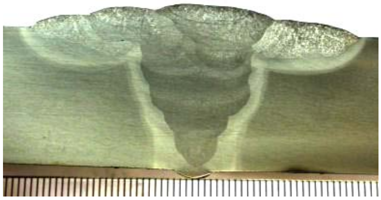

Figure 8. Geometric reinforcement example

<u>Welding Construction Technology for Low Temperature Environment</u>

The Western part of the Second West-East pipeline crosses over Xinjiang and Gansu, areas where the temperature reaches as low as -51.5 ^{o}C according to historic records. For pipeline welding in winter or cold environments, Chinese regulation JB/T 4709-2000 suggests that the temperature of the welding environment should not be lower than -20 ^{o}C; meanwhile, Russian main-line pipeline construction standard СНИП III-42-80 states that welding work can be conducted if the temperature is above -50 ^{o}C. Other oil and gas pipeline construction standards, including API 1104, SY/T 4103, SY/T 4071, GB 50369, provide no statements about welding environment temperature. In China, -5 ^{o}C was normally used as the lowest working temperature for previous pipeline welding work.

When the temperature is very low, the following problems exist for X80 girth welding: 1) weld cooling speed increases, which results in the formation of quenched structures and hardness increases, and therefore, cold cracking sensitivity increases. 2) When restraint intensity is high, and weld cooling speed is too fast, this easily increases macro-segregation in the primary crystallization of the weld, and therefore, the weld centerline forms solidification cracks under relatively high tensile stress. 3) Preheat benefits becomes insignificant, which results in difficulty in maintaining adequate interpass temperature. 4) Cold weather, ice or snow, reduces the reliability of the construction and welding equipment. 5) Welding success rate is affected because welders suffer from cold weather.

To ensure construction quality in winter, low temperature welding simulation tests were conducted on X80 line pipe, as shown in Table VII. Based on the test, an analysis of the conventional mechanical properties, impact toughness, hardness and microstructure of the welded joints showed that, with appropriate construction measures, the quality of welded joints could be guaranteed and the requirements of the project could be met. Finally, the lowest working temperature was set at -25 ^{o}C and the welding techniques programs were designed for winter construction. For example, welding was done in anti-wind shelters to ensure a proper surrounding temperature and that support of pipes was stable and reliable; and complementary application of medium frequency induction heating and flame heating was conducted in the preheating stage to ensure the proper preheat & inter-pass temperature; heat insulation facilities and low temperature lubricants and fuel were used to ensure the proper running of the transmission, hydraulic and electrical systems; workers' labor protection and HSE management were also strengthened [7].

Table VII. Low-Temperature Welding Simulation Process

No	Welding	Welding process	Root pass materials	Fill & cap materials
1	Automatic welding	GMAW (root pass by RMD) + FCAW-G (fill and cap pass by single-torch)	AWS A 5.18 E70C-6M Φ1.2 mm	AWS A 5.29 E91T1-K2 Φ1.2 mm
2		GMAW (root pass by STT) + FCAW-G (fill and cap pass by single-torch)	AWS A 5.18 E80C-Ni1 Φ1.2 mm	AWS A 5.29 E81T1-Ni1 Φ1.2 mm
3	Semi-Automatic welding	SMAW + FCAW-S	AWS A5.1 E7016-1 Φ3.2 mm	AWS A5.29 E81T8-Ni2 Φ2.0 mm
4		GMAW + FCAW-S	AWS A5.18 ER70S-G Φ1.2 mm	AWS A5.29 E81T8-Ni2 Φ2.0 mm
5			AWS A5.18 E80C-Ni1 Φ1.2 mm	AWS A5.29 E81T8-Ni2 Φ2.0 mm

Note: All above welding processes performed under low temperatures -20 ^{o}C and -30 ^{o}C.
-20 ^{o}C requirements: preheat ≥ 120 ^{o}C, inter-pass temperature ≥ 100 ^{o}C, maintain temperature after welding, preheat width on each side of groove ≥ 100 mm;
-30 ^{o}C requirements: preheat ≥ 120 ℃, inter-pass temperature ≥ 120 ℃, maintain temperature after welding, preheat width on each side of groove ≥ 100 mm.

Typical Welding Processes Used for the Second West–East Gas Pipeline Project

Because of the long distance, the project encountered multiple geographic conditions, such as the Gobi desert, Loess plateau, mountainous districts, plains, water networks, landslides, ground settlement, earthquake areas and so on. Therefore, different welding processes were used in different terrains. For example, automatic welding was usually used in the plains while semi-automatic welding was mainly deployed in mountainous districts, plateaus and other complex terrains [8].

The Automatic Welding Process

Material: X80，Specification: Φ 1219 x 18.4 mm, welding process: GMAW, root bead by internal welding machine, filling & cap bead by dual-torch welding machine. The bevel design is shown in Figure 9.

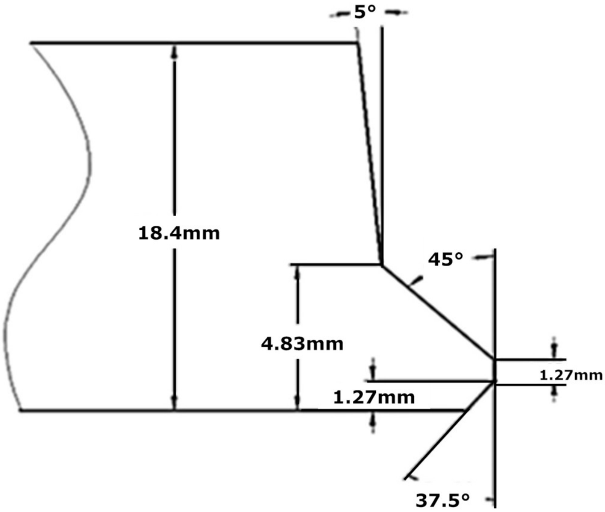

Figure 9. GMAW Process Bevel.

Requirements of the welding process:

- Root pass: ER70S-G (diameter 0.9 mm, 75% Ar + 25% CO_2).
- Hot pass: ER70S-G (diameter 0.9 mm, 100% CO_2).
- Fill and cap pass: ER80S-G (diameter 1.0 mm, 85% Ar + 15% CO_2).
- Preheat temperature: 100 ^{o}C.
- Inter-pass temperature: ≤ 150 ^{o}C.

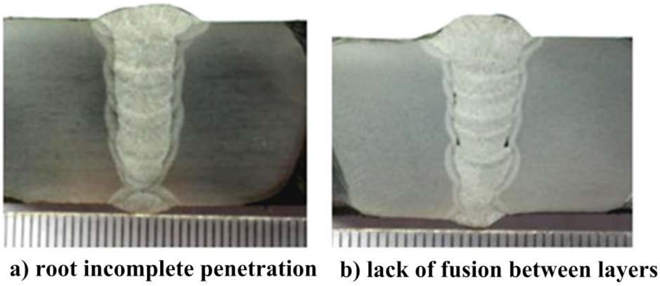

Figure 10. Defects occurring in GMAW welds.

For the dual torch automatic welding process, the most frequently occurring defects included lack of fusion between layers, and incomplete penetration between root pass and hot pass, as shown in Figure 10a and 10b. By strictly controlling the groove making process, adjusting welding current and dwell time, and other methods, satisfactory performance was obtained, as shown in Figure 11.

Figure 11. GMAW welded joint macrograph.

<u>The performance was as follows:</u>

- Tensile tests: Tensile strength was between 740 - 790 MPa, and all specimens broke in the base metal.
- Charpy impact tests: Full-size specimens were tested at a temperature of -10 ^{o}C, impact values for weld centerline and HAZ area were 152 J - 298 J, with ductile fracture appearance. Test data are shown in Table VIII.
- Macro etch test: Weld appearance is acceptable and no obvious defects are shown as illustrated in Figure 11.
- HV10 hardness test: Indentations were made along two traverses approximately 1.5 mm from the external and inside pipe surface. See Figure 12.

Table VIII. Charpy Impact Test Data for GMAW Joint (Full Size, -10 °C

Specimen No.	Notch Position	Item No.	Absorbed Impact Energy (J)	
			Single	Average
164-C1	WCL	1	190	203
		2	220	
		3	198	
164-C2	HAZ	1	152	203
		2	280	
		3	176	
164-C3	WCL	1	186	191
		2	174	
		3	214	
164-C4	HAZ	1	292	277
		2	280	
		3	258	

One of the typical features of the dual-torch automatic welding process is the high welding speed. To complete a pipe with wall thickness of 18.4 mm, only two fill beads are required (two layers are finished simultaneously per pass), and it only takes 1.5 hours to complete welding of the full joint. Obvious improvements can be seen in welding speed, deposition efficiency and consumption of welding materials. The first-time pass rate when inspected by AUT, for the automatic welding group, was higher than 90%. Figure 13 shows the construction set up for the automatic welding process.

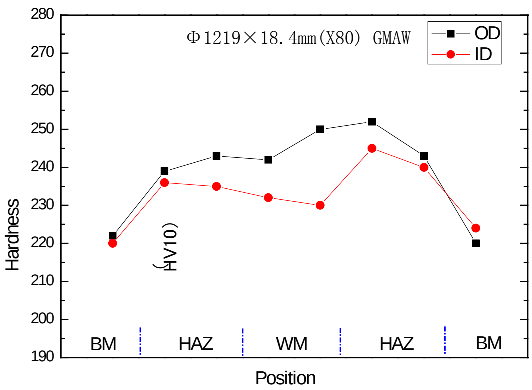

Figure 12. GMAW hardness testing.

Figure 13. Construction arrangement for the automatic welding group.

Semi-Automatic Welding Process Details

Material: X80, Specification: Φ 1219 x 18.4 mm, welding process: GMAW + FCAW, with metal powder-cored wire, semi-automatic for root bead, self-shielded flux-cored wire for fill and cap pass. Bevel design is shown in Figure 14.

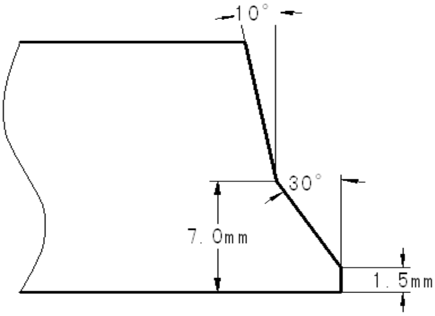

Figure 14. GMAW + FCAW Process Bevel.

This bevel was designed as a dual-V compound groove, of angles 30° and 10°, which reduced the overall volume of the groove. Therefore, the amount of welding filler materials and welder labor intensity were also reduced.

Requirements on the welding process:

- Root pass: E80C-Ni1 (dia. 1.2 mm，80% Ar + 20% CO_2).
- Fill and cap pass: E81T8-Ni2J (dia. 2.0 mm).
- Preheat temperature: 100 °C.
- Inter-pass temperature: ≤ 150 °C.
- For pipes with wall thickness 18.4 mm, five fill passes and one cap pass were required.

The performance of completed weld joints was as follows:

- Tensile test: the tensile strength was between 695 - 710 MPa, and half the specimens broke in the weld. The fracture surface had no obvious defects, and tensile strength was greater than the specified minimum tensile strength of X80 pipe material.
- Charpy impact test: Full-size specimens tested at a temperature of -10 °C, impact values for weld center and HAZ area were 90 - 252 J. Test data are shown in Table IX.
- Macro etch test: Weld appearance was acceptable and with no obvious defects present as shown in Figure 15.
- HV10 hardness test: HV10 was lower than 300. Test result(s) are shown in Figure16.

Table IX. Charpy Impact Test Data for GMAW+FCAW Joint (Full Size, -10 ℃)

Specimen No.	Notch Position	Item No.	Impact Absorbed Energy (J)	
			Single	Average
175-C1	WCL	1	114	116
		2	116	
		3	118	
175-C2	HAZ	1	186	185
		2	172	
		3	196	
175-C3	WCL	1	90	101
		2	104	
		3	108	
175-C4	HAZ	1	252	201
		2	168	
		3	184	

The tests show that the weld joints for semi-automatic welds can meet the project requirements. As a technique that has been proficiently mastered by most pipeline construction contractors in China, it does not require much training and thus time and cost are reduced. Figure 17 shows the construction arrangement for a semi-automatic welding group. The first time pass rate for RT inspection for the semi-automatic welding group was greater than 96 percent.

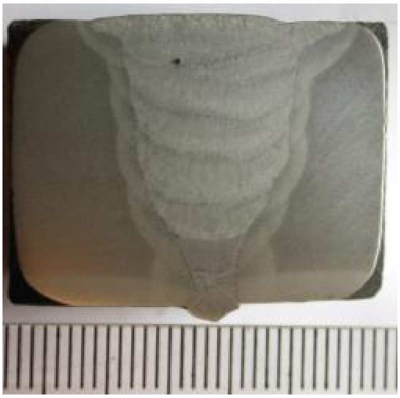

Figure 15. GMAW + FCAW welded joint macrograph.

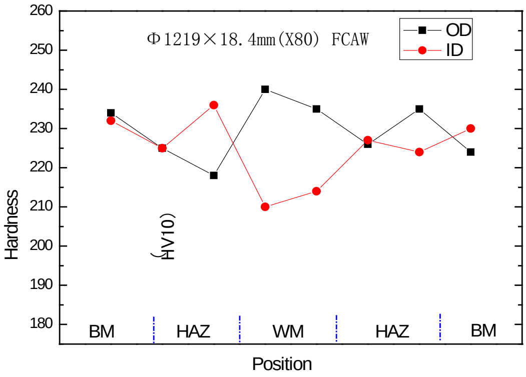

Figure 16. Hardness test results.

Figure 17. Construction arrangement for the semi-automatic welding group.

Conclusion

The comprehensive design techniques applied to the Second West-East Gas Pipeline Project, such as pipe grade, diameter, wall thickness, transporting pressure and distance, transmission capacity, and tight construction period, represent the highest level of pipeline construction technology in China. With respect to welding technical difficulties for the project, several major problems were solved by comprehensive and systematic research on weldability, welding materials, welding process, and especially welding at low ambient-temperatures of actual X80 pipe and strain-based design for high strain-tolerant pipe. The completed research work paved the way for commencement and completion of the project on schedule.

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