Welding Technology Development for an Erosion-Resistant Slurry Pipeline Steel

An investigation into the welding technology enabling the deployment of an erosion-resistant pipeline steel in the oil sands mining industry to achieve significant cost savings

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ABSTRACT

A new erosion-resistant high-manganese steel (HMS) was developed for use as a slurry pipeline material in the oil sands mining industry. This paper describes the parallel development of the welding technology (welding consumable, welding procedures) for the HMS pipe. Thermodynamic simulation, design of experiments (DoE), experimental welding, and physical testing were used to formulate and optimize the welding consumable, which has a unique combination of superior strength, toughness, erosion resistance, and weldability. Welding procedures were developed for the new application and were qualified per the project specification and industry code. Advanced microstructure analysis was conducted to assist the welding development effort. The welding technology has recently been applied in the field for the fabrication of a HMS slurry pipeline. It is anticipated that these developments will provide significant cost savings to the oil sands industry.

KEYWORDS

- Erosion-Resistant High-Manganese Steel
- Oil Sands Mining • Welding Consumable Development
- Design of Experiments • Thermodynamic Simulation
- Welding Procedures Development and Qualification

Introduction

In the oil sands mining industry, piping systems are used to transport mixtures of solid rocks, sand, water, and bitumen in a liquid slurry to a processing plant for oil extraction after which additional pipelines carry the erosive debris back to the mining site or to a storage area (Ref. 1). For a large operation, these piping systems may cover tens, or perhaps, a hundred kilometers. Current slurry hydrotransport pipes are typically made of low-carbon, pipeline-grade steel (e.g., API specification 5L X65 or X70), as shown in Fig. 1A. The slurry pipelines are subjected to significant abrasive/erosive wear and corrosion. This causes pipe wall loss, as shown in

Fig. 1B, and leads to frequent repairs and replacements. As such, these piping systems are often the source of significant operational costs. Various materials, such as martensitic stainless steels, bimetallic hardened-steel products, tungsten or chromium carbide based hardfacing materials, and polymer-lined materials (polyurethane), have been evaluated and used by oil sands mining operators. However, such materials have not achieved widespread application due to either relatively poor wear/erosion performance, high material/fabrication costs, or limited material thicknesses. Slurry pipeline erosion and degradation remains a challenge for the industry, and alternative pipe materials are sought to reduce cost and increase operational efficiency (longer service life) (Refs. 2–13).

ExxonMobil and South Korean steel maker Pohang Iron and Steel Co. Ltd. (POSCO) have collaborated in the development of a new high-manganese steel (HMS) for slurry pipeline service. This steel demonstrates excellent erosion/wear/corrosion performance (Ref. 14). The nominal composition of the steel is 1.2 wt-% C, 18 wt-% Mn, 3 wt-% Cr, 0.5 wt-% Cu, and 0.1 wt-% Si [hereafter, % denotes wt-%]. It is highly work hardenable and has been engineered to incur in situ surface modification that enhances erosion resistance during slurry pipeline service. To enable use of this HMS as a slurry pipeline material, girth welding technology is needed for field fabrication. No commercial technology (consumables, procedures, etc.) meeting the performance targets is available; therefore, a welding development program was undertaken and this included formulation and manufacture of a new consumable wire. Several performance targets were pursued. First, the welds must provide the necessary strength and toughness, including Charpy testing at -29°C . Since the girth welds are exposed to slurry transport during service, they need to have good erosion performance. Additionally, the welds must possess adequate weldability for field fabrication and because the HMS chemistry solidifies as primary austenite, solidification cracking was a particular concern.

Before embarking on a computational and experimental consumable development program, a literature review was conducted (Refs. 15–22). Reference 15 is notable for its

Fig. 1 — A — Slurry pipelines at the Kearl facility in Alberta, Canada; B — cross section of carbon steel slurry pipe near seam weld showing service-related erosion.

Fig. 2 — Effect of alloying elements on the three thermodynamic parameters. A — SFE; B — STR; C — CST.

Fig. 3 — Calculated SFE, STR, and CST for the 16 design chemistries selected for further experimentation. The red line indicates the preferable maximum STR and the blue-shaded region indicates the target SFE range.

breadth, observations, conclusions, and for the fact that it was dated 1954. It is perhaps the earliest comprehensive study of HMS technology and welding including a review of early patents from the 1920s and '30s. Reference 15 focused on 10–14% Mn alloys (Hadfield-type steels), yet many observations are still relevant to a broader classification of HMS alloys like the slurry pipeline chemistry. The challenge of carbide precipitation and the negative effects on toughness were well covered. Warnings were given to apply welding “... with as little heating of the base metal as possible.” Furthermore, “bead cracking” (i.e., solidification cracking)

was noted as a primary problem and phosphorus was identified as a main factor. Although Ref. 15 was notable for its time, it lacked the advantage of modeling, electron microscopy, and identification/knowledge of modern theories about solidification cracking (Refs. 23–30). The more current studies on welding of HMS (Refs. 16–22, 31–36) have done well to apply modern techniques and to quantify the contribution of different alloys to cracking susceptibility. Relevant to the current work are the observations in Ref. 31 identifying that carbon and phosphorus are primary culprits of solidification cracking in HMSs while the presence of sulfur is apparently mitigated by the high Mn content and the quick formation of MnS, thus tying up sulfur.

The subject of this paper is the description of the welding development program for the new slurry pipeline application. After the literature review provided general ideas regarding weld chemistry, a computational thermodynamics approach was used to optimize the chemistry “on paper,” after which experimental weld wires were made and tested to pick a champion. As previously mentioned, solidification cracking was a concern; however, it should be mentioned

Fig. 4 — A — Laboratory weld bevel design; B — plain view of one completed weldment.

that two of the primary factors in cracking susceptibility (C and P) were not manipulated significantly to alter cracking behavior in the experimental wires. The experimental range for C was controlled by the need to meet strength targets. And while measures were taken to minimize P (discussed below), P was not manipulated as an alloy variable in the experimental chemistries. Rather P was a byproduct of the wire making process, thus P was roughly similar amongst all wires tested.

HMS Welding Consumable Development

The first stage of the research was to develop a HMS weld (thus consumable wire) with an optimized chemistry. The steps included 1) selecting alloying elements to make a broad chemistry matrix; 2) calculating three key thermodynamic parameters using computational simulation; 3) investigating the effect of the alloying elements on the thermodynamic parameters using a design of experiments (DoE) approach; 4) using the DoE results to design an experimental matrix consisting of 16 weld wire chemistries for welding and testing; 5) manufacturing the weld wires; 6) performing lab tests using the 16 wires (strength, toughness, erosion resistance, and weldability); 7) and selecting a champion weld wire.

Welding Consumable Alloying Elements Selection

Key alloying elements that were selected for the computation exercise included C, Mn, Si, Cr, Mo, N, Ni, and Al. The anticipated effects of these alloys are explained as follows:

1) Mn is the primary element in HMS. It is a less costly replacement for Ni in stabilizing the austenite structure during cooling and deformation (Refs. 37, 38), and it has an important influence on the stacking fault energy (SFE) of the material system (Refs. 39, 40). It also provides a solid-solution strengthening effect to strengthen the matrix of the HMS (Ref. 41).

2) C serves as a solid-solution strengthener and austenite stabilizer (Ref. 42). Compared with the HMS base metal, the weld metal C content is lowered (<1%) to produce sufficient weldability and to avoid excessive carbide precipitation; however, it cannot be reduced too much or the strength targets will not be met. Despite the reduced carbon, the weld

metal strength can be maintained by alloying with additional elements like Mo and N (Ref. 32).

3) Si can improve the weld pool fluidity during welding (Ref. 43). Since the molten HMS viscosity is higher compared with the conventional carbon steels, addition of Si can increase the ease of welding and help to reduce incomplete fusion defects. It also provides solid-solution strengthening, affects SFE and enhances strain hardening (Refs. 44, 45).

4) Cr is added to increase the corrosion resistance of the weld metal (Ref. 46). However, higher Cr content may lead to the formation of Cr carbides during weld cooling and/or reheating, which needs to be minimized to avoid toughness degradation.

5) The addition of Mo can provide significant solid-solution strengthening to the matrix. Moreover, it is a major element providing erosion and corrosion resistance, especially the resistance to pitting (Ref. 16).

6) N is a potent austenite stabilizer and solid-solution strengthener. It can be a replacement for C and a small quantity of N addition can have a strong strengthening effect (Refs. 20, 47).

7) Ni is an austenite stabilizer and can improve the weld metal toughness (Ref. 48). However, higher Ni addition will result in a decrease of strength and increase in cost.

8) Al is known to be the very effective on increasing the SFE of HMS and therefore strongly influences the HMS deformation mechanisms (Refs. 49, 50).

Thermodynamic Simulations and DoE

High manganese steel alloys have a metastable austenite phase with a face-centered cubic (FCC) structure at room temperature. Upon straining, the metastable austenite phase can undergo dislocation gliding and a number of different phase transformations. These include micro-twins (FCC), ϵ -martensite (hexagonal close-packed lattice), and α' -martensite (body-centered tetragonal lattice), depending on specific steel chemistry, temperature, and/or strain rate. These transformation products are key in producing the unique properties of HMS.

To accelerate and optimize consumable development, thermodynamic simulation of potential alloy chemistries was performed, and then evaluated using a DoE approach. A

Fig. 5 — A typical butt-joint weld macro.

full factorial matrix of eight elements and three concentrations were included (Table 1) for a total of 6561 consumable chemistry combinations. ThermoCalc software (Ref. 51) and the TCFE6 database (Ref. 52) were used to calculate three thermodynamic parameters: stacking fault energy (SFE) (Ref. 53), solidification temperature range (STR), and carbide solvus temperature (CST). These parameters were selected based on their expected influence on erosion resistance, weldability and toughness, respectively.

- **SFE:** Since the HMS girth weld will be exposed to erosive service, it is important to utilize a parameter in the computations that relates to erosion/wear resistance. SFE has been cited (Refs. 19, 54, 55) as a strong determinant of erosion resistance. Low SFE (less than 20 mJ/m²) promotes strain-induced martensitic transformations. Intermediate SFE (20–45 mJ/m²) promotes intense twinning, while higher values (greater than 45 mJ/m²) promote plastic deformation by dislocation gliding (Ref. 22). It is believed that the best hardening rate (and therefore erosion resistance) can be achieved with mechanical twinning and gliding mechanisms during deformation (Refs. 56, 57). Therefore, a SFE range of 20–80 mJ/m² was selected as the target.

- **STR:** HMS alloys solidify as primary austenite, thus weld solidification cracking was considered to be a key technical challenge (Ref. 34). Alloys with lower equilibrium STR (between the liquidus and solidus temperatures) are known to have better resistance to weld solidification cracking (Refs. 28, 58). A target STR of 120°C or less was considered preferable (with less than 100°C considered optimal) for this alloy system.

- **CST:** Another technical challenge for HMS welds is the precipitation and growth of coarse carbides at grain boundaries, which can greatly diminish fracture toughness. Carbides will only precipitate during weld solidification if they are thermodynamically stable at high enough temperatures to allow the necessary diffusion of carbon. Therefore, alloys with a low CST were preferred.

After the calculation of SFE, STR, and CST was completed for the matrix of 6561 chemistries, MiniTab software was used to analyze the influence of each alloying element on

Fig. 6 — Extraction of tensile, CVN, jet impingement, and DTA testing coupons from the test welds (number in parenthesis indicates the quantity of the test coupons).

Table 1 — Selection of Key Elements and Concentrations Evaluated Using Thermodynamic Simulation

	Min	Mid	Max
C	0.4	0.6	0.8
Mn	18	21	24
Si	0.4	0.7	1
Cr	0	3	6
Mo	0	2	4
N	0	0.03	0.06
Ni	0	2.5	5
Al	0	0.5	1

these thermodynamic parameters. Figure 2A–C show the main effect plots for each parameter. Some alloying elements demonstrated a strong effect (indicated by a high slope), while others showed negligible effect (indicated by a flat slope). Al, Si, N, and, most interestingly, Mn were shown to have only minor effects on SFE, STR, and CST within the composition limits that were studied. Of the remaining four elements, only C was found to impact all three parameters. Rather than fully accept the ThermoCalc results, some additional considerations were used to help select elements for the experimental design studies. The computational work found little influence of N on key parameters. This combined with knowledge that N content is difficult to control in arc welds motivated the decision not to pursue purposeful N additions. Prior investigations during base metal development found that 3% Cr provides good corrosion resistance without dominant carbide precipitation; therefore, 3% Cr was selected as the baseline value for the experimental consumables. Previous consumable development work by the authors had found that Si contents in the range of 0.4–0.6% were effective in enhancing weld pool fluidity, so 0.4% was selected for the wire chemistries. Mn content was selected based on a starting point equaling that of the base pipe (18%), yet an additional sensitivity of 21% was explored to err on the side of higher stacking fault energy and

Fig. 7 — Plot of average yield strength and CVN toughness for all test welds.

stabilization of austenite. This was partly motivated to offset the decision to limit carbon for toughness and weldability concerns. The experimental consumables therefore contained variations of C, Mn, Mo, and Ni. Al, N, Cr, and Si were held constant.

A matrix of experimental chemistries was designed according to the above information and with regard to the target criteria for SFE, STR, and CST. Selecting two concentrations from each of the four variable elements generated a full factorial matrix of 16 chemistries, which was considered manageable for the experimental phase. The final selection of nominal wire compositions (designated as FX-1 to FX-16), along with their predicted SFE, STR, and

CST values, are listed in Table 2 (Al and N additions were 0% in all cases).

The plot in Fig. 3 compares these predicted values against the established criteria. These data demonstrate there was some difficulty in fully achieving the desired thermodynamic criteria. While nearly all of the alloys met the SFE criteria, only half met the STR criteria. The 750°–900°C range of CST's predicted in these alloys are near the median value of the CST predicted across the original 3⁸ matrix of simulated alloys. It was therefore anticipated that welding procedure controls may be necessary to prevent solidification cracking and to limit carbide precipitation.

Table 2 — Nominal Alloy Compositions and the SFE, STR, CST Predicted by Thermodynamic Simulation

	C	Mn	Mo	Ni	Cr	Si	SFE (mJ/m ²)	STR (°C)	CST (°C)
FX-1	0.4	18	2	0	3	0.4	22.55	93.3	770.7
FX-2	0.4	18	4	5	3	0.4	62.29	113.8	796.4
FX-3	0.4	21	4	0	3	0.4	24.52	106.6	761.7
FX-4	0.4	21	2	5	3	0.4	70.22	97.4	791.1
FX-5	0.6	18	2	0	3	0.4	34.52	123.8	837.2
FX-6	0.6	18	4	5	3	0.4	74.28	152.6	863.6
FX-7	0.6	21	4	0	3	0.4	35.51	141.2	828.8
FX-8	0.6	21	2	5	3	0.4	81.72	128.6	858.3
FX-9	0.4	18	2	5	3	0.4	62.26	98.6	797.6
FX-10	0.4	18	4	0	3	0.4	19.41	108.3	769.5
FX-11	0.4	21	2	0	3	0.4	27.89	92.5	763.5
FX-12	0.4	21	4	5	3	0.4	70.01	111.7	789.4
FX-13	0.6	18	2	5	3	0.4	74.50	131.2	864.4
FX-14	0.6	18	4	0	3	0.4	31.18	144.7	836.1
FX-15	0.6	21	2	0	3	0.4	39.07	121.9	830.4
FX-16	0.6	21	4	5	3	0.4	81.27	148.5	857.2

Fig. 8 — A — Schematic of the jet impingement test; B — a coupon after testing.

Fig. 9 — Jet impingement test results for the X70 and the four welding consumable alloys.

Fig. 10 — A typical DTA output plot with derivative curve to determine solidus and liquidus (FX-5).

Laboratory Welding

The designed experimental consumable alloys (FX-1 ~ FX-16) were manufactured as 1.2-mm-diameter cored wires (for metal cored arc welding (MCAW)) by Pohang Special Welding Co. Ltd., a subsidiary of POSCO. For each wire, a butt-joint weld was made from which mechanical and metallurgical test specimens were extracted. The HMS base plates were of the type used for pipe manufacture. The dimensions were 20 mm thick, 100 mm wide, and 300 mm long. The weld bevel was a 60-deg geometry (Fig. 4A) as this configuration was anticipated to reduce weld bead depth-to-width ratio, limit residual stresses (compared to typical narrow groove pipeline welds), and thus reduce the tendency for weld solidification cracking.

Welding was performed in the flat (1G) position. 80% Ar/20% CO₂ shielding gas was used at a flow rate of 20 L/min. The shielding gas with the flow rate can provide a combination of good arc stability, weld pool fluidity, and welding speed. Welding heat input was maintained at 1 kJ/mm for all passes and all welds. This heat input was chosen to minimize carbide precipitation in the weld metal and heat-affected zone (HAZ) in order to prevent the degradation of fracture toughness. One completed weldment can be seen in Fig. 4B and an example weld macro is shown in Fig. 5.

Mechanical Testing, Erosion, and Weldability Evaluation

The 16 welds were subjected to all-weld-metal (AWM) tensile, Charpy V-notch (CVN) toughness, erosion, and differential thermal analysis (DTA) tests. Test sample layout is shown in Fig. 6. Two AWM round bar tensile coupons were cut from the midsection of the weld, away from the fusion boundary and root pass, to limit base metal dilution effects. The tensile coupons were of the round bar geometry with a diameter of 6.35 mm and a gauge length of 25.4 mm as per Ref. 59. Tensile testing was conducted at room temperature using an MTS tensile testing system with 55,000-lb load capacity. The CVN coupons were full-size (10 mm × 10 mm × 100 mm), and the notch was cut at the weld centerline (WCL) in the through-thickness direction. The CVN tests were performed per Ref. 60 at -29°C using a 400 ft-lb (540 J) Tinius Olsen Charpy testing machine.

The tensile and CVN results are summarized in Table 3 and plotted in Fig. 7. This figure includes two shaded regions. The broad region is positioned according to the specified minimums of the design code (Ref. 61); 485 MPa and 27 J for yield strength and CVN toughness, respectively. The smaller shaded region was selected as the experimental target. The narrower target was motivated by the expectation

Fig. 11 — Pulsed spray welding current waveform.

Fig. 12 — Microstructure of the FX-5 weldment, showing weld metal, coarse-grained heat-affected zone (CGHAZ), and base HMS steel (from left to right).

that production welding would bring a higher degree of statistical variation, thus a “buffer” was thought to be useful during the experimental phase. Thirteen of the 16 wires passed the code minimum requirements. Four wires, FX-5, FX-8, FX-14, and FX-16, were found to achieve the more re-

strictive targets. An inverse relationship between strength and toughness is noted by the decreasing slope of the data (high strength correlates to lower toughness). FX-5, FX-8, FX-14, and FX-16 were subjected to jet impingement and DTA testing to evaluate the erosion resistance and the solid-

Table 3 — Mechanical Properties of FX-1 ~ FX-16

Alloy	Avg Yield Strength (MPa)	Avg Tensile Strength (MPa)	Avg CVN _{-28°C} (J)
FX-1	462	824	81
FX-2	501	764	70
FX-3	543	847	57
FX-4	504	747	95
FX-5	554	908	77
FX-6	599	865	38
FX-7	609	888	34
FX-8	566	842	87
FX-9	470	713	102
FX-10	495	835	69
FX-11	477	801	79
FX-12	496	745	93
FX-13	523	784	92
FX-14	573	915	62
FX-15	520	869	82
FX-16	551	813	70

Table 4 — Temperature Schedule of the DTA Test

	Temperature (°C)	Heating or Cooling Rate (°C/min)	Time (min)
Heat to	900	50	—
Isothermal Hold	900	—	1
Heat to	1480	10	—
Isothermal Hold	1480	—	1
Cool to	900	10	—
Isothermal Hold	900	—	1
Heat to	1480	10	—
Isothermal Hold	1480	—	1
Cool to	900	10	—
Isothermal Hold	900	—	1

Fig. 13 — FX-5 weld metal SEM images showing: A — Dendritic austenite at low magnification; B — oxides at higher magnification.

ification cracking susceptibility, respectively.

A schematic of the jet impingement test is shown in Fig. 8A. A flat coupon (64 mm × 64 mm × 12 mm) was extracted from the root pass area of the weldment for testing. The root region was selected because in the actual field application, this material is the first to be subjected to slurry erosion and it plays an important role in girth weld performance. In the test, a high velocity jet of water and sand mixture continuously impinges the weld at a 45-deg angle for a prescribed rate and duration. An erosion dimple (i.e., material loss) forms on the weld as shown in Fig. 8B. The coupon mass before and after the test was measured to determine weight loss as a measure of erosion resistance. The smaller the loss, the better the erosion resistance. Although the jet impingement test is not a perfect replication of slurry pipeline conditions, it can provide an indication of relative performance. Figure 9 shows the jet impingement results

for the four alloys along with the conventional X-70 pipeline steel. It can be seen that the mass loss of the four alloys is comparable and about 36%–45% of the X-70 steel. The results confirm that these four experimental alloys (weld wires) have significantly better erosion resistance than X-70.

To explore solidification cracking tendency, DTA testing was performed to measure the STR for the four alloys. DTA testing is a strong indicator of cracking susceptibility, as the measured STR correlates with the span of the weld pool mushy zone during solidification (Ref. 62). Generally speaking, if the STR is less than ~100°C, the alloy usually exhibits good cracking resistance. A higher STR represents higher susceptibility (Ref. 30) and a need for careful weld procedure development.

Two DTA coupons of 5 mm in diameter and 3 mm in length were cut from the midsection of each weld (Fig. 6). DTA testing was performed using a Netzsch STA 409 differential thermal analyzer. Prior to testing, the system was calibrated using

Table 5 — DTA Test Results

Sample	Test	Solidus (°C)	Liquidus (°C)	STR (°C)	Avg STR (°C)
FX-5	#1 (First heating)	1315	1409	94	94.5
	#1 (Second heating)	1318	1415	97	
	#2 (First heating)	1319	1411	92	
	#2 (Second heating)	1321	1416	95	
FX-8	#1 (First heating)	1285	1387	102	99
	#1 (Second heating)	1288	1383	95	
	#2 (First heating)	1283	1381	98	
	#2 (Second heating)	1285	1386	101	
FX-14	#1 (First heating)	1312	1408	96	98.3
	#1 (Second heating)	1313	1413	100	
	#2 (First heating)	1314	1414	100	
	#2 (Second heating)	1316	1413	97	
FX-16	#1 (First heating)	1284	1384	100	101.5
	#1 (Second heating)	1282	1388	106	
	#2 (First heating)	1283	1381	98	
	#2 (Second heating)	1285	1387	102	

Welding Procedure Development and Qualification

For reasons associated with using a new pipeline material (i.e., risk) and desires for easy installation and maintenance, it was decided that a first commercial application of the HMS pipe would be accomplished using double-length pipe joints with flanged connections at each end. The flanged connections allow easy disconnection, inspection, repair, and replacement. The double joints were to be fabricated in a shop environment by butt-joint welding, thus a need existed to develop a 1G-rolled welding procedure. The following summarizes the weld procedure development work and the procedural details are shown in Table 6. A range of welding parameters was selected based on our welding knowledge and experience, and then narrowed down using trial and error welding runs. The development work was conducted using an external pipe welding system (this equipment was selected because it was anticipated that a 5G procedure would be needed in the future).

Two weld metal transfer modes, short circuit and pulsed spray, were used for the root and fill passes, respectively. The lower current and heat input of the short circuit mode enabled root welding without the use of backing to secure the molten weld pool. Adjustments were made to travel speed and torch oscillation to mitigate the common problems of pool drop out, inconsistent root bead profile, and incomplete penetration.

Due to the level of C and Mn in the developed HMS weld metal, as compared to typical C-Mn steel welds, it is challenging to apply traditional welding techniques. HMS weld metal is substantially more viscous when molten than conventional low-carbon steel weld metals. The increased viscosity can result in incomplete fusion defects at weld toes located between the weld bead edges and the base metal.

Moreover, the toughness of the HMS base metal is sensitive to thermal cycles from welding. As a result, if the heat input during welding is too high, the HMS metal HAZ can have an unacceptable level of toughness. Also, as mentioned previously, HMS weld metal solidifies as primary austenite and is therefore prone to solidification cracking if welding is not properly controlled. In order to overcome these challenges, a custom pulsed waveform (as shown in Fig.11) was developed

Fig. 14 — EBSD map of the FX-5 weld metal.

pure Ni, Co and Au. Two coupons from each alloy were heated and cooled under pure argon. The temperature schedule of the DTA test is shown in Table 4. Each coupon was subjected to two heating segments from 900° to 1480°C, during which the solidus and liquidus temperatures were identified from the thermal curve as the deviation points (Fig. 10). STR was determined as the difference between the liquidus and solidus temperatures. The DTA results for the four alloys are summarized in Table 5. The data shows excellent reproducibility between the four measurements of liquidus and solidus temperatures with individual measurements typically within 1° to 5°C of each other. Of the four alloys, FX-5, FX-8, and FX-14 have STRs less than 100°C. FX-5, having the lowest STR of 94.5°C, indicating the best resistance to solidification cracking.

The mechanical, erosion, and DTA test results were taken into account to select the best consumable wire. Among the four alloys, FX-5 and FX-8 have better low temperature toughness compared with FX-14 and FX-16, while maintaining comparable erosion resistance. Between FX-5 and FX-8, FX-5 exhibited the lower STR and therefore better resistance to weld solidification cracking. Because FX-5 had lower Mn and Ni additions than FX-8, it also demonstrated better weld pool fluidity during lab welding. FX-5 was therefore selected as the champion wire for joining the HMS pipelines.

Table 6 — Qualified Pipe Girth Welding Procedures for FX-5

Process	Metal cored arc welding (MCAW)	
Bevel	60-deg included angle, 4-mm root opening	
Welding position	1G	
Shielding gas	80% Ar, 20% CO ₂	
Shielding gas flow rate	24 L/min	
Preheat temperature, min.	100°C	
Interpass temperature	100°C min. 260°C max.	
	Root pass	Fill passes
Current and polarity	Direct current electrode positive	Direct current electrode positive
Transfer mode	Short circuit	Pulsed spray
Voltage	20–22 V	23.9–31.2 V
Current	150–165 A	207–265 A
Travel speed	19.6–21.3 cm/min	46.2–58.4 cm/min
Wire feed speed	586.7 cm/min	1005.8–1120.1 cm/min
Heat input	0.91–1.02 kJ/mm	0.59–0.94 kJ/mm

Fig. 15 — Elemental maps for Mo, Cr, and Mn in the FX-5 weld metal. A — Mo; B — Cr; C — Mn.

for the FX-5 consumable. Welding current pulse parameters such as background current, peak current, current rise slope, current drop slope, and pulsing frequency were optimized through welding trials to produce a pulsed spray transfer with the best combination of welding productivity and weld quality. The custom pulsed waveform provides weld pool fluidity and arc stability that cannot be otherwise achieved with this weld metal.

In addition to the pulsed waveform described previously, weld joint geometry was controlled to enable successful development and qualification of the girth welding procedure. Solidification cracking is dependent on the magnitude and location of weld residual stresses that develop during weld solidification. The use of specific weld bevel geometries can lead to more favorable weld residual stresses and improved

Fig. 16 — Precipitates adjacent to the CGHAZ restricting the grain growth.

resistance to solidification cracking. Open bevels with larger included angles result in weld beads with lower depth-to-width ratios, which reduces solidification cracking susceptibility compared to narrow bevels with smaller included angles and larger thermally induced stresses. As a result of solidification cracking that occurred in the early stages of procedure development, the bevel angle was increased to 30 deg (60 deg included) to improve cracking resistance.

The welding travel speed, current, and voltage were controlled to keep the heat input below about 1 kJ/mm to minimize carbide precipitation in the weld metal and in the base metal HAZ. Early studies indicated that excessive heat input can significantly reduce HMS base metal HAZ toughness to below acceptable levels.

Cross-weld tensile, CVN, and guided side bend tests were performed to qualify the developed welding procedure for FX-5 per the project specification and ASME Section IX (Ref. 63). The test results are summarized in Table 7. The girth weld property requirements were based on a typical API X-70 grade slurry pipeline steel to ensure the weld provides the required strength, toughness, and quality for the slurry pipe application. The FX-5 weld met all the requirements. It can be seen that the tensile strength and elongation are much higher than the requirement. CVN testing was con-

Table 7 — Summary of ASME Section IX Test Results on FX-5 Girth Weld Produced during Welding Procedure Qualification

Test Type	Property	Requirement	FX-5 Weld Result
Cross-Weld Tensile	Yield Strength	>485 MPa	554 MPa
	Ultimate Tensile Strength	>570 MPa	908 MPa
	Tensile Elongation	>16%	51.5%
CVN	CVN WCL (@ -29°C)	>27 J	Avg: 66.4 J
	CVN WI (@ -29°C)	>27 J	Avg: 71.9 J
	CVN WI + 2 mm (@ -29°C)	>27 J	Avg: 71.3 J
	CVN WI + 5 mm (@ -29°C)	>27 J	Avg: 90.4 J
	CVN WCL (@ -46°C)	>27 J	Avg: 70.1 J
	CVN WI (@ -46°C)	>27 J	Avg: 65.5 J
	CVN WI + 2 mm (@ -46°C)	>27 J	Avg: 49.8 J
	CVN WI + 5 mm (@ -46°C)	>27 J	Avg: 70.5 J
Guided Side Bend Tests		No open discontinuity greater than 3 mm	4 out of 4 acceptable

Fig. 17 — A — TEM bright-field image showing the precipitates decorating the grain boundary; B — SADP along the grain boundary.

ducted at the WCL, weld interface (WI), WI + 2 mm, and WI + 5 mm to assess the toughness of those regions at -29° and -46°C . The results indicated both the FX-5 weld metal and the HAZ have sufficient toughness.

Microstructure Analysis of the FX-5 Weld

Microstructural analysis of the FX-5 weld was conducted to determine if any observations could be made to explain the positive property and weldability results. Samples for optical images were prepared using standard metallographic procedures, etched in 2% Nital for ~10 s and then tinted in a solution of 20 g sodium metabisulfite in 100 mL water for ~5 s. Figure 12 shows a typical fusion area image of the weld. Progressing from left to right, this image shows a weld metal with a dendritic structure, a coarse-grained heat-affected zone (CGHAZ) adjacent to the fusion boundary and the base HMS steel microstructure at the right.

Scanning electron microscopy of the weld metal was performed — Fig. 13A and B. Figure 13A shows a dendritic microstructure with solidification grain boundaries clearly displayed. At the higher magnification (Fig. 13B), second-phase particles can be observed. Particles in the weld metal were of particular interest because the HMS chemistries are potentially prone to toughness degradation due to Cr carbide formation. It was determined, however, that these particles were oxide inclusions of the type commonly present in gas metal arc welds. Their size and volume fraction are relatively small, which was attributed to the Ar-based shielding gas and the low heat input (~1 kJ/mm) welding procedure. The presence of these inclusions was inconsequential to the properties as evidenced by the CVN results shown in Table 7 (~70 J at -46°C). Electron backscatter diffraction (EBSD) analysis of the weld metal (Fig. 14) confirmed the formation of austenite and no ferrite or the deleterious martensitic phases were indexed. This confirmed the intended mi-

crostructural design was achieved and the metastable variations, which can degrade toughness, were avoided. It was concluded the austenitic matrix was the dominant microstructural feature that led to good toughness and a ductile fracture mode at very low temperatures.

The elemental maps of three major alloying elements, Mo, Cr, and Mn, in the FX-5 weld metal are shown in Fig. 15A–C. It can be seen that these elements segregate into the interdendritic regions, which is a result of solute redistribution between solid and liquid during the austenitic solidification. The oxides inclusions were found to contain Cr, Mo, and Mn.

Unlike conventional low-carbon steels, the HMS HAZ had a coarse-grained heat-affected zone (CGHAZ) but no fine-grained HAZ (FGHAZ) or intercritical HAZ (ICHAZ). There was no phase transformation from austenite to ferrite in the HAZ because the austenite was stabilized, thus grain growth occurred in response to the welding thermal energy. As shown in Fig. 12, the grain size of the CGHAZ was approximately 65 μm, almost fourfold of that of the HMS base metal. In the region between the CGHAZ and base metal, the grain growth was restricted by precipitates, as shown in Fig. 16.

Transmission electron microscopy (TEM) was performed to study the HAZ precipitates. Figure 17A and B shows the bright-field, high-magnification image and the corresponding selected area diffraction pattern (SADP), respectively. It can be clearly seen that carbides precipitated along the grain boundaries. The SADP indicates the precipitates had an FCC structure and they were in a cube-cube orientation relationship with the austenite matrix, as indicated below.

$$\{001\} \gamma // \{001\} M_{23}C_6$$

$$\langle 001 \rangle \gamma // \langle 001 \rangle M_{23}C_6$$

The precipitates were determined to be $M_{23}C_6$, with M, including Fe, Cr, Mo, and Mn. With the proper control of the

Fig. 18 — A — FX-5 girth weld macro, red dotted area indicating where the hardness mapping test was performed; B — hardness mapping result.

welding procedures, especially the heat input, the grain growth and the carbide precipitation were moderate and did not cause the CVN toughness to drop below the required 27 J at -29°C (Table 7).

Vickers hardness testing was performed on the FX-5 weld per ASTM E 384-11 (Ref. 64) with a 500-g load and a 200- μm indent spacing — Fig. 18A. The resulting hardness map is shown in Fig. 18B. It can be seen there was no softening in the weld metal or HAZ. Instead, slight hardening occurred in the weld root area. This could be attributed to the higher C content in the weld root compared with the fill passes as a result of the weld dilution from the HMS base steel, which contains a higher C content than the consumable. Because the weld root is exposed early to the erosive slurry environment, a harder weld root is preferred on the condition the higher hardness is not at the expense of toughness. As previously mentioned, the CVN results (Table 7) demonstrated the weld metal obtained good toughness.

Commercial Field Application

The HMS welding technology was applied commercially for the first time in July 2016 during the fabrication of approximately 1 km of HMS slurry pipeline at the Kearl Oil Sands Mining Operation in Alberta, Canada. This included use of the girth welding procedures described above and the FX-5 welding consumable. Twelve-meter- (40-ft-) long sections of HMS pipe were joined by girth welding to produce “double joints” of pipe 24 m (80 ft) in length. The fabrication activities were completed without any weldability problems (cracking) and the project was under budget and ahead of schedule. Figure 19 shows a photograph of an installed section of HMS slurry pipeline. As of the writing of this paper, the 1-km HMS slurry pipeline is still in operation. Field erosion/wear performance of the base pipe and girth weld have been verified. Based on this field application, the HMS slurry pipes have performed 3~5 times better than the traditional carbon steel pipes. Larger scale HMS slurry pipeline installation is underway. Field application of this technology demonstrates the developed technology can enable use of HMS slurry pipes, which are now commercially available, to reduce the cost of oil sands slurry pipeline operations.

Fig. 19 — Photograph of HMS slurry pipes installed at Kearl Oil Sands Mining Operation. Fabrication was conducted using the developed welding consumable and procedures.

Conclusions

This paper described the development of welding technology for successfully enabling a new erosion-resistant HMS for slurry pipeline applications. The technology is expected to result in significant cost savings.

For the development of the welding consumable, eight alloying elements (with three concentrations for each element) were selected to create a matrix of 6561 welding consumable chemistries. Thermodynamic simulations were performed on these chemistries to calculate their SFE, STR, and CST. A DoE approach was used to evaluate the effect of the alloying elements on the three key thermodynamic parameters. The results were used to select 16 consumable chemistries from which experimental weld wires were made and tested (tensile, CVN, erosion resistance, DTA). A consumable named FX-5 was selected as the best performing wire due to its superior combination of strength, toughness, erosion resistance, and solidification cracking resistance.

Welding procedures for joining HMS pipes were developed using the FX-5 wire. A short circuit transfer mode was used for root welding and a pulsed spray transfer mode was used for the fill passes. Heat input was kept low (~1 kJ/mm) to minimize carbide precipitation and to reduce welding residual stresses. The final welding procedures were qualified per the project specification and ASME IX. These procedures achieved the demanding mechanical property targets and successfully avoided solidification cracking, a problem known to plague HMS welds.

Microstructure analysis indicated that the FX-5 weld metal consisted of dendritic austenite, with no presence of ferrite or the deleterious martensite. Grain growth and $M_{23}C_6$ carbide precipitation occurred in the HMS HAZ; however, they were moderate as a result of the welding procedure control and did not cause any toughness issues.

The developed HMS welding technology has been successfully applied for the fabrication of an erosion resistant HMS pipeline at the Kearl Oil Sands Mining Operation in Alberta, Canada. The performance thus far has met expectations; therefore, larger scale commercial deployment of this technology is underway. These pipelines are expected to display increased life and result in significant project cost savings.

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