Welding of Thin Wall (10s) Super Duplex Stainless Steel UNS 32750

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Introduction

This study explores current industry practices and requirements when welding super duplex stainless steel (SDSS). The base material was thin wall UNS S32750 welded with modern high productivity semi-automatic Metal Cored Arc Welding (MCAW) and Flux Cored Arc Welding (FCAW) processes. Gas Tungsten Arc Welding (GTAW) was used for comparison purposes.

The results of the study are analyzed and compared to ASME Code and numerous other requirements that appear in oil sands extraction and upgrading industry standards and project (Owner/Engineering) specifications. The requirements of ASME Code Sections IX, B31.3, and Section VIII Div. 1 with regards to tensile, bend and toughness testing are addressed. Additional requirements imposed by industry standards and project specifications including heat input ranges, ferrite-austenite balance limits, oxygen content restrictions for purging and corrosion, notch toughness and hardness requirements.

The results are discussed considering the wide range of acceptance criteria among industry standards and project specifications.

Background

Duplex stainless steels (DSS) combine corrosion resistance and high mechanical strength. They are often used for applications that require higher resistance to chloride stress corrosion cracking, pitting, inter-granular attack and crevice corrosion [1-4] than austenitic stainless steels (ASS). Applications include components for hydro-processing units, sour water strippers, crude and amine units, brackish water piping, fuel gas piping and marine equipment [1,3]. Higher yield strength than ASS is an attractive property which results in significant material savings during design by reducing the required wall thickness [2,4-6]. Thermal conductivity is superior to ASS while thermal expansion is comparable with that of carbon steel [2,4] which reduce the amount of distortion and welding residual stresses.

The pitting resistance equivalent number (PRE\textsubscript{N}=%Cr+3.3%Mo+16%N) is used to assess DSS resistance to chloride pitting. Based on PRE\textsubscript{N} the DSS can be classified as lean (23-31PRE\textsubscript{N}), duplex (30-36PRE\textsubscript{N}), high alloy duplex (32-40PRE\textsubscript{N}), and super-duplex (>40PRE\textsubscript{N}).[3,7]

The SDSS are more highly alloyed than the other duplex grades and can withstand more aggressive environments. The most commonly used SDSS is grade UNS S32750 which contains about 25%Cr, 7%Ni, 4%Mo and 0.24-0.32 nitrogen as alloying elements. Various product forms are typically used in the oil sand industry including welded and seamless piping, forgings, fittings, and plate.
The microstructure of the base material is of a duplex nature with an ideal ratio of 50/50 ferrite to austenite (Figure 1). The dark phase in figure 1 is ferrite while the light phase is austenite. The actual amount of ferrite in base material typically varies from 45% to 55%. To obtain the desired properties of a welded SDSS it is necessary to maintain a reasonable balance of austenite and ferrite. For example 35-65% weld metal ferrite is acceptable in severe sour services per NACE MR0103 or even 25-75% ferrite for less demanding services per AWS D10.18M.

SDSS properties can be negatively affected by the welding thermal cycle. Factors that might be of concern include 475°C embrittlement, precipitation of intermetalics, oxidation heat-tint and maintenance of an acceptable ferrite to austenite balance in the weld metal (WM) and heat affected zone (HAZ).

When SDSS is exposed to temperatures between 340°C and 540°C precipitation of alpha prime within the ferrite phase occurs which results in a significant ductility and toughness loss [1-3,8,9]. This phenomenon is known as 475°C embrittlement. The exposure time to embrittle the material can vary from several minutes to several hours. Increasing the amount of nitrogen and lowering the amount of ferrite have a beneficial effect. ASME Construction Codes such as B31.3 and B31.1 limit the service temperature of UNS S37250 to 315°C (600°F) due to concerns over degradation of mechanical properties related to 475°C embrittlement. However, alpha prime embrittlement is generally not a significant concern during welding fabrication.

Various intermetallic phases, carbides and nitrides may precipitate when the weld area is exposed for sufficient time (matter of minutes) between 950°C and 600°C. In sufficient quantities the precipitates may negatively affect corrosion resistance and low-temperature toughness [1,7,10,11]. The degree of precipitation and the adverse effects depends on many factors including chemical composition, thermal history, time at critical temperature etc.

Colored oxide films typically develop on the surface of SDSS during welding. These oxide films are known as heat tints or discoloration and may affect corrosion resistance during service in various environments [13-16].

**Objective of the Study**

It has been demonstrated in the past that the bend and tensile requirements for welding procedure qualifications per ASME Code Section IX are easily met when welding SDSS with a large range of welding processes. However, owner/engineer specifications frequently impose additional requirements including limits on heat input ranges, purge gas oxygen limits, ferrite range limits, hardness limits, corrosion tests, limits on precipitates and notch toughness energy levels. Furthermore, the welding processes are frequently limited to GTAW and SMAW with no reference to other modern high productivity processes such as Metal Cored Arc Welding (MCAW) and Flux Cored Arc Welding (FCAW).

The objective of this study is to analyze GTAW, MCAW and FCAW super duplex weldments and how they stand up to Code and numerous Owner/Engineer requirements.
Experimental Procedure

A 18"NPS Schedule 10S (0.188" thickness) UNS S32750 SDSS pipe coupon (ASTM A-790) was welded (3G-rotated position) with MCAW EC2594 root and FCAW E2594T1 fill and cap. Another 18"NPS coupon was welded with GTAW ER2594 root, fill and cap. The groove was a single V with 1.58 mm land (1/16"), 3.2 mm gap (1/8") and 75° opening (Figure 2). A ternary-mix shielding gas of 96%Ar-3%CO2-1%O2 at 45 CFH (21.2 L/min) was used for the MCAW process while 75%Ar-25%CO2 was used for FCAW.

Argon shielding was used for the GTAW coupon. The purge gas was a mixture of 95%Ar and 5%N2. The amount of oxygen in the purge was maintained at selected levels by introducing ambient air into the purge enclosure with a hand pump. The quality of the purge was measured with a weld purge monitor (Argweld PurgEye 500) having a measurable range from 1ppm to 1,000ppm. Interpass temperature was monitored with a contact thermocouple (Fluke 52II). Modern inverter power source was used for MCAW, GTAW and FCAW processes (Miller Pipeworx 400). Modified waveform short circuit (RMD) transfer was used for the MCAW root pass.

The following testing and evaluation protocols were employed in the study:

- Metallographic samples were prepared in cross-section, polished then etched with an electrolytic 40% NaOH solution and examined using light microscopy up to 400X.
- Ferrite point counts per ASTM E562 were completed.
- Tensile tests per ASME Section IX,
- Face and root bends per ASME Section IX.
- Charpy V-Notch samples per ASTM A923 Method B as a method to determine the possibility of intermetallic precipitation and indirectly to assess corrosion resistance to pitting. Samples were prepared according to ASTM A370, with the notch centered at the weld metal and on HAZ near the fusion line. Sets of three samples were tested for each location at a test temperature of -450°C (-500°F). The impact specimen cross section size was 10 x 4mm
- Vickers Hardness Testing, 10kg load, cross-sectional hardness survey across the WM, HAZ and BM.
- Corrosion testing per ASTM A923 Method C “ferric chloride corrosion test” to assess the materials resistance to pitting and crevice corrosion in chloride-containing environments.

Results and Discussion

Weld Procedure and Technique Considerations

SDSS has a sluggish puddle but good weldability. However, there are two major challenges when welding SDSS: (1) avoiding intermetallic precipitation and (2) obtaining the proper balance of ferrite to austenite in the HAZ and weld metal [1].

Significant control and attention to detail is necessary to ensure the joint integrity and corrosion resistance of SDSS weldments due to its susceptibility to microstructural degradation.
In practice this is done by procedure control: setting lower and upper limits for heat input and imposing maximum interpass temperatures.

Preheat is not typically required except to dry the surface of the components to be joined or when the ambient temperature is near freezing [2,17]. Interpass temperature is often limited by technical project specifications to 150°C (300°F) maximum. The interpass temperature may be restricted further to 75°C (170°F) when welding on thin wall piping (Schedule 10S) [7] to account for less heat sink. One project document specified the maximum interpass temperature as “room temperature” for thin wall SDSS. For this work, the interpass temperature was controlled to a maximum of 300°F. Figure 3 shows the pass sequence and the measured interpass temperatures for the MCAW-RMD/FCAW and GTAW welds. As illustrated, an MCAW-RMD root offers the advantage of lower interpass temperature before depositing the “cold pass” which increases productivity and potentially better corrosion resistance of the area in direct contact with the process.

The heat input range is important as it significantly affects the cooling rate and in the end the properties of the weld. The cooling rate should be slow enough to allow for sufficient austenite reformation and should be fast enough to avoid intermetallic precipitation [18]. A commonly specified heat input range is 0.5 KJ/mm to 1.5 KJ/mm (12.5-38.1KJ/in) [2,7]. AWS D10.18 specification recommends careful control of the heat input balance between the root and the second pass to achieve maximum corrosion resistance of the surfaces that are in direct contact with the process.

Intermetallic phase precipitation and substantial secondary austenite formation can lower corrosion resistance. This may result from the combination of a lower heat input root (e.g. 1.0 Kj/mm) followed by a higher heat input (e.g. 1.7Kj/mm) second pass [2]. The second pass on an open root groove is termed the “hot pass” across the industry when welding common materials such as carbon and stainless steel. It is suggested that the second pass be called the “cold pass” [19] when welding SDSS to differentiate from general practice for other materials.

Improper phase balance due to high dilution with the base metal and increased risk of precipitation at the root surface may result from the combination of a high heat input root (e.g. 2.2Kj/mm) followed by a much lower “cold” second pass (e.g. 1.3 Kj/mm) is not desired [2].

It is suggested [2] to use a balanced heat input for the root and second pass; a medium heat input root (1.3 Kj/mm) followed by the second pass with a heat input of about 75% of the root pass. A wider range of heat input can be safely used for the subsequent fill passes [2].

A balanced heat input between the root and the second pass, with the “cold” pass having a heat input roughly within ±30% of that of the root is the recommended approach.

To achieve the best corrosion properties it is essential that the welders are properly trained to balance the heat input between the root and the “cold” pass. GTAW welders require supplemental training with regards to continuous addition of filler material to the weld pool in order to ensure that the pool has enough nickel to promote the formation of the desired amount of austenite.
Figure 4 shows the heat input of both MCAW-RMD/FCAW and GTAW coupons. All weldments were performed in the roll position. As illustrated in Figure 4, a typical GTAW open root heat input is higher than that referenced [2] for SDSS and that accomplished with semi-automatic welding processes.

**Metallographic Analysis**

Figures 5 to 7 shows the weld metal microstructure at 400X magnification taken at the centerline of cap, mid thickness and root of the MCAW-RMD/FCAW weld and GTAW weld respectively. The examination of the WM shows a typical dual phase microstructure of austenite and ferrite. There was no indication of intermetallic phase precipitation.

Figures 8 to 10 shows the HAZ microstructure at 400X magnification taken near the fusion line at the cap, mid thickness and root of the MCAW/FCAW weld and GTAW weld respectively. These microstructures show no indication of intermetallic precipitation. As shown in the images it is hard to determine the extent of the HAZ of a SDSS. However, the true HAZ of a SDSS weldment can be divided into two major zones.

The first zone (high temperature HAZ) is near the fusion line and transforms almost completely to ferrite during welding operations. On cooling, this area is required to transform back to the required fraction of austenite. This is the area that will show microstructural changes on an optical image and is of concern regarding the optimum ferrite to austenite balance. Project technical specifications often require metallographic ferrite point count measurements of the WM and HAZ areas as per ASTM E 562 during procedure qualification, to ensure that ferrite is within the required range. Typically the ferrite range is specified as 30 to 60%.

Figure 11 shows the results of the metallographic ferrite point count measurements for both MCAW/FCAW and GTAW welds. The measurements were performed in the WM and HAZ near the root, mid, and cap areas as well as base metal. The point count was conducted at 800X magnification using a 24 point circle grid and 10 fields. The results show that the ferrite-austenite balance met the requirements.

Typically 100% production Feritscope measurements on the root and cap surfaces of the weldments are required by project specifications to ensure that the required ferrite to austenite balance has been achieved. The results of production Feritscope measurements on the root and cap surfaces are superimposed on Figure 11 and indicate that the ferrite production measurements are in close agreement with metallographic measurements.

The second zone (low temperature HAZ) is located adjacent to the high temperature HAZ. This area will experience temperatures during welding within the precipitation range of intermetallics (950°C-550°C). The ferrite to austenite balance is practically unchanged but precipitation of intermetallics may reduce corrosion resistance. Typically, intermetallic precipitation is not homogenous and occurs as “islands” across several grains which make its identification and quantification impractical and often unreliable. The detrimental effects of intermetallic precipitation can be evaluated directly by conducting corrosion tests or indirectly by specifying Charpy V-notch impact testing at -40°C.
**Mechanical Testing**

**ASME Section IX – Bend and Tensile Requirements**
The bend and tensile test requirements for welding procedure qualification to ASME Code Section IX were easily met with MCAW, FCAW and GTAW consumables. This indicates that the weldment has adequate strength, ductility and fusion quality.

**Vickers Hardness**

Vickers hardness testing (HV10) is commonly required by project specifications when developing SDSS welding procedures. Acceptance criteria vary among specifications from 280HV max to 350 HV max. It should be noted that NACE MR0175 – ISO15156 does not currently impose limits on UNS S32750 base materials in oil and gas processing industries and by extension on weldments. It is common to require hardness measurements at a depth varying from 1.5mm to 2.5mm from the outside and inside surfaces. However, on 18NPS, 4.7mm wall thickness this arrangement is not practically possible. The hardness was measured on a transverse at the mid wall of the sample as illustrated in Figure 12. The measured hardness meets the most stringent requirements of reviewed industry specifications.

**Charpy V-notch Impact Testing**

Charpy V-notch impact testing is required by the construction code when low temperature service toughness needs to be assessed; however, ASME B31.3 does not provide an impact testing acceptance criteria for UNS S32750. Other industry standards (e.g., ASTM A923, NORSOK M601) and project specifications do specify impact testing to indirectly assess corrosion resistance through the negative impact of intermetallic precipitates on toughness. It is considered that intermetallics themselves are resistant to direct corrosion but their formation has an adverse effect on corrosion due to a depletion mechanism similar to that of sensitisation in austenitic stainless steels [11].

Project specifications provide a multitude of requirements for notch locations, test temperatures and acceptable energy levels for SDSS. One of the most common requirements is to test the weld metal and HAZ according to ASTM A923 Method B. This method does not provide acceptance criteria for UNS S32750. Other industry standards (e.g., ASTM A923, NORSOK M601) and project specifications do specify impact testing to indirectly assess corrosion resistance through the negative impact of intermetallic precipitates on toughness. It is considered that intermetallics themselves are resistant to direct corrosion but their formation has an adverse effect on corrosion due to a depletion mechanism similar to that of sensitisation in austenitic stainless steels [11].

Figure 13 details the Charpy V-notch (CVN) results obtained at -40°C for the MCAW-RMD/FCAW and GTAW welds. The absorbed energy values obtained for the WM, and HAZ near the fusion line (FL) significantly exceeded the requirement. Typically the WM is inferior in toughness to that of the HAZ due to its relatively large coarse microstructure [7,8]. The acceptance criteria of ASTM A923 for DSS reflect this fact. WM toughness of flux bearing processes such as SAW, FCAW or SMAW show a reduction associated with oxygen pickup from the flux when compared with GTAW or solid wire GMAW [6,7].
Figure 14 shows the typical impact energy at -50°C of the WM deposited with various processes from the manufacturer of the welding fillers used for this project [19]. The reduction in toughness of flux bearing processes is not associated with intergranular precipitation.

**Corrosion Testing**

Corrosion testing is often required by project specifications during procedure qualification. Typically, ASTM G48 Method A or ASTM A923 Method C are prescribed. The two methods are relatively similar in nature; samples are immersed in ferric chloride solution at a predetermined temperature for a predetermined time to detect the effect of intermetallic phases on corrosion behaviour. For this study, the project specification required the specimens to be tested according to ASTM A923 Method C at a temperature of 40°C for 24 hours. All surfaces of the specimens were polished to a uniform finish equal to 120-grit as required by ASTM A923. The corrosion rate was calculated following the methodology described by ASTM A923. The standard provides acceptance criteria of maximum 10 mdd corrosion rate when tested at 40°C for UNS S32750 base metal. Though no acceptance criteria is provided for weld metal, technical specifications have required the same maximum corrosion rate for the weld metal as is specified for the base metal. The corrosion rate determined for both MCAW/FCAW and GTAW specimens was zero mdd. The specimen’s surface condition was examined with an optical stereoscope at 20X magnification and revealed no evidence of pitting.

Formation of a passive oxide film that is high in chromium is responsible for SDSS excellent corrosion resistance. The passive film is very thin, in the range of 1-10 nm and forms on a clean surface in ambient air, fresh water or other oxidizing environments [15]. Damage to the passive oxide layer may have negative effects on its corrosion resistance, depending on the severity of environment/service. During welding, colored oxide films typically develop on the surface of SDSS [13-16]. These oxide films are known as heat tints or discoloration and may affect corrosion resistance when the surface is in direct contact with the process or environment [13]. It is stated in the literature that the corrosion resistance of SDSS is less affected by heat tint than austenitic stainless steels [13]. Back purging is common practice when welding on SDSS pressure piping. A thick black porous oxide is formed on the surface of a GTAW root when back purging is not used. The oxide has the appearance of burnt sugar and is termed in the industry as “sugaring”. This is an indication that besides poor corrosion resistance, the weld has likely other significant defects.

Colored oxides develop on the root areas when oxygen is present in the back purge in sufficient quantities. There is a relationship among the colors of the heat tint, its formation temperature and thickness, regardless of the welding process employed [20]. The structure of the heat tint may be divided in three areas [16].

The first area, starting from the unaffected base metal, is comprised by an oxide layer having a metallic to pale yellow color which could be up to 25nm thick and forms at temperatures up to 400°C. These oxides have similar layout as the passive layer and similar corrosion resistance [16,20].

In the second area, the oxide layers formed at temperatures above 400°C up to 700°C have colors ranging from dark-yellow, red, and blue, up to purple brown and can reach
thicknesses up to 100nm. The oxide layer morphology is completely changed leading to a
duplex structure; the outer layer of the oxide is rich in iron and manganese that are not
protective while the inner protective area is rich in chromium which is generally protective
[16,21]. The higher the temperature, the thicker the outer rich iron and manganese oxide layer
will become. It has been suggested in the literature that the highest ratio of iron in the outer
layer is reached for a heat tint that appears red to brown-red color [16,20]. Others suggest that
areas of the heat tint that have a light blue appearance are the most susceptible to corrosion
attack [22]. Regardless of this difference in opinion it is agreed that it is the second area that
has the highest susceptibility to localized pitting corrosion.

The third area, which forms at temperatures above 700°C, results in an oxide layer that
has a dark blue to black appearance. The oxide duplex structure still exists, but due to
increased chromium diffusion and time at temperature the fraction of chromium is increased in
the outer layer [16]. As a result this area is not as susceptible to pitting corrosion as the adjacent
red to brown-red to light blue area.

Project specifications typically impose limits on the maximum oxygen content in the
purge to reduce the amount and extent of heat tint on the areas that are in direct contact with
the process. However, there is no standard or guideline for acceptable levels of heat tint for use
in the oil and gas industries. The acceptable maximum oxygen content in the purge varies
widely across project specifications from 50ppm to 5,000ppm. Our latest fabrication project’s
ideal maximum oxygen content for the purge was 100ppm. This limit is rarely achieved during
fabrication; however, less than 400ppm was attained. Field site oxygen contents may be higher.
In addition to oxygen limits in the purge gas, some project specifications have imposed a
maximum #3 level of discoloration as pictured by AWS D18.2. However, the severity of the
service determines the level of the oxide tint that is acceptable. For example, AWS D18.1
indicates that a level of discoloration from #4 through #10 as indicated on AWS D18.2 is
unacceptable in the as-welded condition, unless otherwise agreed to between the owner and
fabricator. This is valid for piping systems in sanitary applications such as the food industry and
is not intended for other industries. Specifying such conservative requirements can lead to
significant production costs with little benefit for applications with low pitting potential. AWS
D18.2 is not to be used to determine oxygen content of the purge; it is to be used to identify the
degree of heat–tint oxide by number. The weld discoloration images were taken from an
electrochemically polished surface that is typical of sanitary applications. The appearance of the
heat tint is strongly influenced by the surface finish and the presence of moisture or other
contaminates which is also recognized by AWS D18.2. The presence of any contaminants and
surfaces that are not polished will result in more oxide tint with the same amount of oxygen in
the purge.

The amount of oxygen was varied in the purge. Prior to and during welding oxygen was
introduced with the aid of a hand pump. The oxygen levels for preliminary welds were
maintained between 70-100ppm. At this oxygen level the MCAW deposit was less than ideal.
The MCAW deposit was significantly improved with oxygen levels between 350-400ppm. The
first set of welds were then completed with a 70-100ppm oxygen content for the GTAW welds
and a 350-400ppm oxygen content for the MCAW weld. A second set of welds were performed
with 900-1,000ppm oxygen in the purge. Figure 15 shows the root surface appearance of the GTAW welds performed with <100ppm and 900-1,000ppm oxygen in the backing gas. The surfaces look relatively similar, heat-tint colors typical of first and second area are slightly more pronounced on the specimen with higher oxygen content in the purge. The heat-tint levels cannot be matched with any of the levels depicted by AWS D18.2. This is a clear indication that surface finish strongly affects the appearance of the heat tint and acceptance criteria based on the images of AWS D18.2 is not of practical applicability for the oil and gas industries. Similar surface appearance was noted for the MCAW/FCAW welds.

The specimens were corrosion tested in the as deposited condition per ASTM A923 Method C, modified to allow testing in as deposited condition. Only the sides of the specimens were ground to 120 grit finish while the root and cap were left in the as-welded condition (no buffing, grinding or machining was employed). The corrosion rate determined for the GTAW specimen with 70-100ppm purge oxygen content was 53 mdd while for the specimen with 900-1,000ppm the corrosion rate was 4.88 mdd. Figure 16 shows the surface condition of the GTAW specimens after corrosion testing. ASTM A923 Method C is intended to determine the presence and detrimental effect of intermetallic phases on corrosion properties and not the effect of heat tint; therefore its acceptance criteria cannot be applied in this case. The difference in the corrosion rate between the two specimens may be related to the amount of which the outer layer of the oxide is detaching during testing.

Figure 17 shows the surface condition, before and after corrosion testing, of the MCAW-RMD/FCAW specimens welded with 350-400ppm purge oxygen content. The calculated corrosion rate was 57.8 mdd and was strongly influenced by particulates detaching during testing with no correlation to corrosion attack. The MCAW-RMD/FCAW specimen with 350-400ppm oxygen purge content seems to have a lower degree of oxidation near the weld metal surfaces than GTAW specimen with <100ppm purge oxygen content. This may be related to the time at temperature as MCAW-RMD/FCAW root/second pass combination has typically lower heat input than GTAW.

The specimen’s surface condition was examined with an optical stereoscope at 20X magnification and revealed no evidence of pitting for all GTAW and MCAW-RMD/FCAW specimens.

Summary of Results and Conclusions

This work examined MCAW-RMD/FCAW and GTAW SDSS weldments and how they stand up to Code and various Owner/Engineer project technical requirements. The following results were observed:

- Due consideration of the welding technique is critical to optimizing SDSS weld joint performance
- Examination of the MCAW-RMD/FCAW and GTAW weldments determined that:
  - Ferrite-austenite phase balance met typical requirements in the WM and HAZ
  - Adequate strength, ductility and fusion quality can readily be obtained with modern consumables
The weldment hardness met stringent industry requirements.
Charpy V-notch energy values at -40°C exceeded the most stringent requirements imposed by reviewed project technical specifications.
There was no evidence of pitting in the WM and HAZ. The calculated corrosion rate was zero when tested according to ASTM A923 Method C methodology.
The appearance of the heat tint is strongly influenced by the surface finish and as indicated on AWS D18.2 the colors shown should not be used to gauge purge oxygen content.
Pitting was not observed on the as welded surfaces even with 1,000ppm oxygen in the purge.
- A guideline should be developed to provide a better understanding and agreement on acceptable heat tint levels for applications in the oil and gas industries.
- MCAW-RMD/FCAW provides several notable advantages over GTAW:
  - Lower heat input balance of the root and second pass with benefits on in service overall corrosion performance
  - Higher productivity and welder comfort
  - Easier to train welders
  - Higher degree of confidence that the requirements are consistently met during production welding
  - MCAW wire formulation can be adjusted to meet project specific requirements.

It has been demonstrated that MCAW-RMD/FCAW weldments are capable of producing extremely high quality welds that could be used with confidence in the fabrication and construction of SDSS piping and equipment for a wide range of applications in oil sands extraction and upgrading.
Figure 1: SDSS base metal microstructure: typically 45-55% ferrite. Dark phase is ferrite while the light phase is austenite.

Figure 2: Open root joint design
Figure 3: Joint pass sequence and interpass temperatures a) MCAW-RMD/FCAW, b) GTAW
Figure 4: Joint calculated heat input a) MCAW-RMD/FCAW, b) GTAW
Figure 5: Weld metal microstructure near the cap pass (400X): a) MCAW-RMD/FCAW; b) GTAW

Figure 6: Weld metal microstructure near the weld mid (400X): a) MCAW-RMD/FCAW; b) GTAW

Figure 7: Weld metal microstructure near the root pass (400X): a) MCAW-RMD/FCAW; b) GTAW
Figure 8: HAZ microstructure near the cap pass (400X): a) MCAW-RMD/FCAW; b) GTAW

Figure 9: HAZ microstructure near mid wall (400X): a) MCAW-RMD/FCAW; b) GTAW

Figure 10: HAZ microstructure near the root pass (400X): a) MCAW-RMD/FCAW; b) GTAW
Figure 11: Ferrite point count near root, mid wall and cap areas of BM, HAZ and WM. Weld metal Fisher production ferrite measurements are superimposed for the cap and root areas (WM-Prod): a) MCAW-RMD/FCAW; b) GTAW
Figure 12: Cross-sectional HV10 hardness survey grid. Most stringent acceptance criteria: 280 HV max. a) MCAW-RMD/FCAW; b) GTAW
Figure 13: Average Charpy V-Notch energy at -40°C of MCAW-RMD/FCAW and GTAW weldments.

Figure 14: Typical weld metal Charpy V-Notch energy at -50°C as indicated by filler manufacturer.
Figure 15: GTAW root surface appearance after welding with purge oxygen contamination a) 70-100ppm, b) 900-1,000ppm

Figure 16: GTAW root surface appearance after corrosion testing a) 70-100ppm, b) 900-1,000ppm oxygen purge contamination.
Figure 17: MCAW-RMD/FCAW weldment root surface appearance (a) before and (b) after corrosion testing; 300-400ppm oxygen purge contamination.
References: