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ABSTRACT

This paper addresses the formation of unmixed zones which can form during the weld fabrication of INCO* alloy 25-6MO (UNS N08925), one of the 6% molybdenum alloys. Using the proper weld fabrication procedures and joint design, these unmixed zones can be shown to be minimized and the weld corrosion integrity of the joint confirmed using standard ASTM corrosion test procedures. No effect of heat tint or heat input on corrosion resistance was discerned and the root pass weld was not preferentially attacked.

INTRODUCTION

The bleach plant corrosion testing piping program was first initiated through TAPPI in 1986, when EPA regulations,(1) forced the pulp and paper industry to switch from direct chlorine injection to other bleaching systems -- predominantly chlorine dioxide. The principal goal was to reduce the dioxin levels in waste water discharges. The result was a potentially more corrosive bleaching environment and the standard austenitic stainless steels were becoming more aggressively attacked.

To address the corrosion problem, in-field testing programs(2) were initiated, and austenitic alloys containing 6% molybdenum or greater in their composition were found to offer suitable resistance to pitting and crevice corrosion. Hence, the next phase of an industry study involved the evaluation of these types of materials in actual piping systems.

Under the direction of the TAPPI metals sub-committee, a series of weld fabricated 6% molybdenum and nickel basealloy pipe sections were produced in two foot flanged lengths and placed in three selected pulp mill applications which involved aggressive C and D stage environments. These systems were allowed to operate for approximately one year before being removed and evaluated. The results of these initial bleach pipe tests(3) showed that the base metal pipes performed very well, but corrosion attack had occurred at the root pass of the butt weld of a 6% Mo alloy pipe section. The cause was attributed to "unmixed zones" in the weld. The cause was attributed to unmixed zones in the root pass of these 6% Mo butt welds.

Experience to date has shown that the 6% Molybdenum alloys have performed well in many fabricated bleach washer and drum applications, where over matching filler metals are used in the welding of plate sections. Although the joint configurations are different than for pipe sections, high integrity welds have provided outstanding service in this corrosive media. Consequently, the resolution of the weld fabrication of piping can be influenced by welding procudures and the standard practice for making good quality butt welds in ferritic grades of stainless steels would have to be modified in order to produce equally good quality butt welds in the higher molybdenum content alloys.

Unmixed Zones

This is a recognized phenomenon associated with many alloy systems, including the iron-chrome-nickel-molybdenum series of alloys, whereby a thin layer of base metal is melted and trapped between the molten weld metal and the base metal, therefore, never fully being mixed into the molten weld pool during welding. Controlled welding procedures, to ensure adequate mixing within the weld molten pool during welding, will assist in reducing or overcoming some of these unmixed zones.

To ensure the integrity of the 6% molybdenum alloys in providing a viable and practical cost effective approach in servicing the bleach plant service and environments, this study and paper will hopefully serve to guide the industry, fabricators and material suppliers in the resolution of ensuring a high quality weld fabrication for use in these types of service. Metallographic examination was also performed to determine the effects of various welding procedures on the fusion zone and fusion boundary areas.

Weldability of 25-6MO Pipe

There have been several papers(4)(5)(6) describing welding techniques which provide good corrosion resistance on 6% molybdenum stainless steels. In the past, 6% molybdenum study findings (7) (8) have shown preferential corrosion occurring in the unmixed regions in the root pass of the pipe welds. However, there has not been any solid evidence of accelerated corrosion related failures in the field when using the higher molybdenum containing filler metals INCONEL* alloy Filler Metal 625 (FM 625) or alloy Filler Metal C-276 (FM C-276).

The use of overmatching filler metals is a good rule of thumb when welding any corrosion resistant material. When welding high alloy material, segregation occurs between the primary and secondary arm spacing of dendritic growth found within the cast structure of the fusion zone of a weld.(9) The two critical elements which provide corrosion resistance in the weld are molybdenum and chromium and if either one of these become depleted within the structure of the weldment, then this region can become susceptible to preferential crevice and pitting corrosion attack. Both FM C-276 and FM 625 sufficiently overmatch the 6% molybdenum base metal to prevent these types of preferential corrosion.

Gas Tungsten Arc Welding (GTAW) and pulsed Gas Metal Arc Welding (GMAW) techniques were used to fabricate 1/4" thick 4" diameter pipe. In this study, various joint designs and welding techniques were used with both FM C-276 and FM 625 to prepare the weld samples for corrosion testing, using ASTM standard test methods G-48A and G-48B for crevice and pitting corrosion. The heat tint which appears on the base metal surface adjacent to the weld was also tested for corrosion resistance, using the "Yellow Death" test solution. (Localized corrosion attack of alloy 904L in these regions has been reported.)(10) With the proper joint design, welding process, welder technique/parameters, and using FM 625 or FM C-276, 25-6MO pipe welds can be produced which will have corrosion resistance equal to or better than the base metal. Choice

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of welding processes, joint design, parameter settings, and filler metal selection are based on current practices found in industry.

Pipe Weld Corrosion Sample Preparation

All pipe welds were made in the 1G position (commonly found in shop welding), using GTAW and GMAW techniques, to keep the weld dilution as consistent as possible. 5G and 6G positions (found commonly in field applications) should be tested in the future to evaluate their corrosion resistance. Table 1 lists the various welding procedures used to produce the corrosion samples.

The two filler metals that were used for this study were FM 625 and FM C-276. Welds were made with and without weld ring inserts in order to determine which approach would offer the greatest degree of integrity --- both from a welding and corrosion resistance perspective. Two different welding techniques were evaluated --- one using a keyhole welding technique and the other using a normal puddling technique. The different techniques were evaluated using GTAW practice, as is the general rule for making the root pass in pipe welds.

The root pass was made using 100% argon shielding gas with a flow rate of 15 cfh, using a 3/8" nozzle, 1/4" stick-out, 1/16" diameter tungsten and using dc straight polarity. Helium was used as a backing gas with a flow rate of 8cfh and a 1/8" diameter outlet hole. A 2 minute pipe gas purge with 20 cfh helium flow rate was performed each time the pipe backing gas dams were removed and reapplied.

The "High" and "Low" labels stand for high and low amperage settings, as shown in Table 1. These current levels were chosen to determine whether different corrosion rates would occur when changing the current and/or heat input. It is possible that the amount of weld pool stirring and dilution can be directly affected by changing the level of current and/or heat input.

The pipe weld joint design was chosen for ease of joint accessibility for the welder and to control weld metal dilution. (see Figure 1). Modifications were made to the joint design when the FM 625 inserts were used. A 1/16" land width was used instead of a 3/32", in order to accommodate a wider insert (1/16" x 1/8").

GMAW Parameters

For the GMAW welds, 100% argon was used for the shielding gas with a flow rate of 40-50 cfh and a helium flow rate of 8 cfh for the back-up gas after the initial purge. The torch orientation used by the welder was approximately 15° past top dead center with a push angle of 5°. The pipe was rotated opposite the push direction and fixed in the 1G position. Tables 2 and 3 list the various welding parameters used with and without inserts.

GTAW Parameters

When using gas tungsten arc welding (GTAW), the electrode orientation for the welder was located approximately at a 20° push angle and positioned 10° from the top dead center of the pipe joint. The pipe rotated opposite the push direction in a 1G position. Tables 4 through 10 list the various weld parameters used to make the corrosion samples with and without inserts.

In the case of the keyhole root weld technique, the helium backing gas, after the initial purge, was increased to 12 cfh. Note: To begin the keyhole root pass, a small hole was made before beginning the weld.

Heat Tint Corrosion Sample Preparation

Three 6% molybdenum alloy (3/8" x 13" x 3") plates (heat# Z2113P) were used to produce 32 heat tint samples. Both sides of the plates were ground to a 240 grit finish, with the finished side cleaned using a solvent and allowed to dry for more than five minutes before welding. The plates were restrained during welding to help control distortion. Care was taken with the placement of the fixturing in order to avoid any preferential heat loss between the plate and the fixturing components.

The following welding parameters were used: 5/32" diameter 2% thoriated tungsten electrode: argon shielding gas of 20 cfh: 255 amps; 12.5 volts; 1/4" electrode stick-out; dc straight polarity. Two passes were made on each plate using two travel speeds. A low heat input weld (27 kj/in) was centered on half the plate and a high heat input weld (42kj/in) pass was centered on the other half of the plate, with the weld direction along the length of the plate.

After the first weld was made, the plate was cooled by forced air to room temperature before the second pass was made. This procedure was repeated for the remaining plates. The heat tint side of the plate was sectioned into 1.5" x 1" corrosion sample sizes, with the weld running along the 1.5" dimension. A cut-off saw was used for sectioning to eliminate contact with cutting lubricants. Careful attention was taken not to disturb the heat tint side of the sample during and after cutting.

CORROSION RESISTANCE

Effect of Welding Technique

Tables 11 and 12 present the effects of the various welding techniques on corrosion resistance. The welds varied in heat input, filler metal, weld process, and procedure. The samples were evaluated in the ASTM G-48A pitting corrosion test (6% ferric chloride at 35C for 72 hours) and a modified ASTM G48-B Crevice corrosion test (6% ferric chloride at 24C for 72 hours).

All the alloy 25-6MO welded pipe exhibited excellent corrosion resistance in the pitting test environment and there was only some limited incipient crevice corrosion (< 1 mil penetration) observed in the modified ASTM G48-B test. These are both very aggressive environments and < 1.5 mil penetration is considered excellent corrosion resistance in the modified ASTM G48-B crevice corrosion test. Consequently, it can be fairly concluded that there are no corrosion rate differences between the various welding techniques, as listed in Table1. This also includes the use and non-use of weld filler metal inserts.

Additional corrosion studies were run to evaluate the effects of weld heat input, using the same corrosion test methods, i.e. ASTM G48-A and the modified ASTM G48-B solutions. The results are shown in Tables 13 and 14. Again excellent corrosion resistance (no attack) was observed, whether high or low heat input welding procedures were used.

Effect of Heat Tint

The effect of heat tint on the corrosion resistance of INCO alloy 25-6MO was evaluated in two test environments --- Yellow Death (acidified salt solution) and the Streicher Test (ASTM G28A, ferric sulphate-sulphuric acid). The first of these environments is an acid chloride pitting test, while the Streicher Test discerns the effect on the intergranular corrosion susceptibility of the alloy, and in particular, the heat affected zone.

Tables 15 and 16 summarize the results of both of these tests. Test plates were bead on plate, autogenously welded, with low and high heat inputs on the surface of the 3/8" thick plate. In addition, duplicate welded plates were produced with heat tint removed and not removed. In all cases there was no effect of heat input or of heat tint on the corrosion resistance of the specimens. No localized corrosion occurred in the Yellow Death environment and all corrosion rates for the Steicher Test ranged between 14 and 16 mils per year (0.36 and 0.41 mm/yr.). Corrosion rates of less than 36 mils per year are considered excellent for wrought 6% molybdenum alloys in the Steicher Tests.

DISCUSSION

Welding

Choice of welding processes, joint design, parameter settings and filler metal selection were based on current practices found in industry. None of the weldments were shown to be susceptible to preferential corrosion in or around the heat affected zone and fusion zone of the weld.

Tack welding the insert rings, can be a very critical step. Figure 2 is a photograph of the inside diameter (I.D.) of a tack weld after the root pass was made. Lack of fusion and heavy oxidation is found in the area opposite the tack welds. This was caused by oversized tack welds and oxidation of the pipe I.D. from overheating of the insert. By using smaller and more numerous tack welds, the weld penetration becomes more consistent and oxidation is prevented. Use of backup gas during welding will prevent the oxidation of the pipe I.D., but will not prevent the possibility of lack of fusion if the tack welds are oversized. Tapering the arc off to the side of the joint is a good practice in order to avoid crater cracking when completing the weld. Excessive travel speeds cause a teardrop puddle to form which can lead to center-line cracking, while slower travel speeds help maintain an elliptical puddle and prevent center-line cracking by decreasing the contact angle between the converging solidification fronts in the weld puddle. Purging the pipe before welding and using backing gas are very critical parameters when welding any high alloy material.

As stated in the procedures, all pipe welds were made in the 1G position using GTAW and GMAW welding processes. When comparing Figures 3 and 4, the width/size of the root pass of these corrosion samples E107 (FM 625 insert; 78 amps) and E109 (FM 625 insert; 115 amps) are considerably different. It is visually noticeable that the weld made with the low current, high heat input setting compared to the high current, low heat input setting is wider and larger at the base of the root pass. The larger the fusion zone, the higher amount of fusion zone dilution from the increased amount of base metal melted.

Past reports have shown that 6% molybdenum stainless steels can be susceptible to preferential corrosion in the root pass where improperly mixed weld constituents can occur thereby causing segregation of the vital elements, which otherwise give the base metal its good corrosion resistant properties.(3) Weld pool stirring or heat input may have a direct affect on the frequency or size of unmixed regions occurring immediately inside the fusion boundary (see Figure 5).

METALLOGRAPHY

To study the unmixed zone phenomena, three weld samples (E107; E109; E105) had microscopic and quantitative, energy dispersive spectrometry (EDS) performed on the transverse cross section of the root pass. Figure 6 shows a photomicrograph of the root pass where the FM 625 insert was melted with a high current, low heat input setting taken from corrosion sample E105. An EDS traverse was started just above the Knoop hardness reading taken in the base metal. The readings were taken at 5, 20, 40, 60, and 80 microns away from the fusion line of the weld, traveling toward the center of the weld. The results of the traverse performed are shown in Figure 7.

The same procedures were used when performing an EDS traverse on the root pass of the FM 625 insert melted with the low current, high heat input, and the FM C-276 insert melted with the high current setting. The results of these traverses are shown in Figures 8 and 9.

EDS analysis of the fusion zone revealed very similar dilution levels when comparing the high heat input, low current (achieved by using slow travel speeds) and low heat input, high current weld samples (achieved by using fast travel speeds). The dilution levels were calculated from the EDS iron concentration readings, giving an error range for dilution of ±5%. All of the EDS traverses revealed appreciable increases in dilution 5 microns from the fusion boundary, but none revealed any appreciable increase at 20 microns from the fusion boundary.

The weld sample using the FM 625 insert, low current, high heat input, had an appreciably higher amount of dilution at 5 microns from the fusion boundary as compared to that for the FM 625 insert melted at the higher current, lower heat input levels. The cause of the increase in the width of the unmixed zone region along the fusion boundary could be due to the use of these lower welding currents and higher heat inputs. The temperature gradient would be less steep at the fusion boundary, thus melting more base metal, and the lower welding current would be insufficient to mix the additional base metal melted just inside the fusion boundary. There was no area in the fusion zone in which chromium and molybdenum was found to be any lower than the base metal chromium and molybdenum levels.

An EDS analysis was also performed in the areas of apparent banding located throughout the fusion zone. This analysis was undertaken to determine whether the preferentially etched areas, using an electrolytic etch technique, reflected differences in chemical composition. By reference to Figure 6, two Knoop hardness indentations can be identified in the center of the fusion zone. One indentation was placed in the center of a light etched area and the other placed in a dark etched region. EDS readings in both areas revealed a substantial difference in chemistry (see Table 17). For comparison, a different etchant (Kane's swab etchant) was used to enhance the contrast between these dark and light areas on a specimen in which a FM C-276 insert was used (reference Figure 10). The EDS readings that were taken on this specimen are also reported in Table 17.

From these EDS results, it can be stated that the light etched areas are filler metal rich and the darker (background matrix) etched areas are filler metal diluted with a certain percentage of base metal. Even though incomplete mixing of the filler metal does occur, it did not lower the overall molybdenum or chromium concentrations in the fusion zone below those of the base metal.

By review of Figures 3 and 4, the compositional differences may explain the reason why the sample in Figure 4 did not etch as heavily as that in Figure 3 when using the same etching and developing procedures. The weld shown in Figure 4 was subjected to a lower heat input, lowering the amount of dilution and making the fusion zone richer in the filler metal elements which etch light. The weld in Figure 3 with lower current, but higher heat input would increase the amount of base metal diluted into the fusion zone. Furthermore, it was noted that; the welder tended to work the puddle or manipulate the torch from side to side. This resulted in greater stirring or mixing of the weld puddle resulting in a more homogenous weld deposit. Both the higher diluted and homogenous weld deposit contributed to the darker etching of the fusion zone in Figure 3.

A postulation can be made about the difference in the weld center background matrix dilution levels, since the amount of dilution between the weld samples shown in Figures 7 & 8 did not vary considerably with heat input or area of base metal melted. Using the FM 625 insert with high currents and low heat inputs (fast travel speed), a heterogeneous fusion zone composition results. This heterogeneous deposit increases the overall base metal dilution in the background matrix (dark etched regions) to 40% ± 5%, even though, the low heat input melts less base metal. With low currents and high heat inputs (slower travel speed), more base metal is melted, but now the fusion zone is a homogeneous mixture of filler metal and base metal, so that the background matrix is diluted (48% ± 5%) by the base metal. The slower travel speed allows the welder to work the puddle (puddling) creating a homogenous weld deposit.

CONCLUSIONS

1. It is concluded that high heat input/low current levels (slow travel speeds) should be used for the root pass to ensure more complete mixing in the molten weld pool to provide high quality corrosion resistant butt welds in 6% Mo pipe. It is also shown that there is a considerable range of heat inputs within which these high quality butt welds can be made.

2. By using any of the welding techniques described and overmatching filler metals FM 625 and FM C-276, excellent weldments can be produced having equivalent corrosion resistance to the base metal.

3. Although unmixed zones cannot be totally eliminated, the size and/or width of these zones can be minimized when using these overmatching high alloy filler metals and proper welding techniques. High heat input/low current levels, when welding 25-6MO pipe with Filler Metal 625, increases the width of the unmixed zone occurring immediately inside the fusion boundary, while low heat input/high current levels minimizes this effect.

4. Low heat input/high current levels (fast travel speeds), results in a heterogeneous (less mixing) overall weld deposit consisting of areas rich in filler metal elements. Concentration differences were found throughout the fusion zone, but molybdenum and chromium levels never fell below the 6% molybdenum alloy base metal levels. Lower welding speeds allows for greater puddling which enhances weld pool stirring to achieve a more uniform homogeneous distribution of filler metal elements.

5. Even using the accelerated intergranular susceptibility test and severe acid chloride pitting and crevice corrosion tests, there was no knifeline attack related to the unmixed zones, nor was there any attack of the initial root pass.

6. No relationship was found between the effects of heat tint and corrosion resistance. There were also no corrosion rate differences found between the filler metals, welding processes, weld joints, and welder techniques used.

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TABLE 1

Filler Alloy	Welding Process							
	GMAW			GTAW				
	No Insert	(Insert) GTAW Root Pass Only		No Insert		(Insert)		No Insert Root Pass Autogenous
		High I	Low I	Non Key-Hole	Key-Hole	High I	Low I	
C-276	E154 E155	E146 E147	E144 E145	E156 E157	E158 E159	E105 E104	E111 E110	E164 E165
625	E152 E153	E150 E151	E148 E149	E160 E161	E162 E163	E109 E108	E107 E106	---- ----

TABLE 2

25-6MO Pulsed (120 pps) GMA Pipe Welds (no inserts)
(0.035" diameter filler metal)

Weld Pass	FM	Heat Number	Current (amps)	Wire Feed Speed (ipm)	Background Voltage	Peak Voltage	Travel Speed (ipm)
Root	C-276	ZO786CK	195	475	20.0	425	18.0
Cap*	C-276	ZO786CK	195	475	21.0	425	24.0
Root	625	NX4538AG	180	430	21.0	400	19.5
Cap	625	NX4538AG	180	430	21.0	400	22.5

*** Held Long Arc Length**

TABLE 3

25-6MO Pulsed (120 pps) GMA Pipe Welds (inserts)
(0.035" diameter filler metal)

Weld Pass	FM	Heat Number	Current (amps)	Wire Feed Speed (ipm)	Background Voltage	Peak Voltage	Travel Speed (ipm)
Root#	C-276	Z0783CK	115	N/A	12.0	N/A	4.0
2nd	C-276	ZO753CK	175	425	20.0	360	11.5
3rd	C-276	Z0753CK	160	370	22.5	360	35.0
Root*	625	VX0708AK	115	N/A	12.0	N/A	1.5
2nd	625	NX4538AG	175	425	20.0	360	12.5
3rd	625	NX4538AG	160	370	22.5	360	30.0
Root#	C-276	Z0783CK	75	N/A	10.0	N/A	4.0
2nd	C-276	Z0753CK	175	425	20.0	360	11.5
3rd	C-276	Z0753CK	160	370	22.5	360	35.0
Root*	625	VX0708AK	75	N/A	10.0	N/A	1.5
2nd	625	NX4538AG	175	425	20.0	360	12.5
3rd	625	NX4538AG	160	370	22.5	360	30.0

*** FM 625, 1/16" x 1/8" insert, GTAW root pass only**
 # FM 276, 1/16" x 3/32" insert, GTAW root pass only

TABLE 4

FM C-276, GTAW (With Insert)
(0.062" diameter)

Weld Pass	Dep. Rate in./min.	Current amps	Voltage volts	Travel Speed in./min.	Heat Input kj/in.
Root	0.62	100	10.0	3.1	17.2
2nd	9.90	110	11.0	3.8	18.9
3rd	7.70	110	11.0	2.4	30.2
4th	8.00	110	11.5	2.0	38.0
Root	0.35	72	10.0	3.0	14.7
2nd	5.85	90	9.5	1.9	27.7
3rd	6.26	80	10.0	1.4	34.2
4th	6.50	83	11.0	1.4	40.0

TABLE 5

FM 625, GTAW (With Insert)
(0.062" diameter)

Weld Pass	Dep. Rate in./min.	Current amps	Voltage volts	Travel Speed in./min.	Heat Input kj/in.
Root	8.4	115	11.5	3.41	23.3
2nd	5.5	115	11.0	2.35	32.3
3rd	4.6	115	12.0	2.10	39.4
4th	-	115	12.0	-	-
Root	4.1	78	9.5	3.42	27.6
2nd	2.9	75	10.0	1.20	37.5
3rd	3.4	75	9.5	1.61	39.7
4th	2.1	75	11.0	1.14	43.3

TABLE 6

FM C-276, GTAW (No Insert)
(0.062" diameter)

Weld Pass	Dep. Rate in./min.	Current amps	Voltage volts	Travel Speed in./min.	Heat Input kj/in.
Root	5.2	100	9.5	1.6	35.6
2nd	5.8	125	11.0	2.7	30.5
3rd	6.0	125	11.0	2.8	29.5

TABLE 7

FM 625, GTAW (No Insert)
(0.062" diameter)

Weld Pass	Dep. Rate in./min.	Current amps	Voltage volts	Travel Speed in./min.	Heat Input kj/in.
Root	10.0	100	9.5	2.0	28.5
2nd	7.3	125	11.0	2.9	28.6
3rd	8.3	125	11.0	3.2	26.7

TABLE 8

FM C-276, Keyhole Root, GTAW (No Insert)
(0.062" diameter)

Weld Pass	Dep. Rate in./min.	Current amps	Voltage volts	Travel Speed in./min.	Heat Input kj/in.
Root	4.8	105	11.0	1.5	46.2
2nd	5.8	125	11.0	2.7	30.5
3rd	6.0	125	11.0	2.8	29.5

TABLE 9

FM 625, Keyhole Root, GTAW (No Insert)
(0.062" diameter)

Weld Pass	Dep. Rate in./min.	Current amps	Voltage volts	Travel Speed in./min.	Heat Input kj/in.
Root	4.5	105	11.0	1.7	40.8
2nd	7.3	125	11.0	2.9	28.6
3rd	8.3	125	11.0	3.2	26.2

TABLE 10

Autogenous Root Pass, GTAW, FM C-276 Fill
(0.062" diameter)

Weld Pass	Dep. Rate in./min.	Current amps	Voltage volts	Travel Speed in./min.	Heat Input kj/in.
Root	0	80	9.0	2.0	21.6
2nd	5.8	125	11.0	2.7	30.5
3rd	6.0	125	11.0	2.8	29.5
4th	3.0	125	11.0	4.0	20.6

TABLE 11

ASTM G48A Pitting Corrosion Test Data for Welded alloy 25-6MO 4-1/4" O.D. x 1/4" Wall Pipe Specimens*, Evaluated for 72 Hours at 35°C

Specimen Number	Weld/Comment	Current Level	Pitting		
			Base Metal	Heat Affected Zone	Weld
E105	GTAW C-276 FM/C-276 Ring Insert	High	No	No	No
E111	"	Low	No	No	No
E109	GTAW 625 FM/625 Ring Insert	High	No	No	No
E107	"	Low	No	No	No
E146	GTAW C-276 FM/C-276 Ring Insert	High	No	No	No
E144	"	Low	No	No	No
E150	GTAW 625 FM/625 Ring Insert	High	No	No	No
E148	"	Low	No	No	No
E152	GMAW 625 FM/No Insert	Normal	No	No	No
E154	"	"	No	No	No
E156	GTAW C-276 FM/C-276 Butt Joint	"	No	No	No
E158	"	"	No	No	No
E160	GTAW 625 FM/625 Butt Joint	"	No	No	No
E162	"	"	No	No	No
E164	GTAW C-276 FM/Autogenous Root Pass	"	No	No	No

*** Specimens approximately 1-1/2" square, sanded to a 120 grit surface finish.**

TABLE 12

Modified ASTM G48B Crevice Corrosion Test Data for Welded alloy 25-6MO, 4-1/4"O.D. x 1/4" Wall Pipe Specimens*
Evaluated for 72 hours at 24°C

Specimen Number	Weld/Comment	Current Level	Crevice Corrosion		
			Base Metal	Heat Affected Zone	Weld
E104	GTAW C-276 FM/C-276 Ring Insert	High	No	No	No
E110	"	Low	No	Yes**	No
E108	GTAW 625 FM/625 Ring Insert	High	No	Yes**	Yes**
E106	"	Low	No	Yes**	No
E147	GTAW C-276 FM/C-276 Ring Insert	High	No	No	No
E145	"	Low	No	No	No
E151	GTAW 625 FM/625 Ring Insert	High	No	No	No
E149	"	Low	No	No	No
E153	GMAW 625 FM/No Insert	Normal	No	No	No
E155	"	"	No	No	No
E157	GTAW C-276 FM/C-276 Butt Joint	"	No	No	No
E159	"	"	No	No	No
E161	GTAW 625 FM/625 Butt Joint	"	No	No	No
E163	"	"	No	Yes**	No
E165	GTAW C-276 FM/Autogenous Root Pass	"	No	No	No

* Specimens approximately 1-1/2 inch square, sanded to a 120 grit final surface finish. A 1 inch diameter acetal crevice device, centered 1/2 over the weld and 1/2 over the Heat Affected Zone and base metal. Torque = 55 in.-lbs.

** Incipient attack <1 mil penetration.

TABLE 13

ASTM G48A Pitting Corrosion Test Data for Welded alloy 25-6MO 3/8" Plate Specimens*, Evaluated for 72 Hours at 35°C

Specimen Number	Weld/Comment	Specimen Surface Condition	Pitting		
			Base Metal	Heat Affected Zone	Weld
E74	Autogenous/High Heat Input	Sanded	No	No	No
E75	Autogenous/High Heat Input	Sanded	No	No	No
E76	Autogenous/Low Heat Input	Sanded	No	No	No
E77	Autogenous/Low Heat Input	Sanded	No	No	No

* Specimens l-l/2" x 1-3/4", sanded to a 120 grit final surface finish. A 1" diameter acetal crevice device, centered 1/2 over the weld and l/2 over the Heat Affect Zone and base metal. Torque = 55 in.-lbs.

TABLE 14

Yellow Death* Corrosion Test Data for Welded alloy 25-6MO 3/8" Plate Specimens**, Evaluated for 24 Hours at 35°C

Specimen Number	Weld/Comment	Specimen Surface Condition	Crevice Corrosion		
			Base Metal	Heat Affected Zone	Weld
E140	Autogenous/High Heat Input	Sanded	No	No	No
E141	Autogenous/High Heat Input	Sanded	No	No	No
E142	Autogenous/Low Heat Input	Sanded	No	No	No
E143	Autogenous/Low Heat Input	Sanded	No	No	No

* Yellow Death = 4% NaCl + 0.1% $Fe_2\ (SO)_3$ + 0.01M HCl

** Specimen size 3/4" x l-3/8" with the weld down the center of the short dimension, the sanded samples were finished to a 120 grit surface finish.

TABLE 15

Yellow Death* Corrosion Test Data for Welded alloy 25-6MO 3/8" Plate Specimens**, Evaluated for 24 Hours at 35°C

Specimen Number	Weld/Comments	Specimen Surface Condition	Corrosion Rate		Comment
			mpy	mm/yr	
E132	Autogenous/High Heat Input	With tint	1	0.025	NLC
E133	Autogenous/High Heat Input	With tint	1	0.025	NLC
E134	Autogenous/High Heat Input	Sanded	<1	<0.025	NLC
E135	Autogenous/High Heat Input	Sanded	<1	<0.025	NLC
C136	Autogenous/Low Heat Input	With tint	1	0.025	NLC
E137	Autogenous/Low Heat Input	With tint	1	0.025	NLC
E138	Autogenous/Low Heat Input	Sanded	<1	<0.025	NLC
E139	Autogenous/Low Heat Input	Sanded	<1	<0.025	NLC

* Yellow Death = 4% NaCl + 0.1% Fe_2 $(SO)_3$ + 0.01M HCl

** Specimen size 3/4" x l-3/8" with the weld down the center of the short dimension, the sanded samples were finished to a 120 grit surface finish.

NLC No Localized Corrosion.

TABLE 16

ASTM G28A (Streicher Test) Corrosion Data for Welded alloy 25-6MO 3/8" Plate Specimens*

Specimen Number	Weld/Comments	Specimen Surface Condition	Corrosion Rate	
			mpy	mm/yr
E112	Autogenous/High Heat Input	With tint	16	0.41
E113	Autogenous/High Heat Input	"	15	0.38
E114	Autogenous/High Heat Input	Sanded	15	0.38
E115	Autogenous/High Heat Input	"	15	0.38
E116	Autogenous/Low Heat Input	With tint	16	0.41
E117	Autogenous/Low Heat Input	"	16	0.41
E118	Autogenous/Low Heat Input	Sanded	14	0.36
E119	Autogenous/Low Heat Input	"	14	0.36

* Specimen size 3/4" x 1-3/8" with the weld down the center of the short dimension, the sanded samples were finished to a 120 grit final surface finish.

TABLE 17

EDS Readings and Analysis of Cross Section of Weld Showing Key Element Distribution

Sample Type	Region	Ni Wt%	Cr Wt%	Mo Wt%	Fe Wt%
Transverse Cross Section FM 625 Insert & Filler Metal	Light Etch	61.8	23.6	9.8	4.8
	Dark Etch	52.1	22.1	7.4	18.4
Longitudinal Cross Section FM C-276 Insert & Filler Metal	Dark Etch	37.4	19.5	8.2	32.3
	Light Etch	55.9	17.1	13.4	7.3

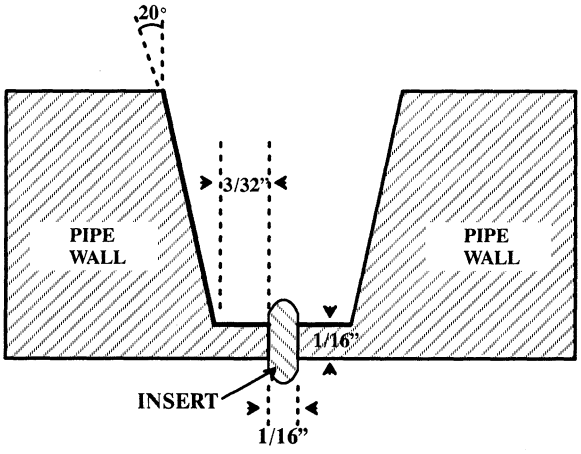


Figure 1. Pipe weld joint design with insert.

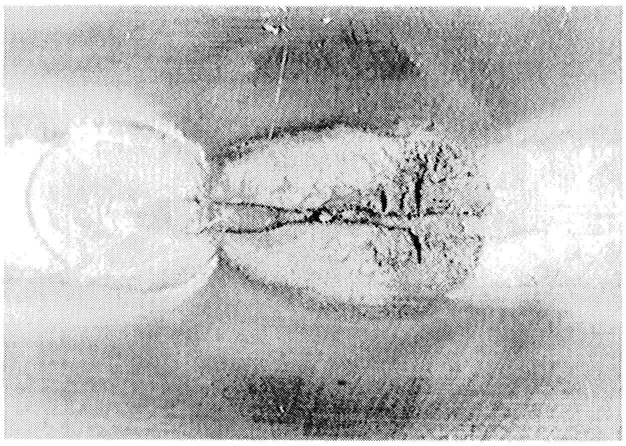


Figure 2. Weld cut-out showing root side of a circumferential pipe weld.

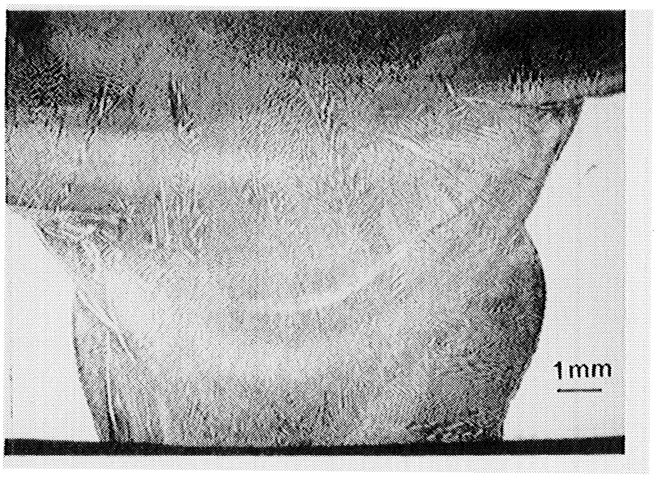


Figure 3. 12.5X Neg. No. 0283AM

Cross Section of a GTA Weld, FM 625 Insert & FM. Low Current, High Heat Input. Etchant: 50% (H_3PO_4+1.5%CrO_3) + 50% H_2O, Electrolytic

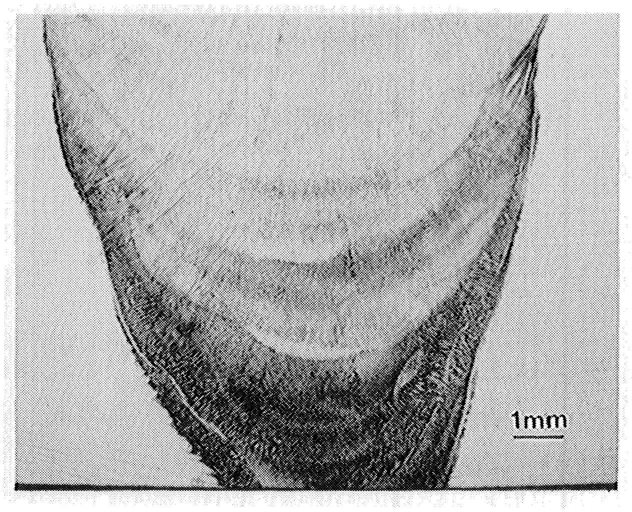


Figure 4. 12.5X Neg. No 0283AM-4

Cross Section of a GTA Weld, FM 625 Insert & FM. High Current, Low Heat Input. Etchant: 50% (H_3PO_4+1.5%CrO_3) + 50% H_2O, Electrolytic

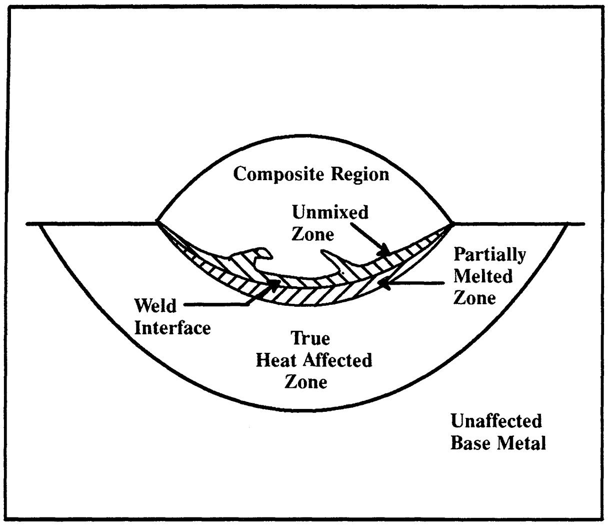


Figure 5. Schematic illustrating location of differing solidification areas in and around a weldment.(11)

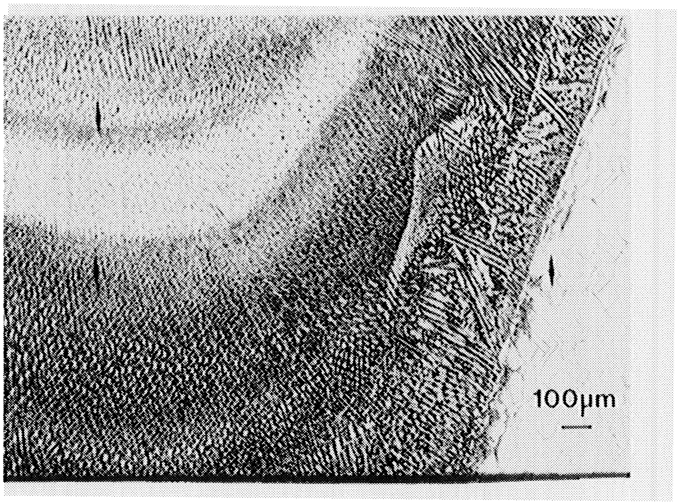
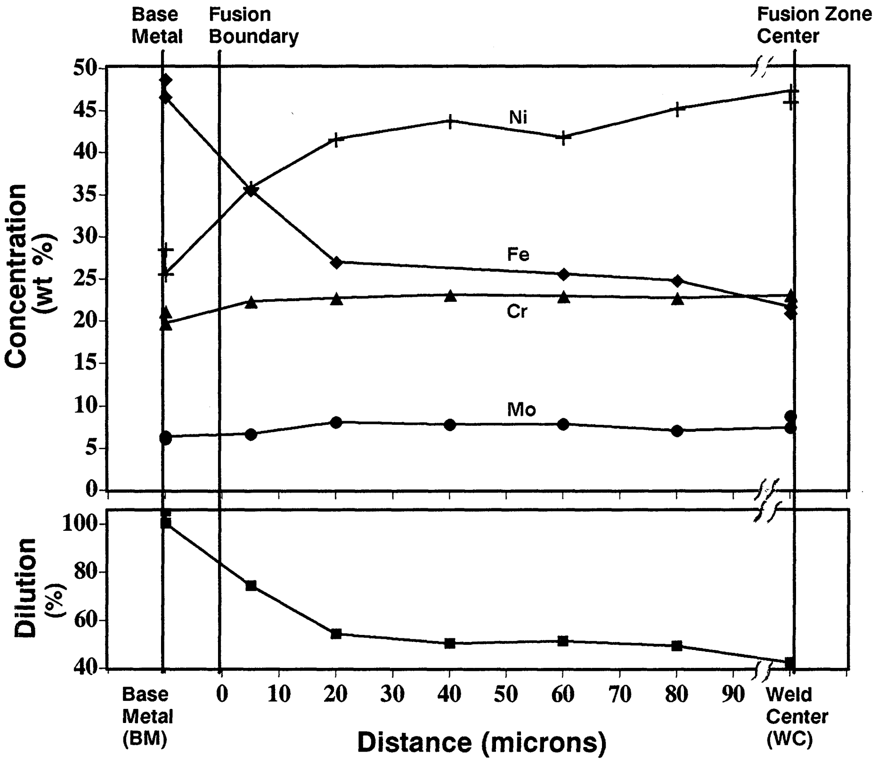


Figure 6. 50X Neg. No. 0283AM-5

Cross Section of a GTA Weld, FM 625 Insert & FM. Etchant: 50% (H_3PO_4 + 1.5%CrO_3) + 50% H_2O, Electrolytic

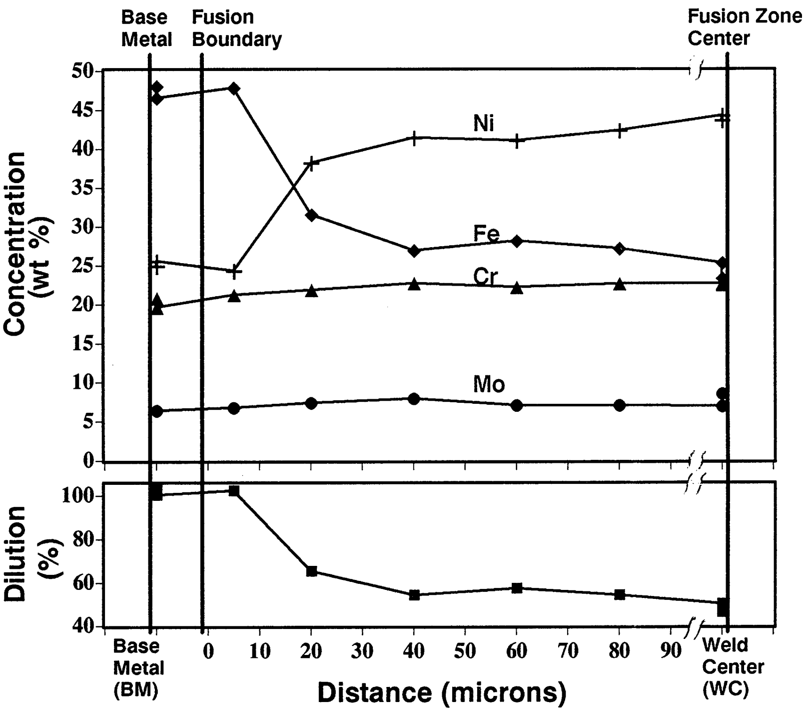
High Current, Low Heat Input, FM 625



Distance (microns)	Dilution (%)	+ Ni	▲ Cr	◆ Fe	● Mo
BM Heat Analysis	100	25.5	19.6	46.5	6.3
BM SEM	105	24.4	21.0	48.6	6.0
5	74	35.7	22.2	35.5	6.6
20	54	41.5	22.6	26.9	8.0
40	50	43.7	23.0	25.0	7.7
60	51	41.7	22.8	25.5	7.8
80	49	45.1	22.6	24.7	7.0
WC #1	42	47.2	22.9	21.5	7.3
WC #2	40	45.9	23.0	20.8	8.7

Figure 7. Graph and Table of EDS Traverse Results from Corrosion Sample E109

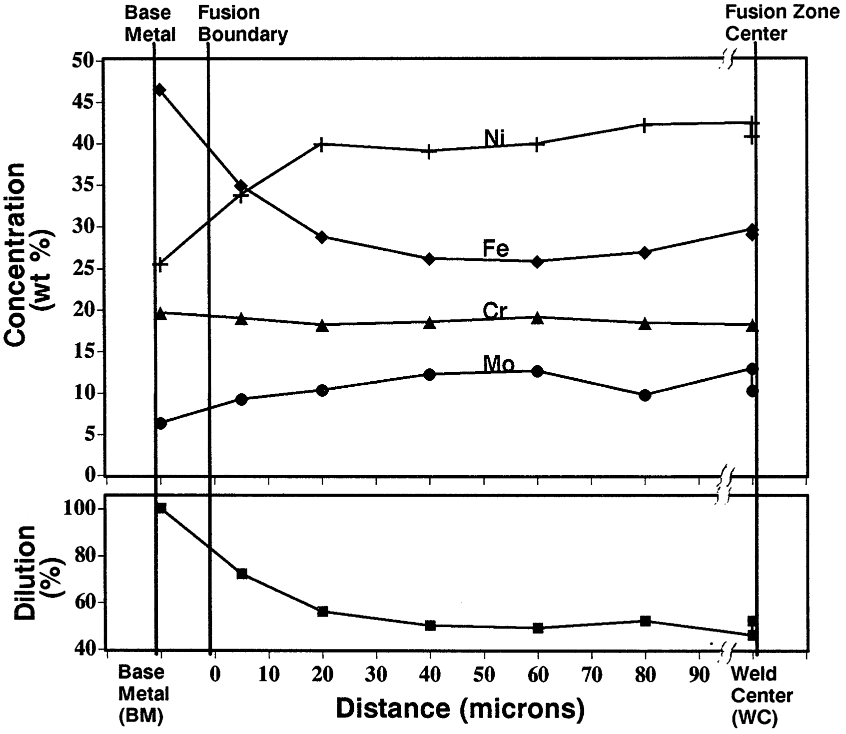
Low Current, High Heat Input, FM 625



Distance (microns)	Dilution (%)	+ Ni	▲ Cr	◆ Fe	● Mo
BM Heat Analysis	100	25.5	19.6	46.5	6.3
BM SEM	105	24.9	20.8	48.0	6.3
5	102	24.3	21.2	47.8	6.7
20	65	38.2	21.8	31.5	7.3
40	54	41.4	22.7	26.9	7.9
60	57	41.8	22.2	28.1	7.0
80	54	42.3	22.6	27.1	7.0
WC #1	50	44.2	22.7	25.3	6.9
WC #2	46	43.6	22.5	23.3	8.5

Figure 8. Graph and Table of EDS Traverse Results from Corrosion Sample E107

High Current, High Heat Input, FM C-276



Distance (microns)	Dilution (%)	+ Ni	▲ Cr	◆ Fe	● Mo
BM Heat Analysis	100	25.5	19.6	46.5	6.3
BM SEM	100	24.2	20.9	48.3	6.3
5	72	33.7	19.0	34.9	9.2
20	56	39.7	18.2	28.7	10.3
40	50	39.1	18.5	26.1	12.2
60	49	38.4	19.1	25.8	12.6
80	52	41.8	18.4	26.9	9.7
WC #1	46	42.4	18.2	24.6	10.9
WC #2	52	40.8	18.2	27.0	10.2

Figure 9. Graph and Table of EDS Traverse Results from Corrosion Sample E105

Figure 10. **12.5X** **Neg. No. 0283AM–8**

Longitudinal Cross Section of a Weld FM C–276 Insert and FM. Etchant: Kane's, Swab