FORGING AHEAD

PCC METALS GROUP

INCONEL Filler Metal 680

PCC Proprietary & Confidential Information

PCC ENERGY GROUP

AGENDA

- Acknowledgements and Introduction
- Alloy Development
- Welding Procedure Development
- Properties and Actual Performance
- Summary and Conclusions

SPECIAL METALS WELDING PRODUCTS

- INCONEL filler Metal 625
- INCONEL Filler Metal 686CPT
- INCONEL filler Metal 725NDUR
- INCONEL Filler Metal 622
- INCONEL filler Metal 680

ARC SPECIALTIES ID CLAD X-70 WITH 625

- **Dan and Dave Hebble applied their Tri-pulse technology with INCONEL Filler Metal 625 under controlled conditions such that the 0.2% YS of the X-70 averaged 80.75 ksi after cladding.**

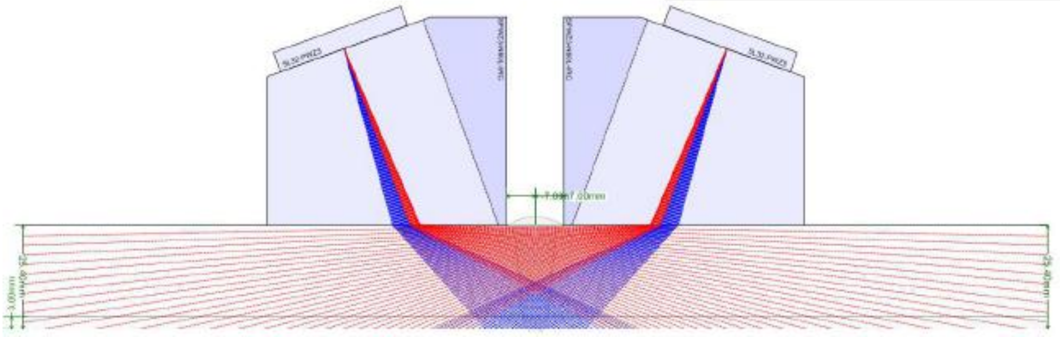
CRC-EVANS P-GMAW NARROW GROOVE WELD

This is a cross section of a rollout narrow groove weld made with an early FM 680 in X-65. The orbital weld that CRC-Evans made in the X-70 pipe clad by Arc Specialties appears later.

CRC-EVANS P-GMAW PAUT INSPECTION

- The phased array ultrasonic inspection is capable of finding even the smallest discontinuities

- ….but I am getting ahead of our discussion…..



WHY WE DEVELOPED INCONEL FM 680

- **Allows use of higher strength steel tubing for weight and cost reduction**
- **Provides 100% joint efficiency for X-70 and some X-80 tubing**
- **No other welding product available was able to provide the combination of properties needed to weld X-70 and X-80**
- **Delivers optimal combination of strength, toughness and hardness.**

WHY WE DEVELOPED INCONEL FM 680

SPECIAL METALS

- Improved corrosion resistance for reliable service, even in sourest crudes
- Increased as-welded hardness provides improved abrasion resistance and denting resistance
- Provides 20ºC higher critical crevice temperature (CCT) than 625

PROPOSED APPLICATIONS

- Joining X-70 and X-80 pipe strings
- Valve and ring groove overlays (allows the use of 625 ring gasket vs 825)
- Subsea and land based ID pipe overlays
- Ball valve overlays for improved galling resistance
- Metal-to-metal seals due to improved crevice corrosion resistance

PROPOSED APPLICATIONS

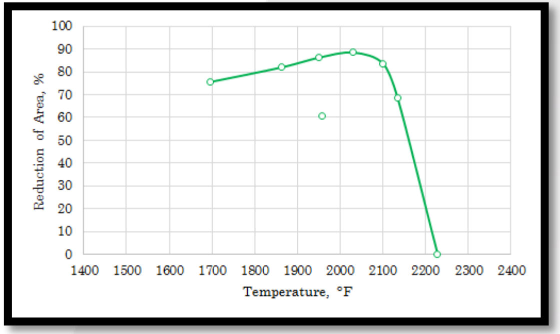
- Riser connections and tie-backs
- Manifold fabrication and connections
- Frac Valve and drill collar refurbishment
- After PWHT, provides better erosion resistance for fracking applications
- Reeling applications after CTOD-SENT improvement

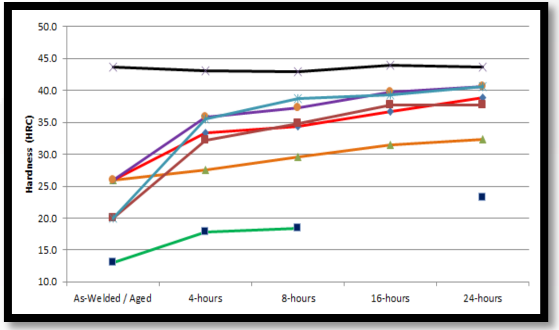
INCONEL FILLER METAL 680-ALLOY DESIGN

- Ni-20.5Cr-6.5Mo-3.5Nb-6.5W-1.5Ti alloy (UNS N06680-AWS A5.14 ERNiCrMoWNb-1) approved
- High Yield Strength in as-welded condition
- High Impact strength at sub-zero temperatures
- Higher Corrosion Resistance than 625 weld overlay

INCONEL FILLER METAL 680-ALLOY DESIGN

- Good weldability to X-65, X-70, and X-80
- High resistance to solidification cracking
- Excellent ductility dip cracking resistance predicted by Gleeble® results
- Greater as-welded hardness than 625 and 718; provides improved denting resistance
- Hardenable by PWHT, but controllable by time and temperature





NI-CR-MO CHEMICAL COMPOSITIONS

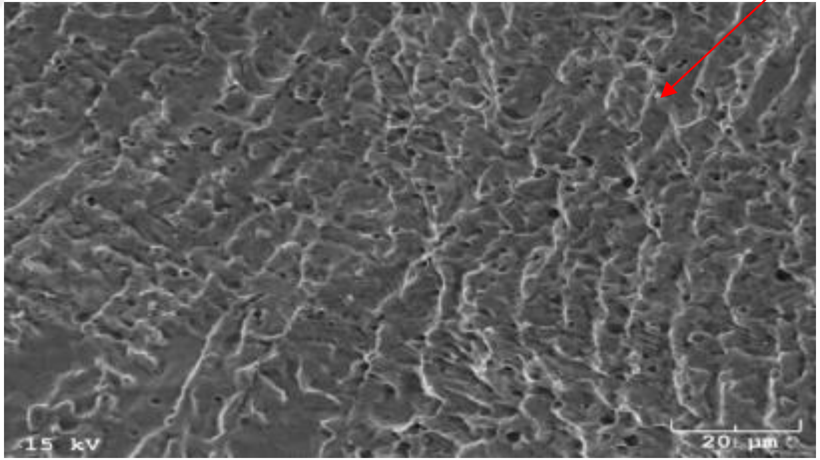
Alloy	AWS A5.14	Ni	Cr	Fe	Mo	W	Nb	PRE
686	ERNiCrMo-14	59.5	21	0.1	16.3	4	-	51.5
622	ERNiCrMo-10	57.3	21.5	2.33	14.2	3.2		47.6
680	**ERNiCrMoWNb-1**	**60**	**21.5**	**0.1**	**6.5**	**6.5**	**3.5**	**45.3**
725	ERNiCrMo-15	57	21.5	<1	8.5		3.5	39.5
625	ERNiCrMo-3	Bal	21.5	0.61	9	-	3.5	40.3

PRE = %Cr+1.5 (%Mo+%W+%Nb)

IMPACT TEST RESULTS: FRACTURE SURFACES

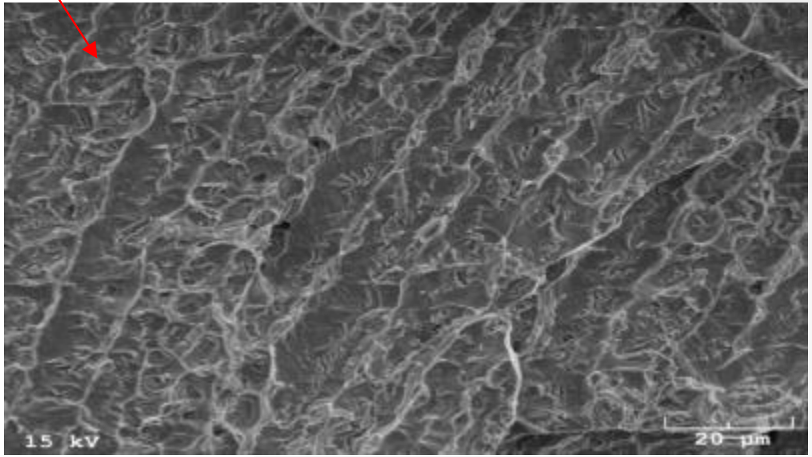
Precipitates

FM680 welded in alloy 600



Impact toughness = 137 ft-lbs (186 Joules). Fe content is 1.5 wt%

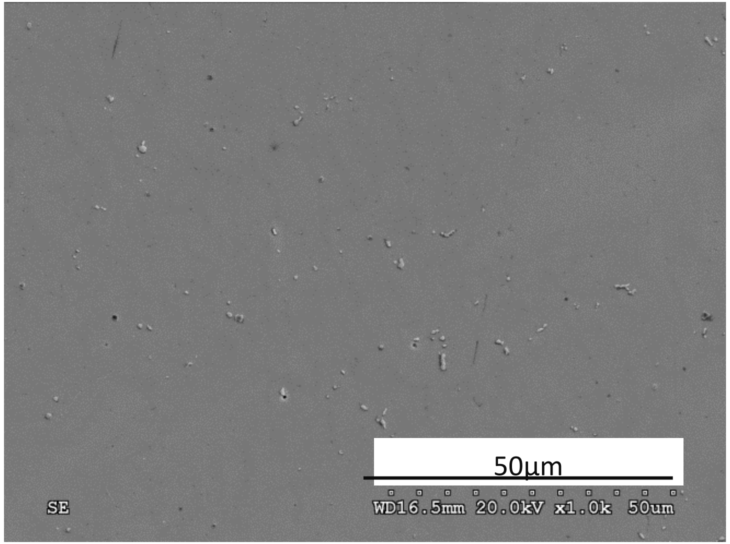
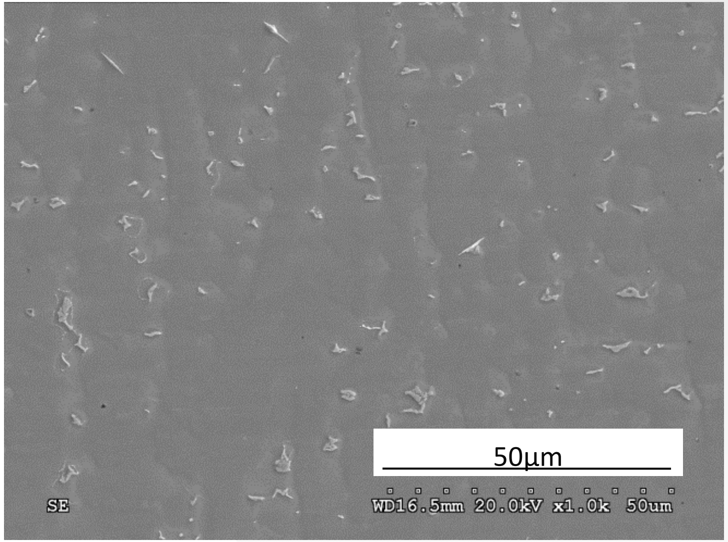
FM680 welded in X-65 steel



Impact toughness = 43 ft-lbs (58 Joules). Fe content is 9.4 wt%

SEM photos of fracture surfaces of impact tested samples from mid-wall of the welds

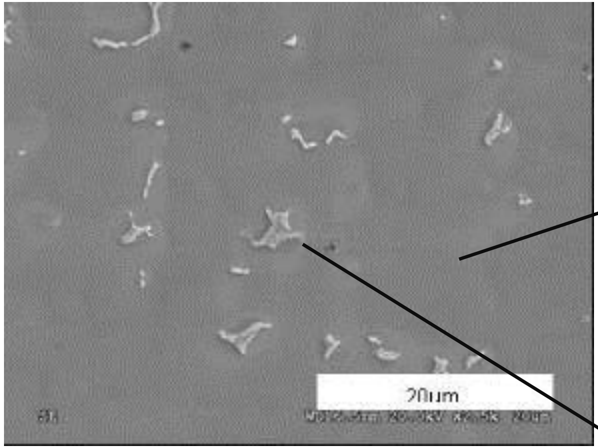
IMPACT TOUGHNESS RESULTS

FM680 welded in alloy 600	FM680 welded in X-65 steel
	
Impact toughness = 137 ft-lbs (186 Joules). Fe content is 1.5 wt%	*Impact toughness = 43 ft-lbs (58 Joules). Fe content is 9.4 wt%*

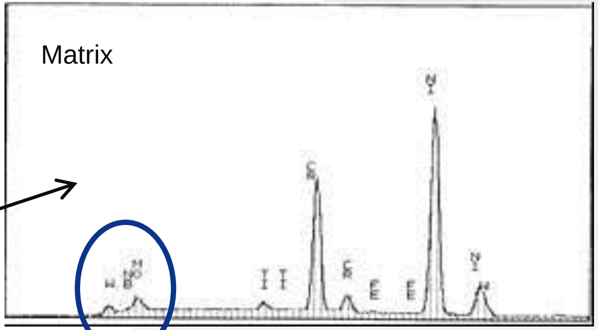
SEM photos of mounted and etched samples of root of the weld

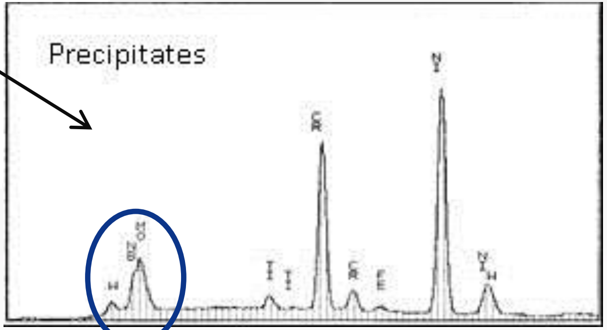
MICROSTRUCTURE ANALYSIS RESULTS

Elements	Matrix, wt%	Second phase particle, wt%
Ti	0.7	0.8
C	1.7	1.2
W	**4.6**	**6.9**
Nb	**3.7**	**17.2**
Mo	**7.3**	**15.7**
Cr	18.5	14.5
Fe	11.9	8.13
Ni	51.6	35.5

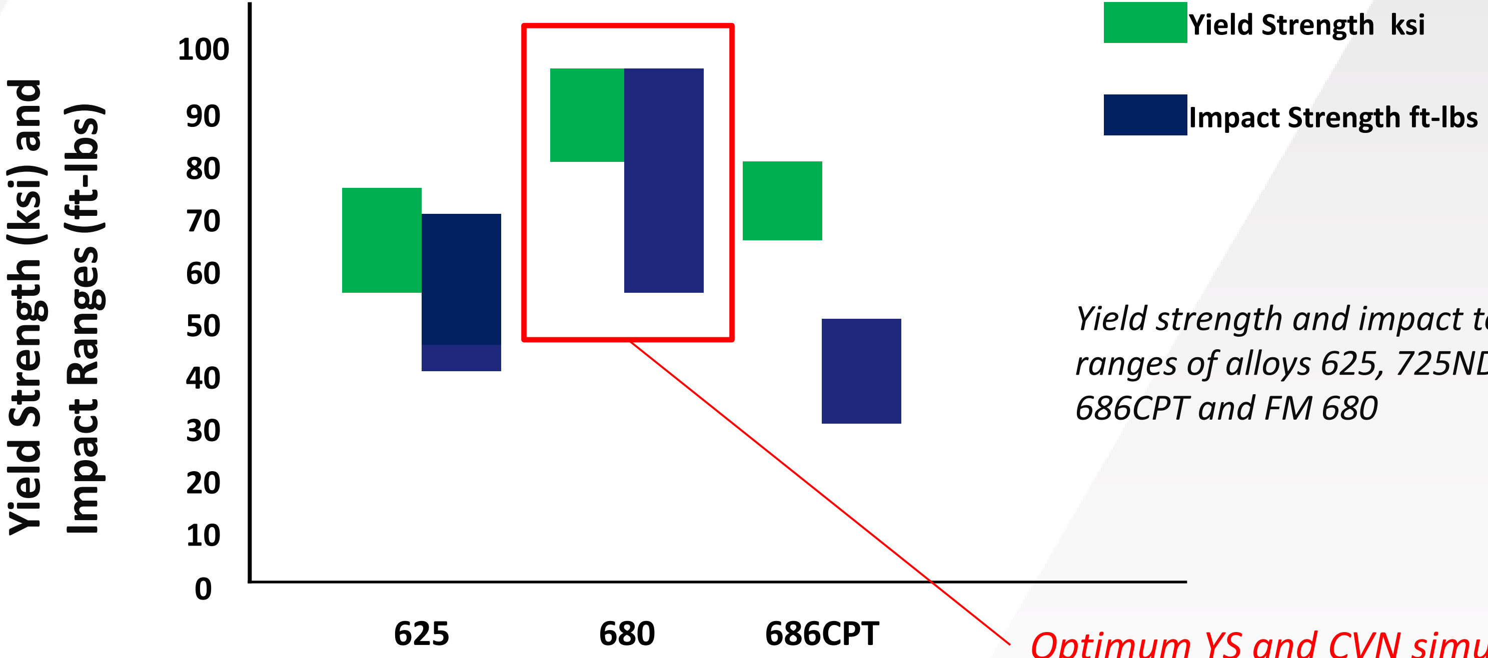


Microstructure of weld metal of X-65 steel, welded with FM680. The second phase precipitates in the weld are rich in Mo, W, and Nb.





YIELD STRENGTH AND IMPACT TOUGHNESS



Yield strength and impact toughness ranges of alloys 625, 725NDUR, 686CPT and FM 680

Optimum YS and CVN simultaneously

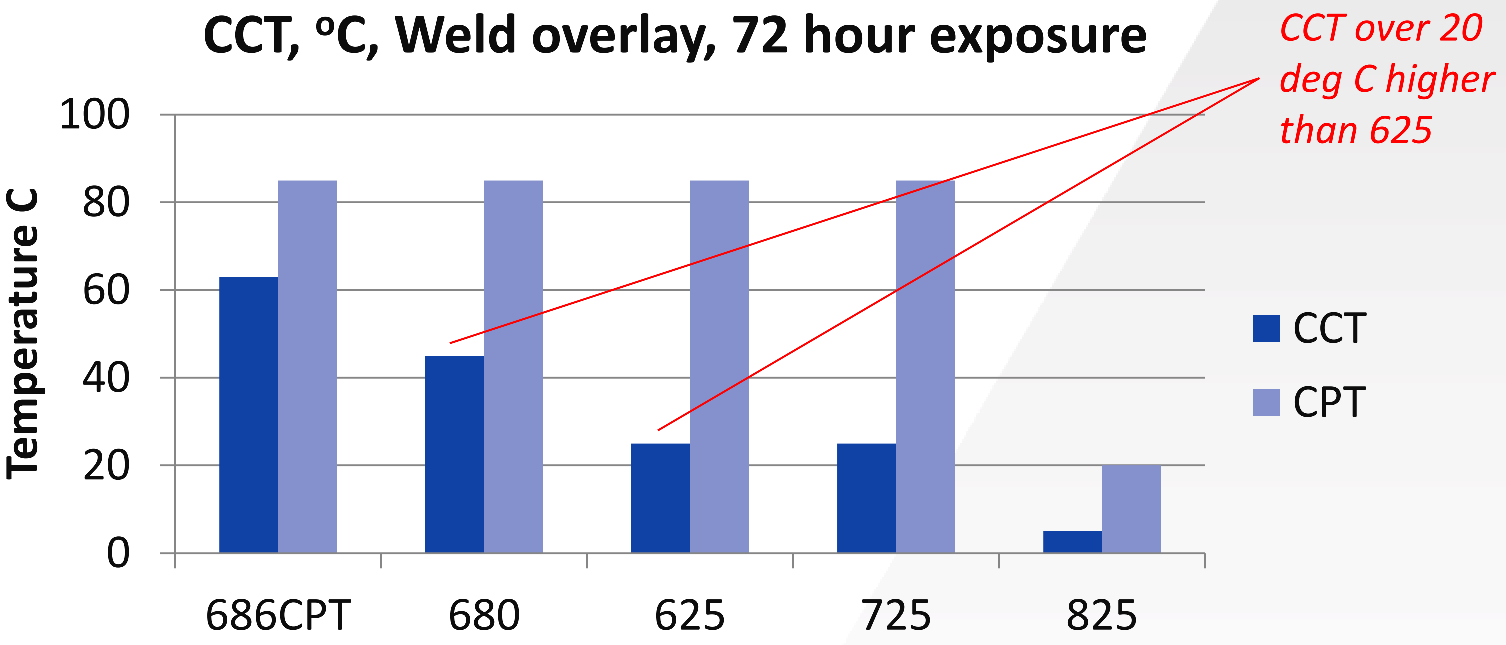
ASTM G48D ACTUAL TEST RESULTS

SPECIAL METALS

The following actual test results show how 680 performs better than 625 in CCT:

Filler Metal	Temperature °C (°F)	Crevice Attack (Y/N)	Max Depth of Attack Mils (mm)	Comments
625	20 (68)	N	No Attack	-------
625	25 (77)	Y	2 (0.051)	2 areas (8%)
625	25 (77)	Y	3 (0.076)	2 areas (8%)
680	20 (68)	N	No Attack	
680	25 (77)	N	No Attack	-------
680	25 (77)	N	No Attack	-------
680	30 (86)	N	No Attack	-------
680	35 (95)	N	No Attack	-------
680	40 (104)	N	No Attack	-------
680	45 (113)	Y	3	3 areas (12%)
Critical Crevice Temperature (CCT) of Alloy 625 Overlay = 25°C (77°F) Critical Crevice Temperature (CCT) of Alloy 680 Overlay = 45°C (113°F)				

CREVICE CORROSION RESISTANCE- ASTM G48D



20% IRON DILUTION COMPROMISES STRENGTH

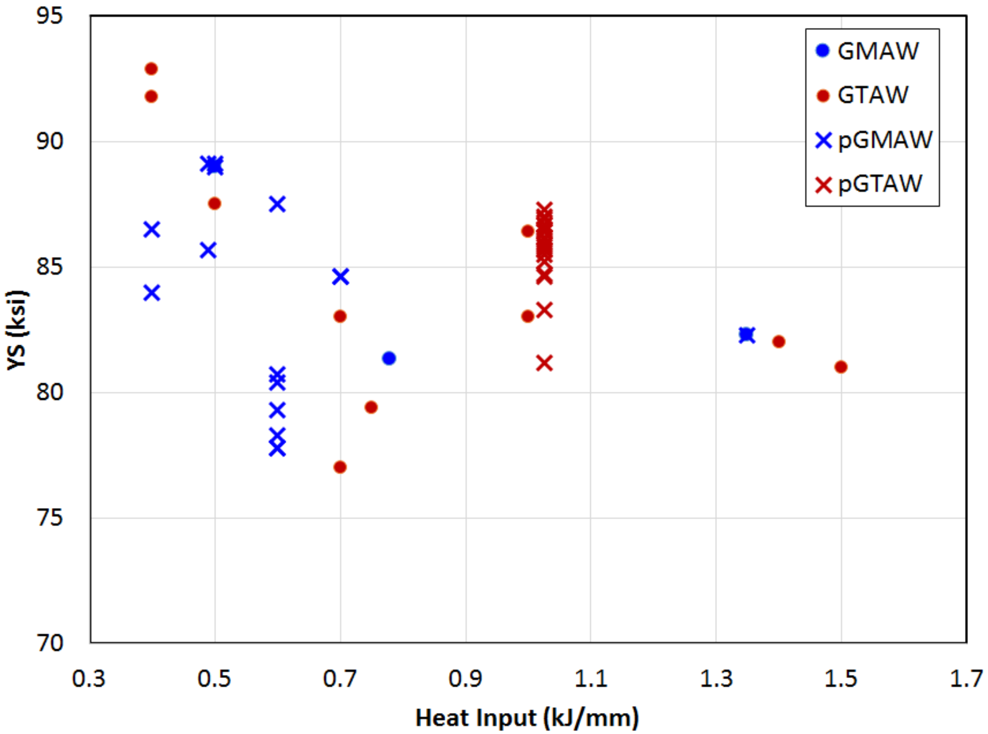
Welding details	YS, ksi (MPa)	UTS, ksi (MPa)	% El	% RA	CVN Impact toughness, ft-lbs (Joules)	Fe content, wt%
GTAW AWM, 680 in alloy 600	87.7 (605) 85.5 (589) 92.9 (641) 91.8 (633)	130.0 (896) 129.0 (890) 134.0 (924) 129.0 (890)	43.0 43.2 33.0 31.3		137.0 (186)	1.5%
GMAW-P TW, 680 in X-80 steel	81.1 (560) 80.9 (558)	91.8 (633) 91.2 (629)	22.4 23.1	80.8 80.4	80.2 (109)	0.56
GMAW-P AWM, 680 in X-80 steel	85.7 (591) 89.1 (614)	118.4 (816) 120.1 (828)	35.6 31.0	41.5 39.1		0.99
GTAW AWM, 680 in A36 steel	70.9 (489) 68.4 (472) 70.7 (488) 70.0 (483)	114.4 (789) 115.7 (798) 115.3 (795) 119.3 (823)	28.3 32.9 25.5 32.6	32.9 31.8 29.2 36.7		20.0
X-70 base metal	81.2 (560) 80.8 (557)	92.1 (635) 91.4 (630)	26.9 26.6	80.1 80.5		N/A

GUIDELINE WELDING PARAMETERS

Welding Process	Manual GMAW-P	Semi-Auto GTAW	Manual GTAW
Amperage, A	105-200	125-180	80-120
Voltage, V	25-31	12-15	9-10
Travel Speed, inch per minute (mm/min)	10-27 (254-689)	8-10 (203-254)	5.5-6.5 (165-140)
Wire Speed, inch per minute (mm/min)	200-275 (5080-6985)	25-50 (635-1270)	5-10 (127-254)
Heat Input, kJ/mm	0.30-1.46	0.44-0.63	0.35-0.45

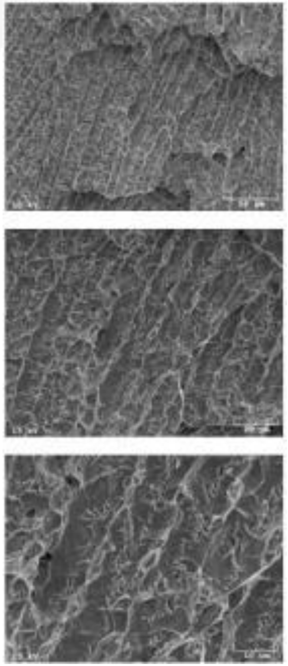
Note : Joint Design was Single V 25° Bevel. Shielding Gas was 50/50 Argon/Helium.

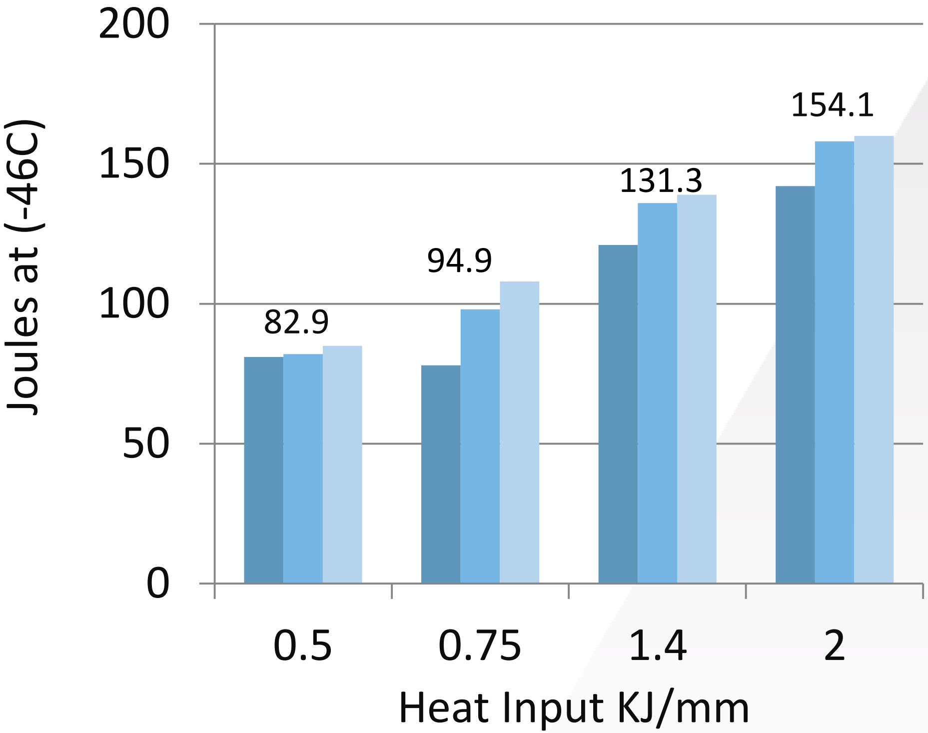
YIELD STRENGTH AND HEAT INPUT TRENDS



Yield strength data are actuals observed across a wide variety of heat inputs, setups and base metals.

IMPACT STRENGTH: A FUNCTION OF HEAT INPUT





Impact Strength FM 680 welds as a Function of heat input

< 5% Fe Dilution

TENSILE PROPERTIES: X-65 PIPE JOINT

For ASME Section IX these are passing results, but for welding research, it does not tell anything about weld metal strength…

GTAW Tensile (T-3 & T2) - Utilizing X65 Pipe w/HV1654 (As-Welded) from SMWPC						
ID*	Sample	Yield (Ksi)	UTS (Ksi)	% Elongation	ROA %	Failure
Phase -1 #1	T3	72.3	91.5	23.6	75.4	Base Metal
Phase -1 #2	T3	72.6	91.9	24.8	72.6	Base Metal
Phase -1 #1	T2	78.7	95.3	22.2	76.0	Base Metal
Phase -1 #2	T2	76.6	94.1	25.2	76.8	Base Metal
Phase -2 #1	T3	74.1	92.2	23.2	75.0	Base Metal
Phase -2 #2	T3	73.9	92.8	23.8	75.4	Base Metal
Phase -2 #1	T2	80.9	98.1	21.6	74.4	Base Metal
Phase -2 #2	T-2	77.6	94.8	19.85	75.1	Base Metal

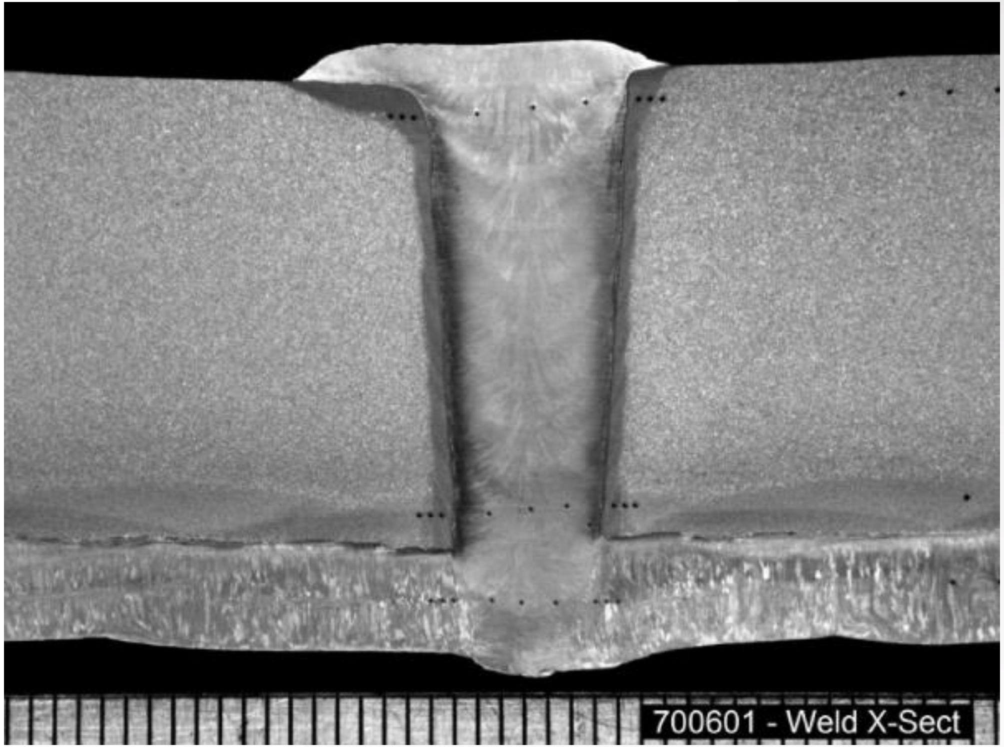
CROSS WELD TENSILE SPECIMENS

Weld

All the cross weld tensile specimens broke in the base metal

CROSS WELD TENSILE SPECIMENS

- CRC Evans orbital pulsed GMAW narrow-groove weld made with FM 680. ID-cladding of X-70 made with FM625 by Arc Specialties.

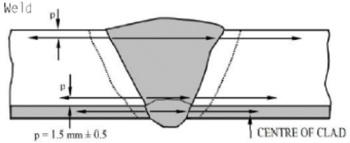


CRC-EVANS P-GMAW HARDNESS SCAN

- **Highest hardness in the weld scan is 296 Vickers.**

Hardness Survey - ASTM E92-16

Item 008: Weld



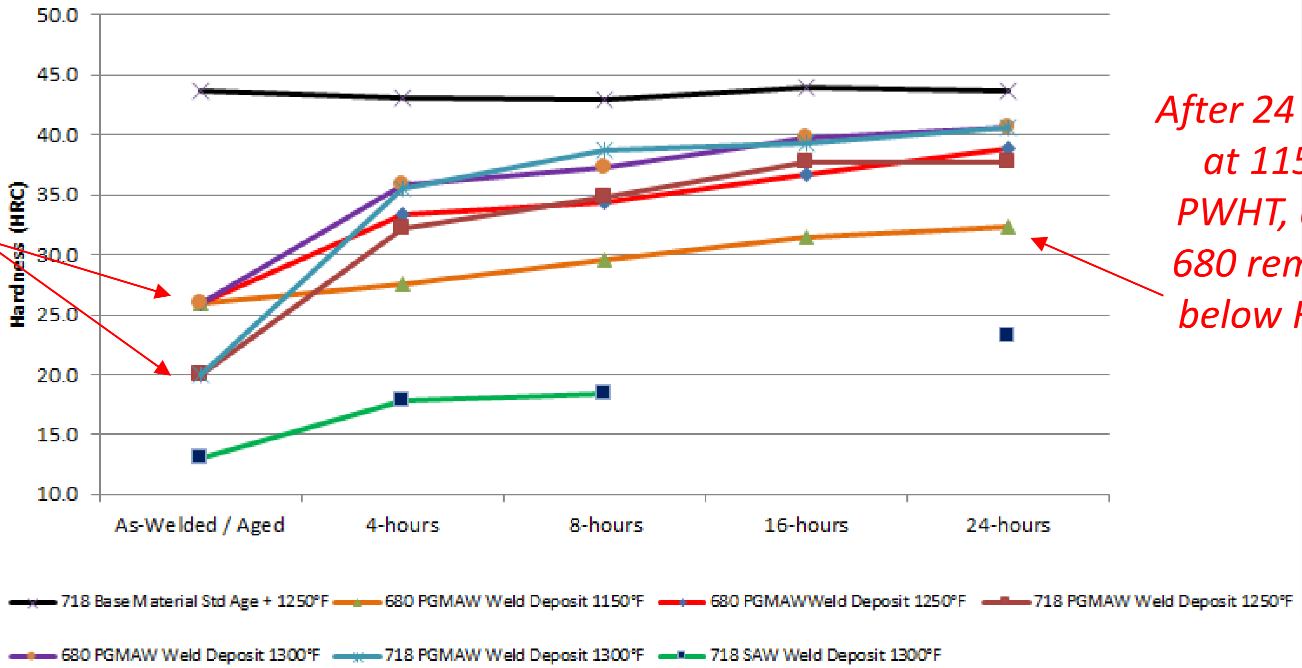
10 Kg Vickers Hardness Survey

Position	Spacing	Cap	Root	Overlay
Base	2.0mm	1) 211	16) 197	31) 244
		2) 210	17) 195	32) 241
		3) 210	18) 194	33) 242
HAZ	0.5mm	4) 203	19) 204	34) 236
		5) 211	20) 217	35) 244
		6) 222	21) 220	36) 254
Weld	Equal	7) 235	22) 269	37) 267
		8) 268	23) 296	38) 268
		9) 258	24) 267	39) 257
HAZ	0.5mm	10) 212	25) 220	40) 277
		11) 225	26) 205	41) 287
		12) 212	27) 200	42) 274
Base	2.0mm	13) 218	28) 192	43) 242
		14) 220	29) 197	44) 210
		15) 225	30) 187	45) 223

Cap and Root Traverses taken 1.5mm from the surface.
Overlay Traverse taken at the center of the cladding.

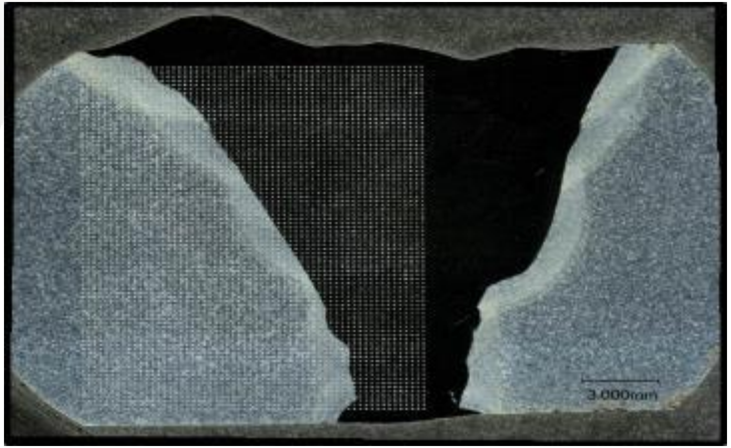
PWHT OF 680 VS. 718

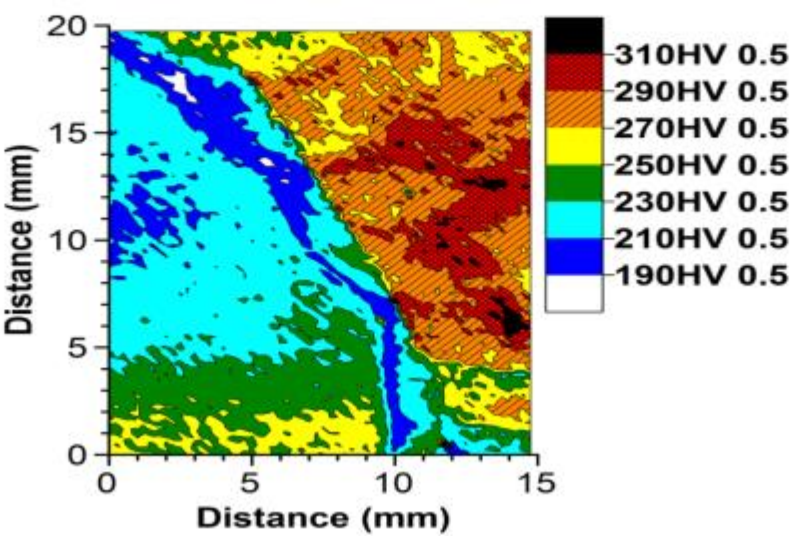
As-welded hardness of alloy 680 exceeds alloy 718 by 6 R_c points.



After 24 hours at 1150F PWHT, alloy 680 remains below R_c 35

HARDNESS SURVEY, X-80 BASE METAL





<u>Hardness Parameters:</u>

- *Vickers, 500g load*
- *0.25 mm spacing*
- *4800 Total indents*
- *Area mapped is 300 mm2*
- *(20 mm tall by 15 mm wide)*

Hardness Survey of X-80 steel welded with FM680 using GMAW-P process. No hardness greater than R_c 35.

EARLY MECHANICAL PROPERTIES: 600, X-80

Welding details	Yield Strength, ksi (MPa)	% Elong	CVN Impact toughness, ft-lbs (Joules)	Fe content, wt%
GTAW **AWM**, 680 in alloy 600 **MANUAL**	87.7 (605) 85.5 (589) 92.9 (641) 91.8 (633)	43.0 43.2 33.0 31.3	137.0 (186)	1.5%
GMAW-P **AWM**, 680 in X-80 steel	85.7 (591) 89.1 (614)	35.6 31.0	-	0.99
GMAW-P **TW**, 680 in X-80 steel	81.1 (560) 80.9 (558)	22.4 23.1	80.2 (109)	0.56

Alloy 600 is Ni-16Cr-9.5Fe. X-80 steel is primarily Fe

Mechanical properties of weldments with alloy 600 and X-80 steel welded using FM680

EARLY MECHANICAL PROPERTIES: X-65

Welding details	Yield Strength, ksi (MPa)	% Elong	Impact toughness ft-lbs (Joules)	Fe content wt%
GTAW **AWM**, 680 in ID clad X-65	84.7 (593) 85.8 (592) 84.6 (593)	45.3 43.8 46.9	74.3 (101)	0.3
GTAW **TW**, 680 in ID clad X-65	81.5 (562) 86.7 (598) 82.7 (570) 82.2 (567)	23.2 23.3 21.1 21.5	42.8 (58)	9.4

Mechanical properties of ID-clad (alloy 625) X-65 steel welds, welded using FM680

CTOD-SENB TESTING

INCONEL FM 680 provides good values for single edge notched bending (SENB) values well above acceptable values of .25-.30mm. Values measured in pulsed GTAW and pulsed GMAW welds made in X-65 were on the order of 0.8-0.9mm.

Average Crack Length [mm]	25.33
a_0/w	0.522
Fracture Mode	M
Average Stable Crack Length [mm]	N/A
Test Temperature [^{0}C]	0
0.2%Proof Stress@Test Temp[N/mm^2]	617
Rate inc init. SIF [$MPam^{0.5}s^{-1}$]	1.6
Knife Edge Thickness [mm]	0
Applied Force [kN]	57.61
Clip Gauge Opening - Plastic [mm]	3.46
Crack Tip Opening Displacement [mm]	0.982

CTOD-SENB TESTING

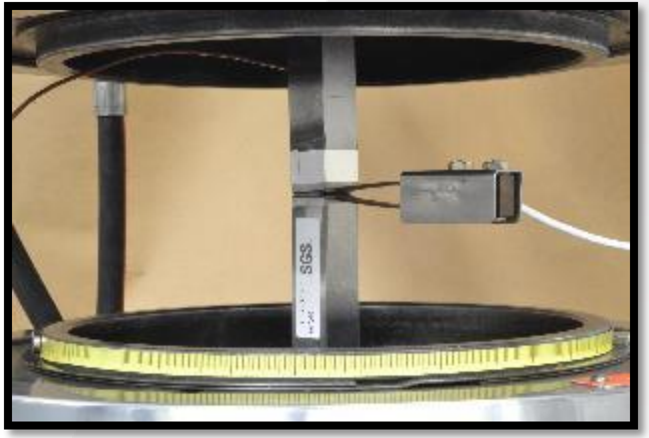
INCONEL FM 680 provides good values for single edge notched bending (SENB) values well above acceptable values of .25-.30mm. Values measured in pulsed GTAW and pulsed GMAW welds made in X-65 were on the order of 0.8-0.9mm.

Average Crack Length [mm]	25.93
a_0/w	0.534
Fracture Mode	M
Average Stable Crack Length [mm]	N/A
Test Temperature [°C]	0
0.2%Proof Stress@Test Temp[N/mm^2]	606
Rate inc init. SIF [$MPam^{0.5}s^{-1}$]	1.7
Knife Edge Thickness [mm]	0
Applied Force [kN]	57.23
Clip Gauge Opening - Plastic [mm]	3.39
Crack Tip Opening Displacement [mm]	0.935

CTOD-SENT TESTING

- J-R Curves produced from CTOD-single edge notched tensile specimens produced a J-R fracture toughness curve that was about 30% lower than expected.

- Metallographic investigation has been completed and a program to improve the SENT fracture toughness is in progress.



FURTHER WORK

- Complete development of improved CTOD-SENT properties
- Develop additional tensile data to complete our data base
- Perform tensile testing on higher strength base metals to measure our actual tensile and yield strengths in transverse tests
- Explore and develop the auto-aging components of as-welded Yield Strength
- Tell us more about what data you will need for your work

SUMMARY AND CONCLUSIONS

- INCONEL Filler Metal 680 provides optimum combination of high yield strength, good -50F CVN toughness simultaneously, along with better crevice corrosion resistance than 625
- Low Fe Dilution and low Heat Input produces highest strength and good toughness
- CTOD-SENB results are good and provide for the use of FM 680 to be used in “S-Lay” and “J-Lay” pipe string installation
- CTOD-SENT is in the process of being improved

FORGING AHEAD

QUESTIONS?

PCC ENERGY GROUP