Challenges Associated with Welding for Hydrogen Service and a Case Study

2023 APGA Conference
Perth, Australia
October 17, 2023

CRC EVANS

MICRO ALLOYING

Presentation Outline

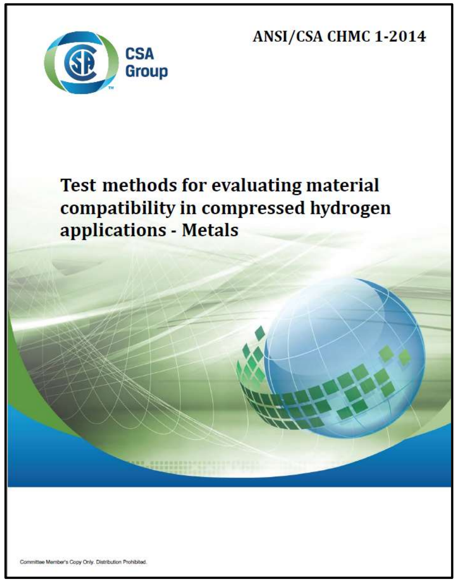
- Hydrogen Pipelines
  - Girth Weld Fracture Performance
- Hydrogen Transport Ships
  - Seam Weld Fatigue Performance

Hydrogen Pipelines

- Major Concern with Hydrogen Pipelines is Girth Weld Performance.
    - Potential for High Local Strains / Stress
    - Presence of Girth Weld Hi-Lo Misalignment
    - Potential Presence of Girth Weld Flaws
- Unlike Liquid Pipelines, Gas Pipelines generally experience Low Fatigue Demand, particularly girth welds.
- Major concern is Fracture at Girth Welds due to High Local Stress and Reduced Toughness.
- CRC is actively engaged in the API 1104 Hydrogen Task Group to develop Girth Weld Qualification Requirements for Hydrogen Pipelines

Hydrogen Fracture Toughness Test Methods

1) ASME B31.12 – 2019 " Hydrogen Piping and Pipelines"
    - Constant Load or Constant Displacement Tests
2) ANSI / CSA CHMC 1-2014, "Test methods for Evaluating Material Compatibility in Compressed Hydrogen Applications – Metals"
    - Slow Rising Load Tests



CSA Group

ANSI/CSA CHMC 1-2014

Test methods for evaluating material compatibility in compressed hydrogen applications - Metals

Committee Member's Copy Only. Distribution Prohibited.

Fracture Toughness Tests in Hydrogen

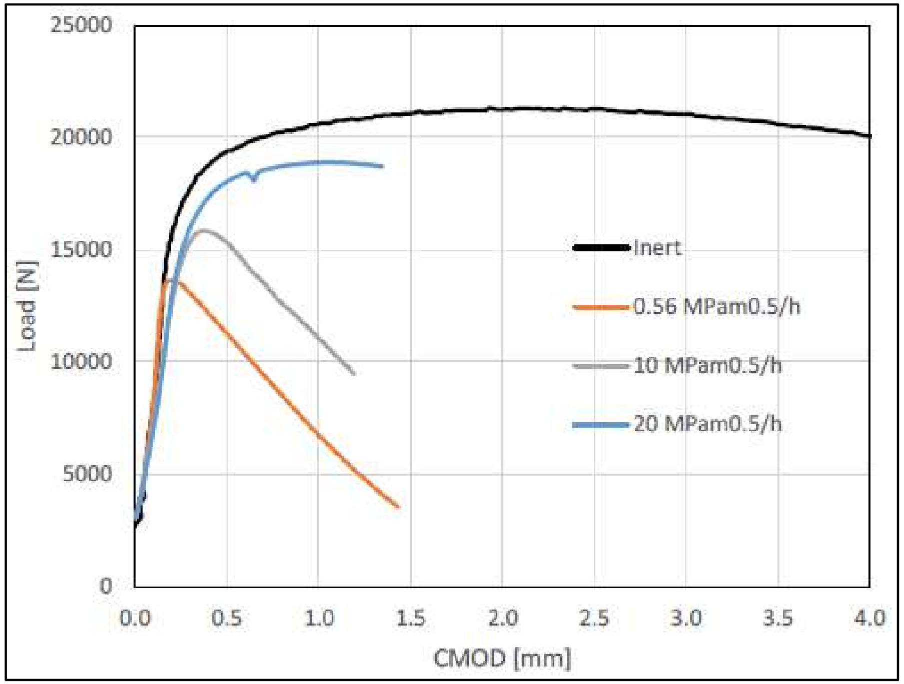
ASME B31.12 – 2019:

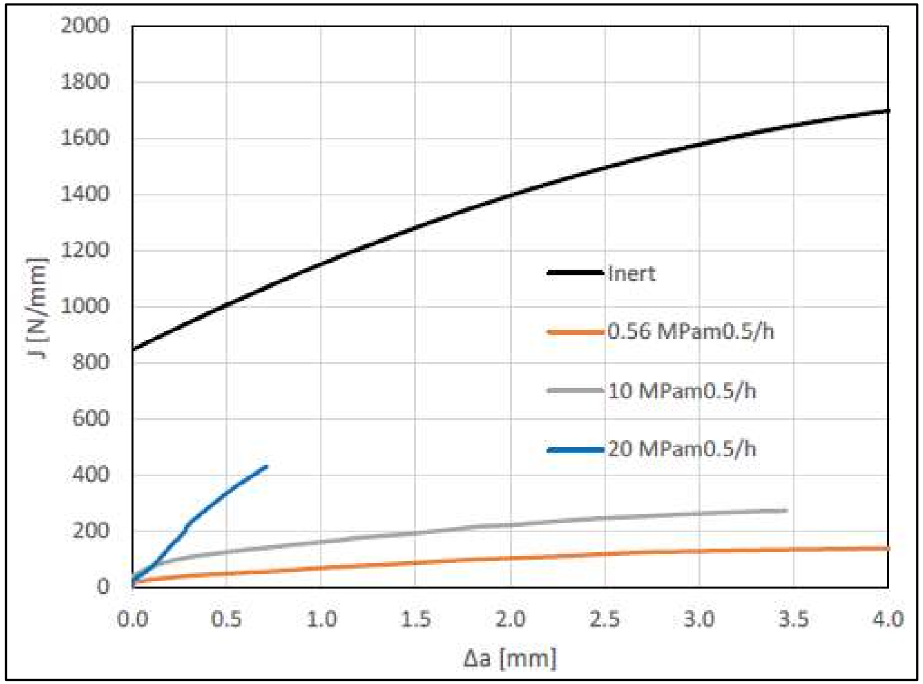
- ASME B31.12 may be well suited for Heavy Wall pressure vessel applications but not hydrogen pipelines (Thinner Wall).
- ASME B31.12 should be limited to ranking materials and demonstrate hydrogen compatibility.

ANSI / CSA CHMC 1-2014

- ANSI / CSA CHMC 1-2014 is much closer to Best Practice.
  - Slow Rising Load Tests (0.1 – 1.0 MPa√m/minute)
  - Underlying Standard ASTM E1820 (J / CTOD)
  - CT or SENB Specimens
  - Initiation Toughness defined as $J_{0.2/BL}$ or $CTOD_{0.2/BL}$

Hydrogen Embrittlement (DNV JIP)





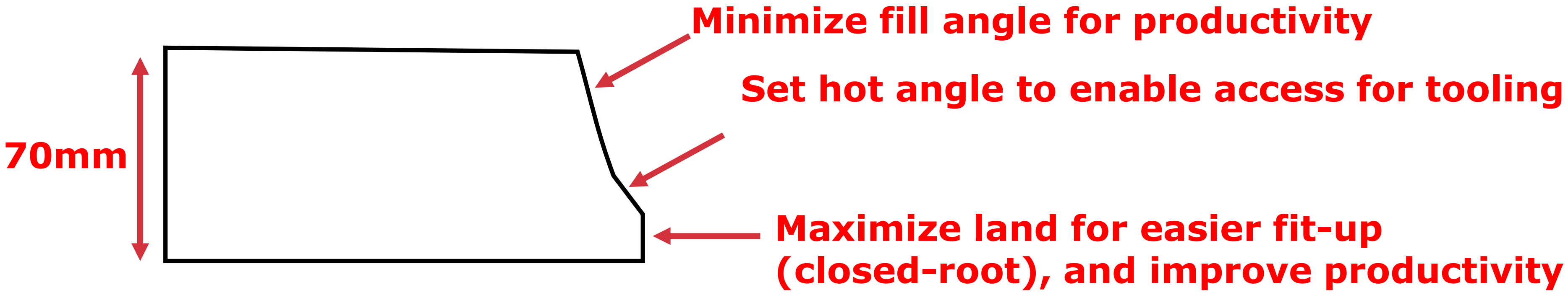
ANSI / CSA CHMC 1-2014

- The Loading Rates specified in ANSI / CSA CHMC 1-2014 are an order of magnitude faster than typical Loading Rates for Sour Service Tests:
  - 0.1 – 1.0 MPa√m/minute : (ANSI / CSA CHMC 1-2014)
  - 0.01 – 0.1 MPa√m/minute : (Sour Service)
- Reducing the Loading rate will produce a lower J or CTOD R-Curve and may reduce Initiation Toughness.
- There is extensive sour service Test Data to support the Loading Rates used in Sour Service Tests.

Application: Hydrogen Transport Ship

- Project commissioned by Provaris Energy Ltd. in support of their compressed hydrogen ship program.

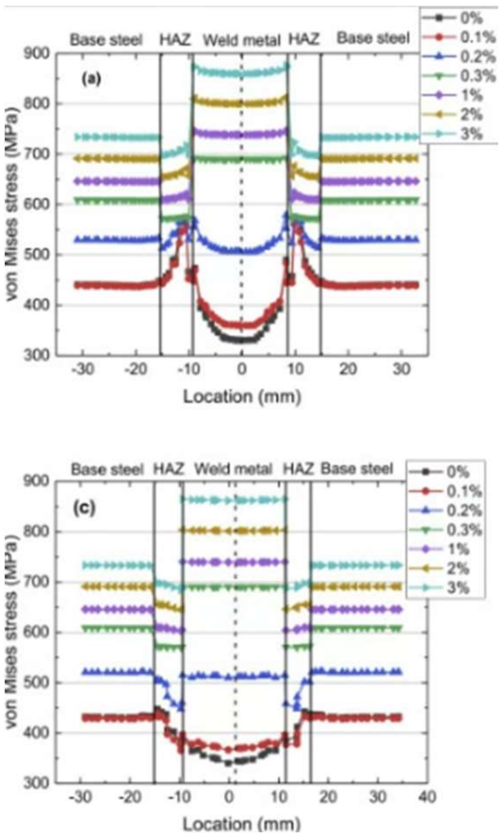
- Proprietary multi-layered hydrogen tank comprised of a stainless steel liner layer and 5 structural layers of 70mm thick high-strength steel plate with a SMYS of 80 ksi (550 MPa).
- Fatigue testing is required to prove the resistance of the longitudinal 2G seam weld to high-stress low-cycle fatigue due to pressure cycling during loading and unloading
- CRC Evans : Develop Weld Procedures to Optimize Fatigue Performance.
- CFER Technologies : Fatigue Analysis and Small & Large Scale Fatigue Tests.



Criticality of Weld Root

The weld root is critical for several reasons:

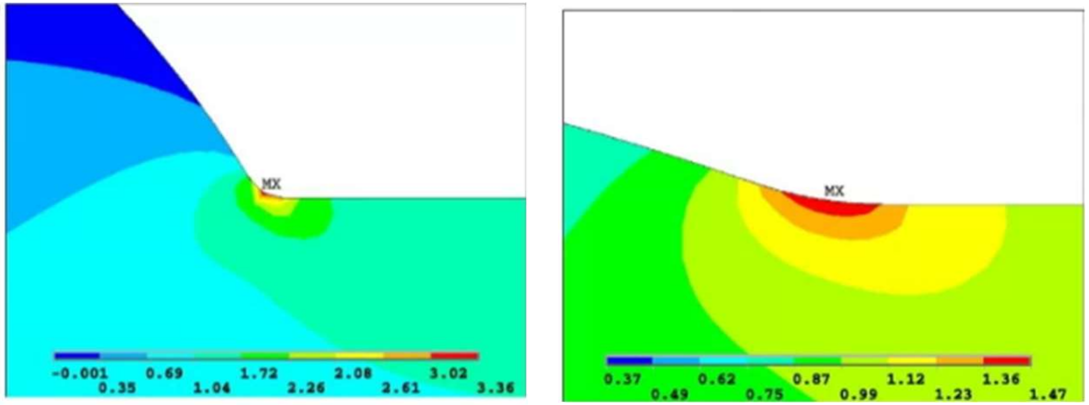
1) Geometry of Weld toes serve as stress risers for crack initiations
2) Typical single sided weld joints (ex. “V”) tend to cause deflection toward the weld cap causing residual tensile stresses in the root
3) Root is exposed to the high pressure hydrogen environment directly with highest anticipated concentrations of hydrogen at the weld toes [2]
4) Misalignment of pipe joints (Hi/Lo) can result in further elevation of stresses in the joint
5) Most sensitive pass where fit-up, and technique are vital to producing a quality bead



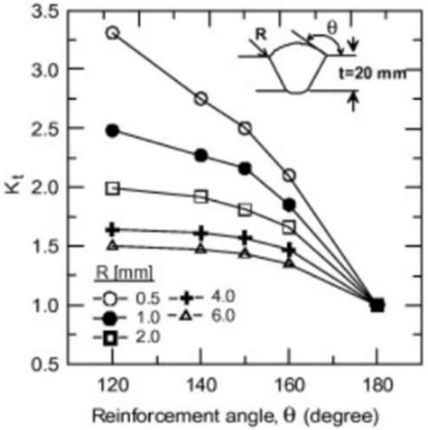
Modelled Von Mises stresses in an X80 girth weld near weld root (top) and cap (bottom)[2]

Root Geometry

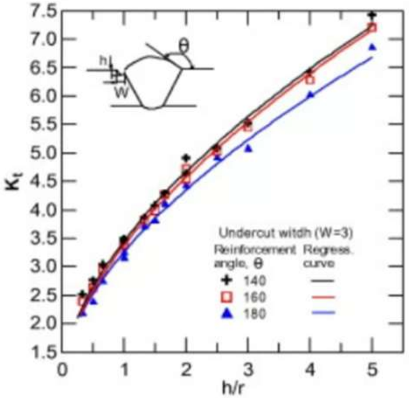
- The magnitude of stress risers at the weld toe are greatly influence by the radius and contact angle of the reinforcement
- Reinforcement with large contact angles and small radius discourage crack initiation
- Internal undercut can massively increase the stress concentration factor



Map of stress concentration factor in weld reinforcement at large contact angles (left) and small contact angles (right)[3]



Effect of reinforcement radius and contact angle on stress concentration factor[3]

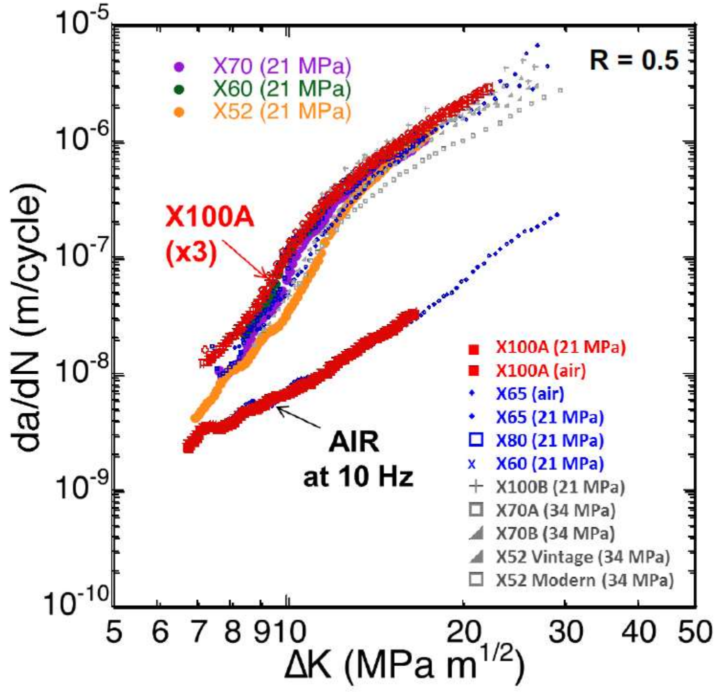


Effect of undercut width on stress concentration factor[3]

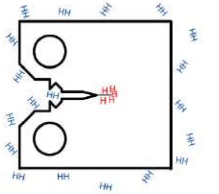
Hydrogen Gas Transport Modules

- Unlike Hydrogen Pipelines, Gas Transport Modules experience very High Fatigue Demand due to large Pressure Cycles.
- Fatigue and Fracture Performance of Seam Welds is Critical.
- It is important to ensure that the Weld Procedure produces a smooth Defect Free root weld to enhance fatigue performance.
- Need to optimize and verify Root Weld S-N Fatigue Performance.

Fatigue Crack Growth in Hydrogen



- A wide variety of pipeline steels display nominally the same fatigue response in high-pressure gaseous hydrogen
- The effect of pressure on fatigue crack growth rates is modest for high-pressure hydrogen

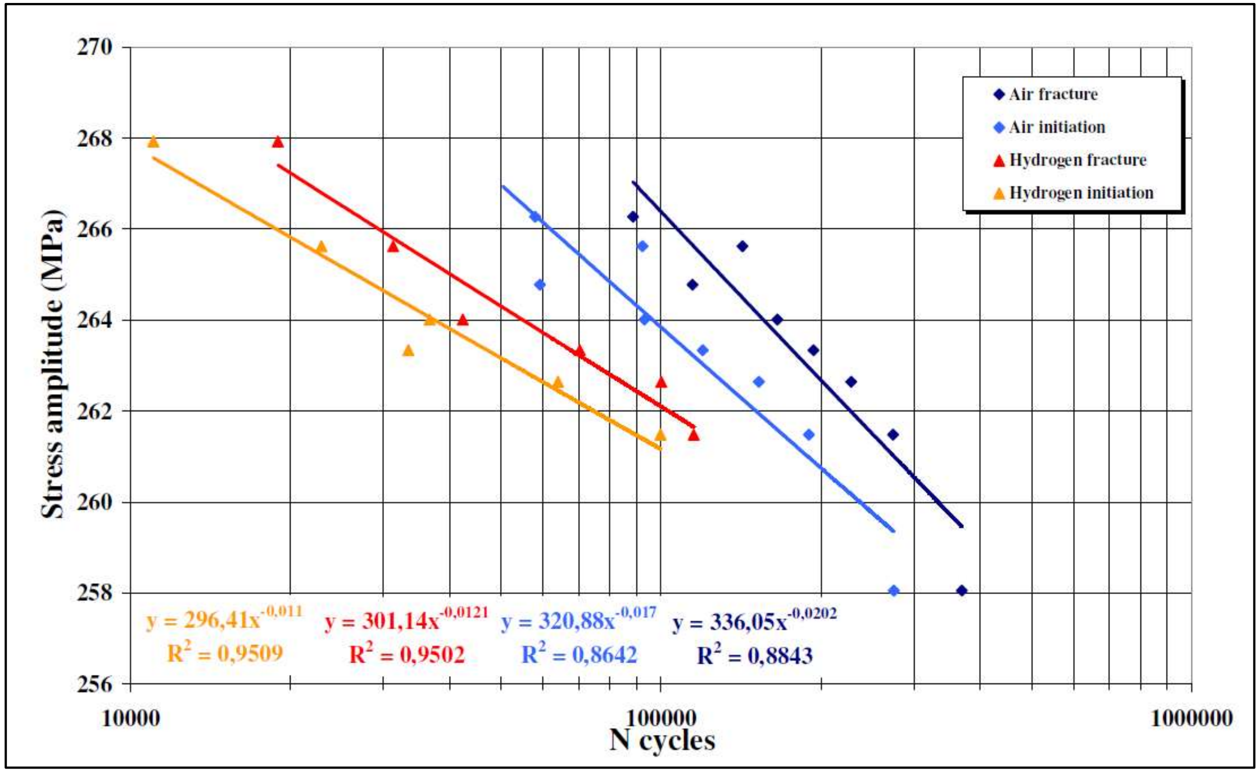


Crack Growth Acceleration Factor (CGAF) can vary from 5 (low ΔK) to 30-50 (high ΔK).

Low partial pressure of hydrogen has nominally same effect as pure hydrogen on pipeline steels

S-N Fatigue Performance in Hydrogen

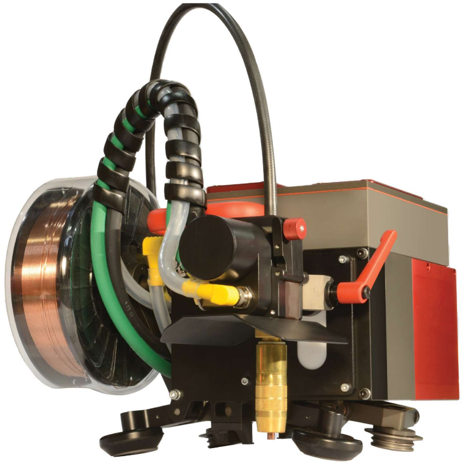
- The S-N Knock Down Factor (KDF) is higher at High Stress Ranges (Consistent with FCGR Test Results).



Design of Root Pass: Overview

- Mechanized root (CRC-Evans M500 Welding Bug) to minimize operator error, and improve quality/consistency

- 3 modified short-arc processes compared (Miller RMD, Fronius CMT, and Fronius LSC)



Determination of Intensity and Distribution Parameter of Heat Source

- 1G Rotated – Bead on Pipe tests
- Maximized Wire Feed Speed for each process, then tested range of Travel Speeds to fit to thermodynamic model[5]

$$z_{\max} \quad \text{II} \quad \frac{q}{2\pi k\,(T_c - T_0)} \quad f(\mathrm{Ry}) \cdot g(\mathrm{Ry}, \sigma^*)$$

$$f \quad \left[1 + \left(\sqrt{\frac{2}{e\mathrm{Ry}}}\right)^{n_1}\right]^{1/n_1}$$

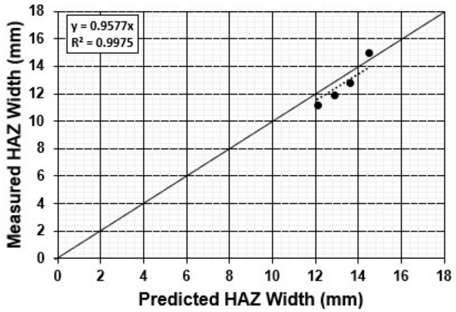
$$g \quad \left\{1 + \left\{\frac{\pi}{2}\ln\left(\frac{\sigma^*_{\max}}{\sigma^*}\right)\left[1 + \left(1.495\mathrm{Ry}^{-\frac{1}{6}}\right)^{n_3}\right]^{1/n_3}\right\}^{n_2}\right\}^{1/n_2}$$

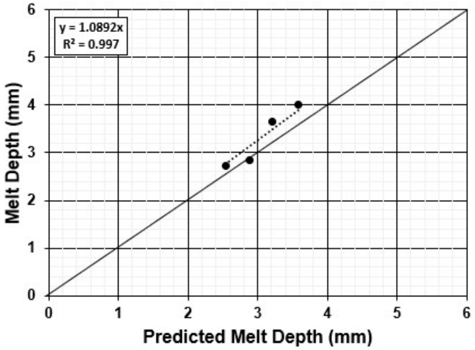
$n_1 = -1.47$

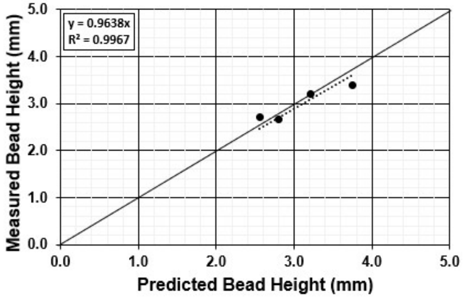
$n_2 = -1.96$ 9.7

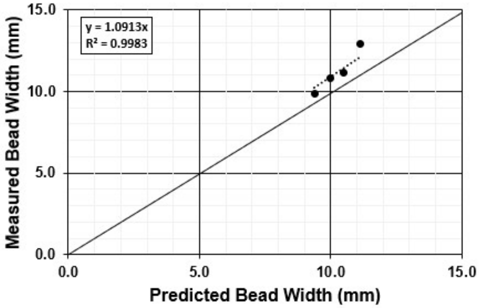
$n_3 = -3.22$ * * *

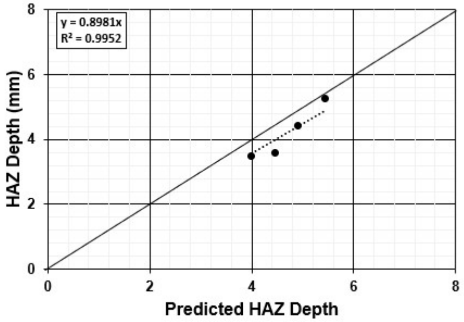
**



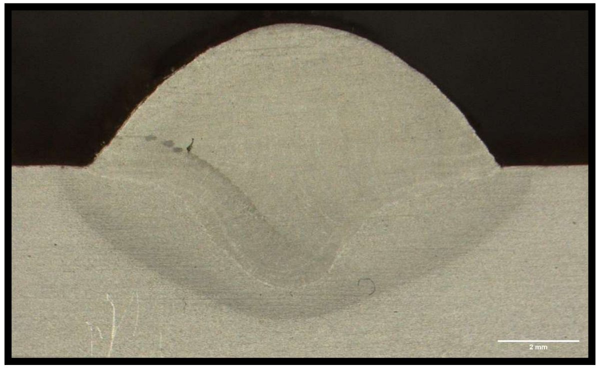






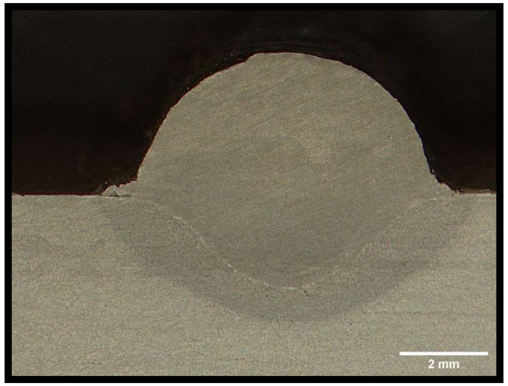


Comparison of Root Processes (1G Bead on Pipe)



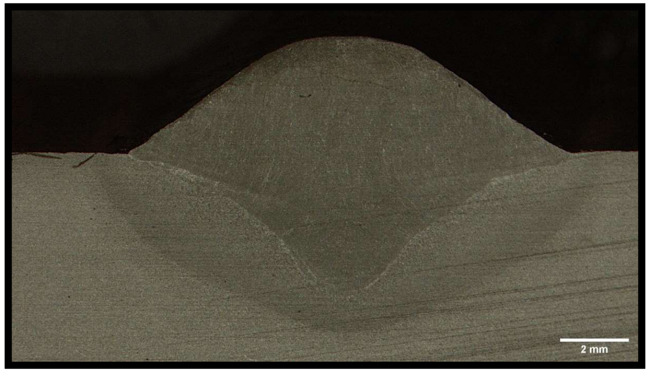
CMT

Distribution Parameter (σ): 2.3mm
Max Intensity: 233W/mm^2
Max Instantaneous Power: 4228W
Travel Speed: 10ipm
Deposition Rate: 7.7lbs/hr
Penetration (bead on pipe): 2.9mm



RMD

Distribution Parameter (σ): 1.2mm
Max Intensity: 638W/mm^2
Max Instantaneous Power: 2886kW
Travel Speed: 12ipm
Deposition Rate: 5.9lbs/hr
Penetration (bead on pipe): 2.1mm

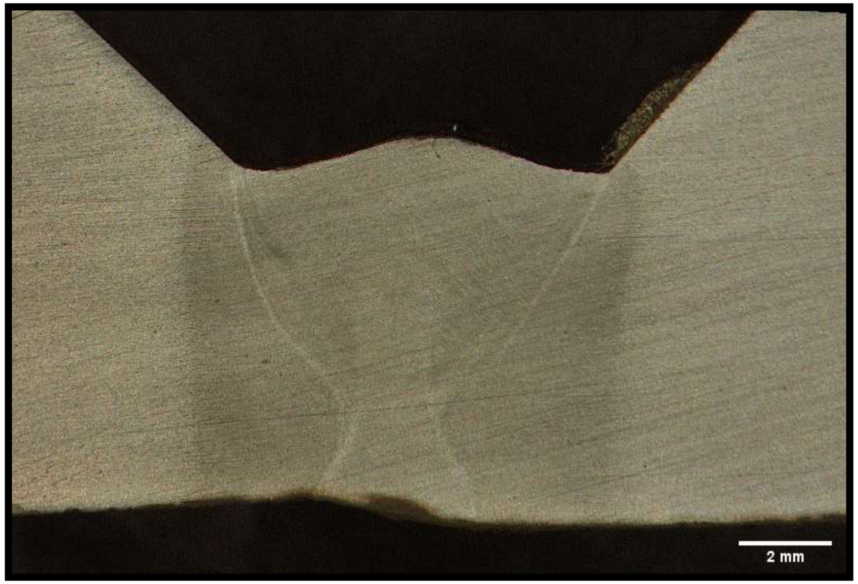


LSC

Distribution Parameter (σ): 2.5mm
Max Intensity: 316W/mm^2
Max Instantaneous Power: 6278W
Travel Speed: 12ipm
Deposition Rate: 9.3lbs/hr
Penetration (bead on pipe): 4mm

Larger Intensity produces deeper penetration, whilst larger distribution parameter results in broader, shallower penetration. An ideal process for maximum land has a combination of large intensity and distribution parameter.

Root Process in 2G Bevel and Finalized Weld Design



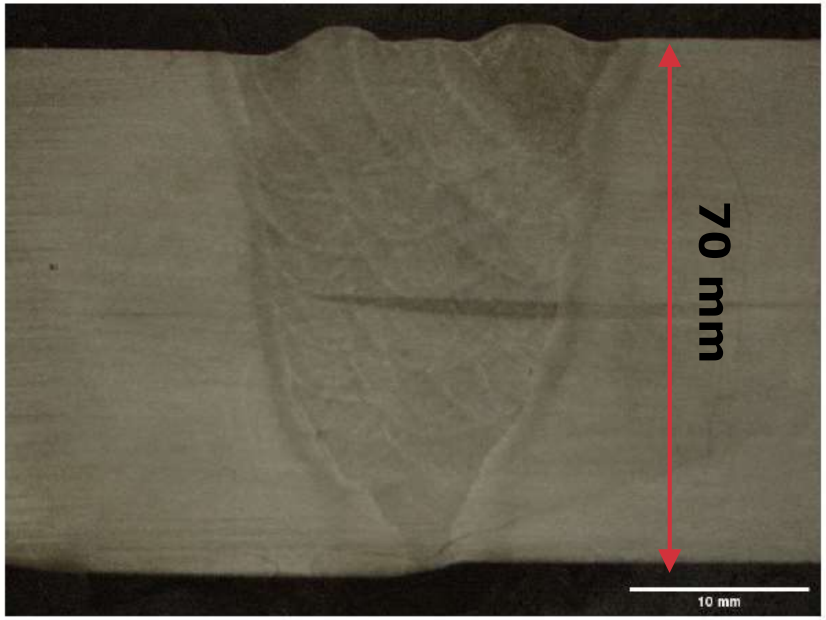
LSC Root in 45° bevel

Parent Metal	HAZ			Weldmetal			HAZ			Parent Metal
			231	250	230	223	210			
222	201	228	241		228		234	227	197	198
214	208	223	228		226		228	223	203	210
227	210	217	234		220		228	219	204	210

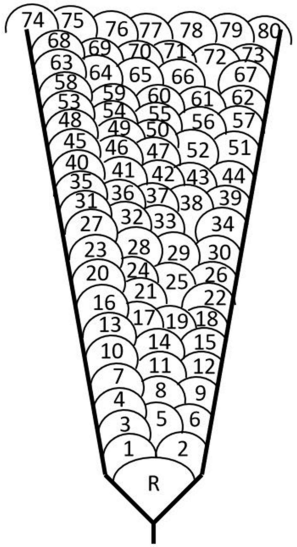
Preliminary weld to evaluate hardness

Final Large Scale Specimens

(ref. Provaris Energy compressed H_2 ship project)



Cross-Section of Final Weld (taken from run-off tabs)



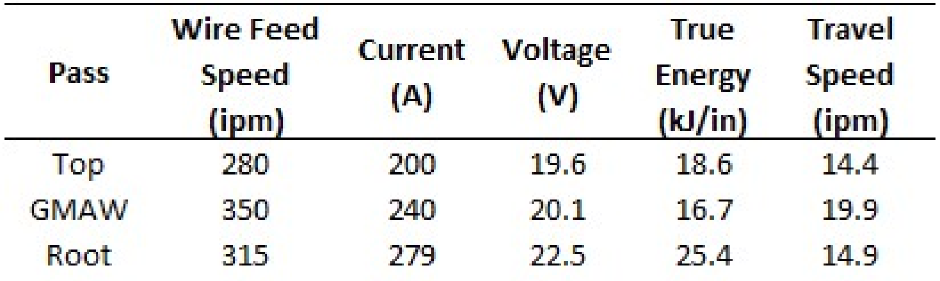
8′ x 4′ Fatigue Specimen
2.76 inches thick

Final Large Scale Specimens

(ref. Provaris Energy compressed H2 ship project)

As-welded root profile

As-welded cap profile



Pass	Wire Feed Speed (ipm)	Current (A)	Voltage (V)	True Energy (kJ/in)	Travel Speed (ipm)
Top	280	200	19.6	18.6	14.4
GMAW	350	240	20.1	16.7	19.9
Root	315	279	22.5	25.4	14.9

Power Source	Fronius TPS 400i
Pulse Program	Root: LSC Adv. Remaining: PMC
Motion Control	M500 Single Torch Bug
Shielding Gas	90%Ar / 10% CO_2
Wire	ER100S-1

Summary

- CRC / Microalloying are actively engaged in Weld Procedure Development and Qualification for:
- Hydrogen Pipelines
    - API 1104 Hydrogen Task Group
    - ECA / Girth Weld Toughness Test Procedures
- Hydrogen Gas Transport Modules.
    - Weld Root Optimization
    - Full-Scale S-N Fatigue Testing

CRC EVANS

crcevans.com