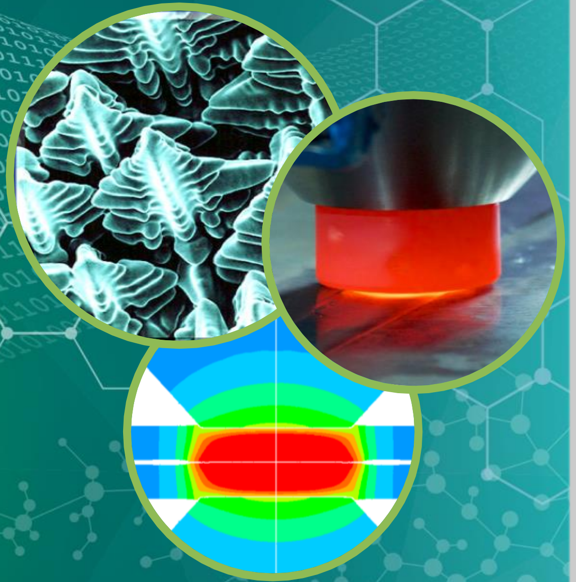
Robust Welding Repair Technology for Oil/Gas Pipelines



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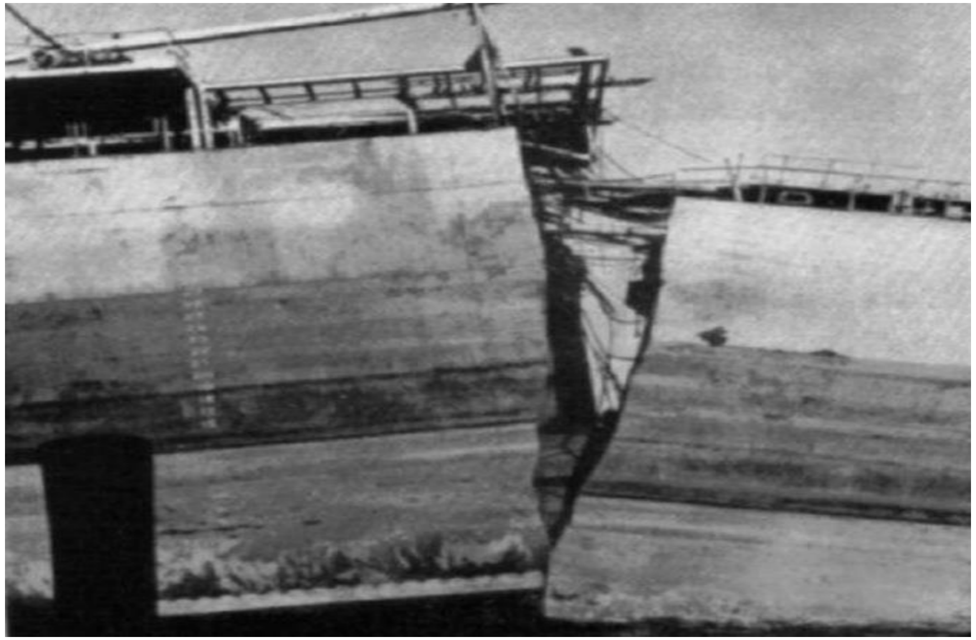
Project Overview

- Goal: To significantly reduce repair costs and improve structural integrity and reliability of repaired structures, which are essential to sustain or revitalize the aging oil/gas pipeline infrastructure in the US.
- Approach: Extend, optimize and reformulate, if necessary, ORNL's award winning innovative low temperature phase transformation (LTPT) weld wire/consumables to oil/gas steel pipelines repair, and new construction
  - Eliminate hydrogen induced cracking (HIC) in repair welding
  - Improve the fracture and fatigue properties of the repaired weld
  - Eliminate pre-heating and/or post-weld heat treatment
  - Cover wide range of steel pipelines (X60 to X100)

Background

- Hydrogen induced cracking (HIC) is one of the long-standing issues in welding and repair of high-strength steel structures including oil/gas pipelines
  - **Hydrogen enters into molten weld pool, typically from atmosphere and surface containments (oil/rust/moisture) of pipeline. A very small amount of hydrogen (few ppm level) will cause HIC**



Catastrophic failure in World War II Liberty Ship due to HIC

Rupture of an oil pipeline due to HIC

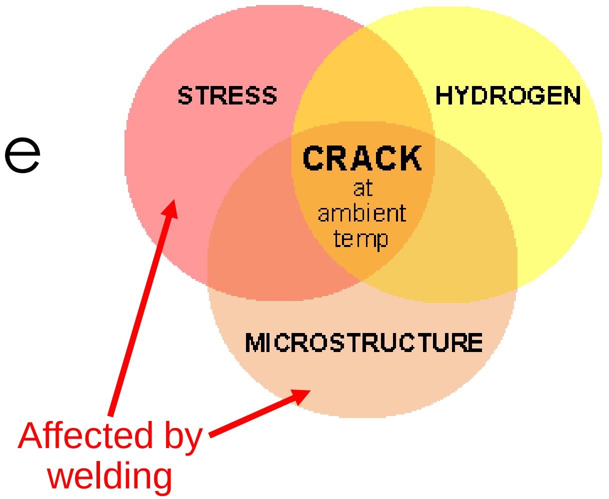
Prevention of HIC can be expensive

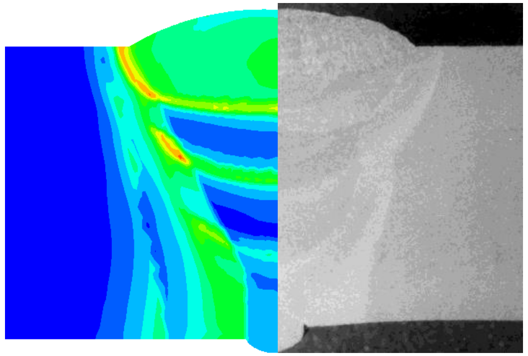
- Stringent, code compliant welding procedures are followed to ensure the weld quality
  - Pre-heating, post weld heat treatment and low hydrogen welding practices
- Amount to a significant portion of construction cost of pipelines (20-50%)
  - Time consuming
  - Labor extensive
  - Repair welding in-field or on-site even more challenging

Example of field welding for illustration only, Courtesy of ExxonMobil)

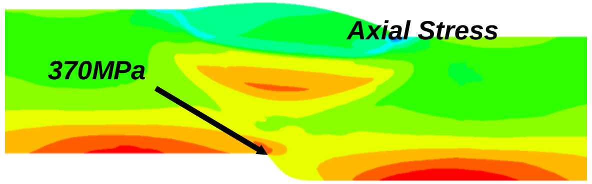
Fundamental factors leading to HIC

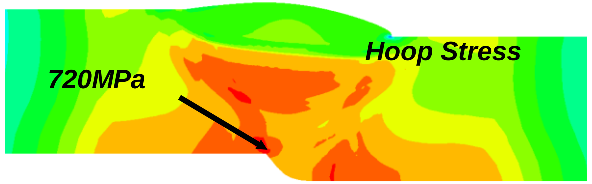
- Hydrogen present to sufficient degree
- High tensile residual tensile stress
- Susceptible microstructure
- Ambient temperature

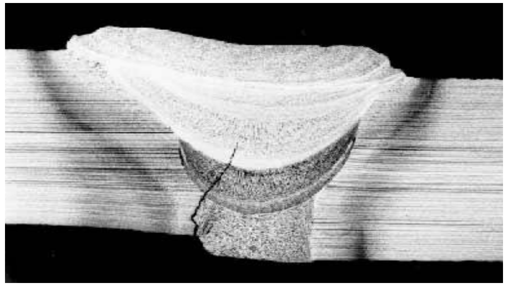




Microstructure and property prediction in a multi-pass X65 pipeline steel weld







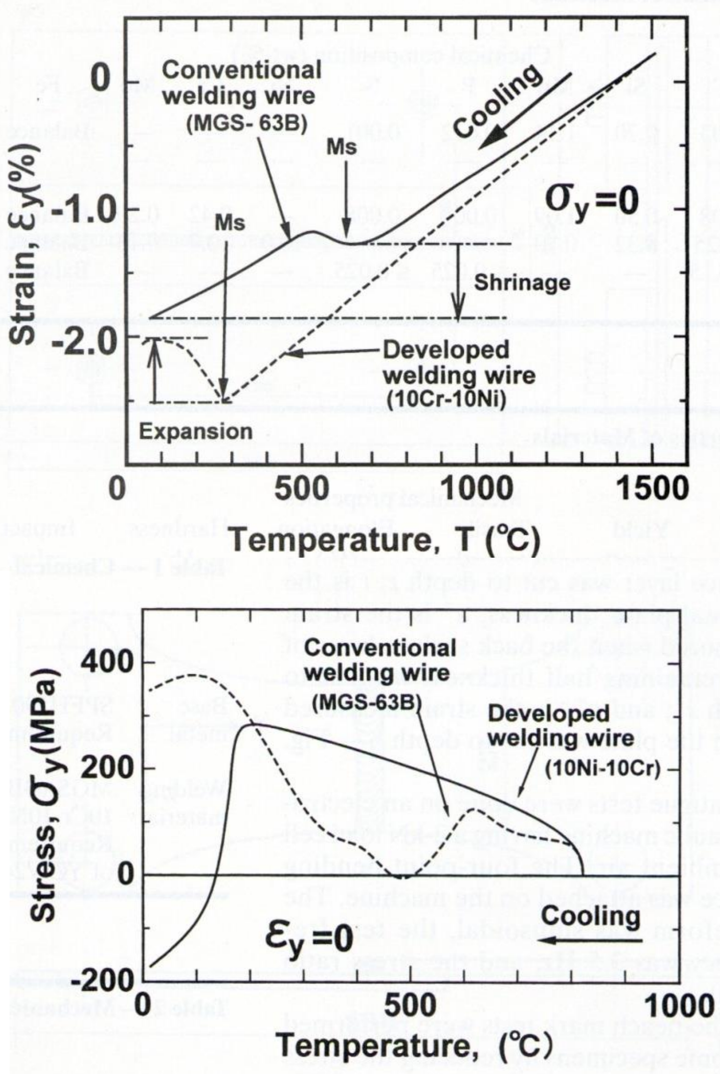
Feng et al, 2002

- All four factor must be simultaneously present

- **Welding of steel pipeline favors all these conditions for HIC**

Mitigating HIC Through In-Process Weld Residual Stress Control

- Over the years, pre-heating and post-weld heat treatment has been the only practical (and costly) approach to reduce weld residual stresses
  - They are difficult to apply in repair welding, time consuming and costly
- **In-process residual stress control (this project)**
  - Principle: control and alter the “normal” thermal expansion/contraction sequence of welding
  - **Special weld filler metal by means of low-temperature phase transformation (LTPT)**
    - Special filler wire is formulated to form compressive residual stresses in the weld region by volumetric expansion of martensite transformation through very low-temperature martensite phase transformation.
  - Benefit: no added steps, potentially resulting in significant cost savings



Ohta et. al. 2003

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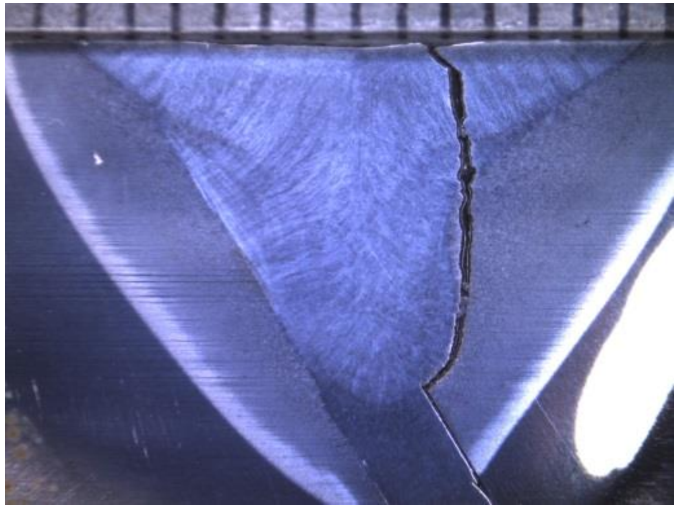
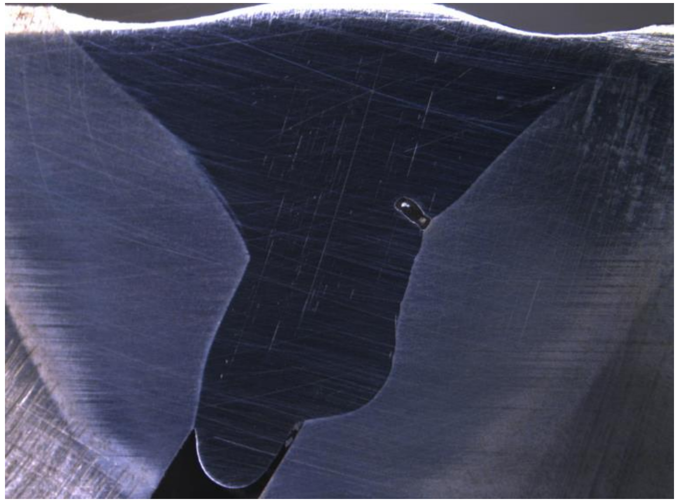
Technology Description

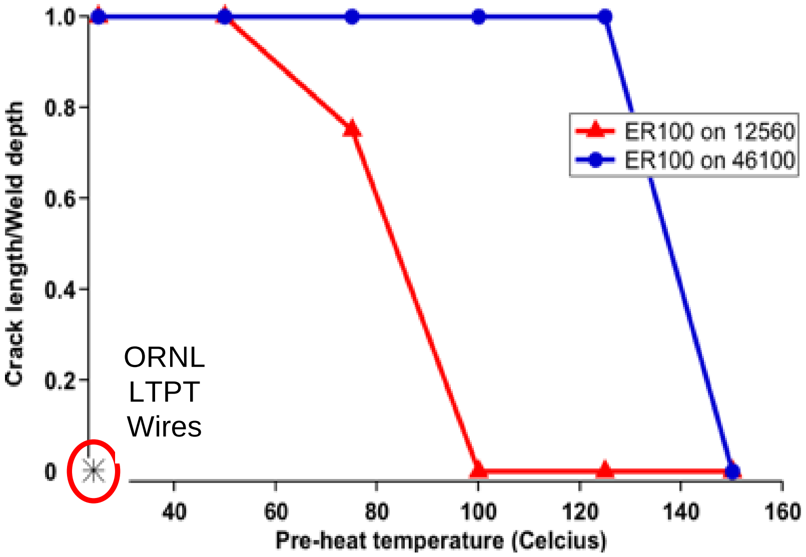
- Working with US Army, ORNL developed a new class of weld wires effectively eliminating HIC in welding armored steels and other high-strength steels.
  - The principle is to reduce or even create compressive residual stresses in the weld region by low temperature phase transformation (LTPT)
  - Extensively rely on ICWE to design and optimize weld metal chemistry



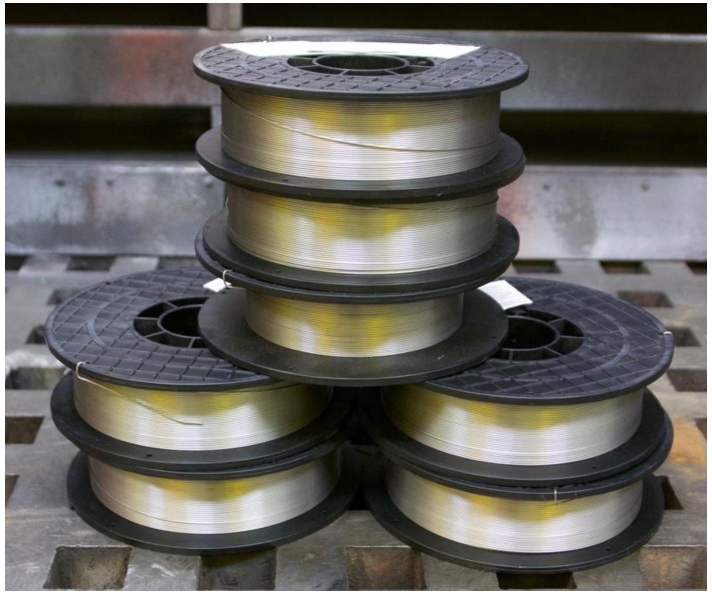
Conventional filler wire has HIC

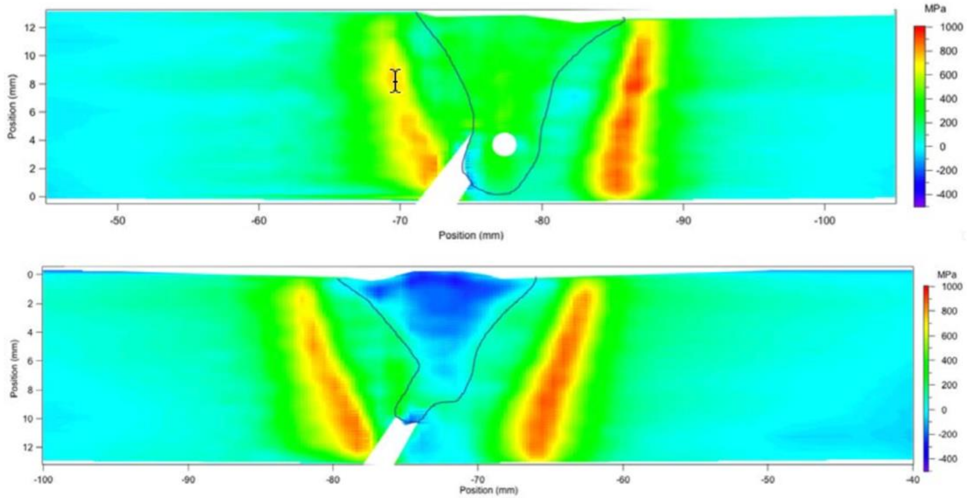


ORNL weld wire is free of HIC



2017 RD100 Award: Filler materials for welding and 3D printing)





Weld residual stress control

A Two-Phase Project Plan

- Phase I: Develop and demonstrate sound technical basis of the new welding wires suitable for pipeline steels. This include formulation of welding wire chemistry, demonstrate the effectiveness of repair welding without the need of pre-heat and post-weld heat treatment to avoid HIC and have adequate weld properties. **(Completed)**

- Phase II: Further refinement and optimization of LTPT weld consumables for pipeline steels. Scale up the development for field trials and technology demonstration with industry partners. Partner with industry (end users and wed wire suppliers) for technology transfer and commercialization.

Industry Survey and Partnership

- Conducted a series of survey and communications with oil/gas pipeline industry stakeholder
  - Identify specific needs, requirements and potential applications of the LTPT weld consumables for pipeline repair and new construction
- Developed partnership with
  - ExxonMobil, Shell, Lincoln Electric, ESAB, JFE, ArcelorMittal
  - PRCI, through its Design, Materials & Construction (DMC) Technical Committee which oversees pipeline welding and integrity R&D activities
  - US Navy
- Confirmed the significance and needs of the repair welding technology
  - Eliminating pre-heat and post weld heat treatment would be a major cost saving in repair
  - Significant reduction of operation downtime
  - Potential service life enhancement for cyclic/fatigue loading conditions
  - Potential benefits for hydrogen or hydrogen + natural gas blend pipelines

Recommendations and guidance from industry survey

- Initially focus on X60-65 grade pipeline steel (the workhouse pipeline steel in the US). Expand to X80, X100 and X120 steels which has greater HIC issues
  - For each steel grade, include both rich and lean chemistries from different steel suppliers
- Toughness of the weld metal
  - Target a minimum Charpy value of **100J** at 0C for weld metal. Achieving such toughness level would be highly desirable as it would ease the weld flaw management requirement for strain-based pipeline design and service
- While recognizing not a direct outcome of weld consumable research which is the primary goal of the project, the industry would like to have a robust repair welding process to control the hardness of the HAZ of X65 steel below **250Hv**, for sour service conditions
- A special concern issue for pipeline welding
  - Need to investigate the possibility of and develop solutions to the **hardened fusion line** due to enrichment of alloying elements from the welding wire in the partial melting zone. This would impair the performance in sour service conditions, and hydrogen pipelines
- Our research plan has been revised and expanded to incorporate these industry recommendations

3 weld candidate weld wires/consumables in Phase I

- Designated as L1766, L1764, LNi10

Weld wire ID	Ni, %wt (7-10%)	Cr, %wt (1-12%)	C, %wt	Ms, C	Mf, C
L1766	Mid	High	~0.02	280	80
L1764	Low	Mid	~0.02	220	Below RT
LNi10	High	Low	~0.1	260	50

- Initial welding and testing were on X60 steel and X100
- Additional welding and testing were on X65, and planned for X80

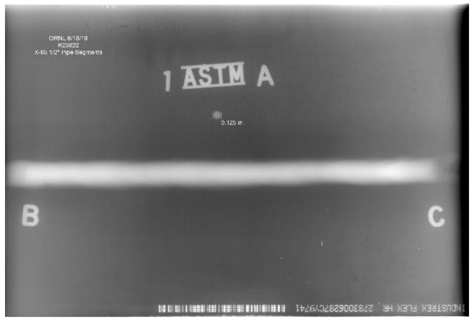
Basic welding conditions in weld wire development (X60)

	X60-1	X60-2	X60-3
process	GMAW-P	GMAW-P	GMAW-P
material	API 5L X60 sch, 20	API 5L X60 sch, 20	API 5L X60 sch, 20
Pipe OD and thickness	12.750 OD x 0.25 wall	12.750 OD x 0.25 wall	12.750 OD x 0.25 wall
Joint design	30° double vee groove	30° double vee groove	30° double vee groove
Filler metal and number of beads	**L1766, 2 passes**	**L1764, 2 passes**	**LNi10, 2 passes**
Electrical or flame characteristics	DCEP (pulsed weld volts and Amps are averages)	DCEP (pulsed weld volts and Amps are averages)	DCEP (pulsed weld volts and Amps are averages)
position	Flat (±15°)	Flat (±15°)	Flat (±15°)
Time lapse between passes	>10 min, pipe allowed to cool below 50°C	>10 min, pipe allowed to cool below 50°C	>10 min, pipe allowed to cool below 50°C
Cleaning and/or grinding	Grind between backing weld and cover pass	Grind between backing weld and cover pass	Grind between backing weld and cover pass
Preheat/postweld heat	Ambient temp 23°C	Ambient temp 23°C	Ambient temp 23°C
Shielding gas and flow rate	95%Ar5%CO2, 40 CFH	95%Ar5%CO2, 40 CFH	95%Ar5%CO2, 40 CFH
Speed of travel	7.8-9.8 ipm	9.8-10.5 ipm	11.2-11.9 ipm

All welds showed no HIC and other weld defects

All welds made without pre-heating

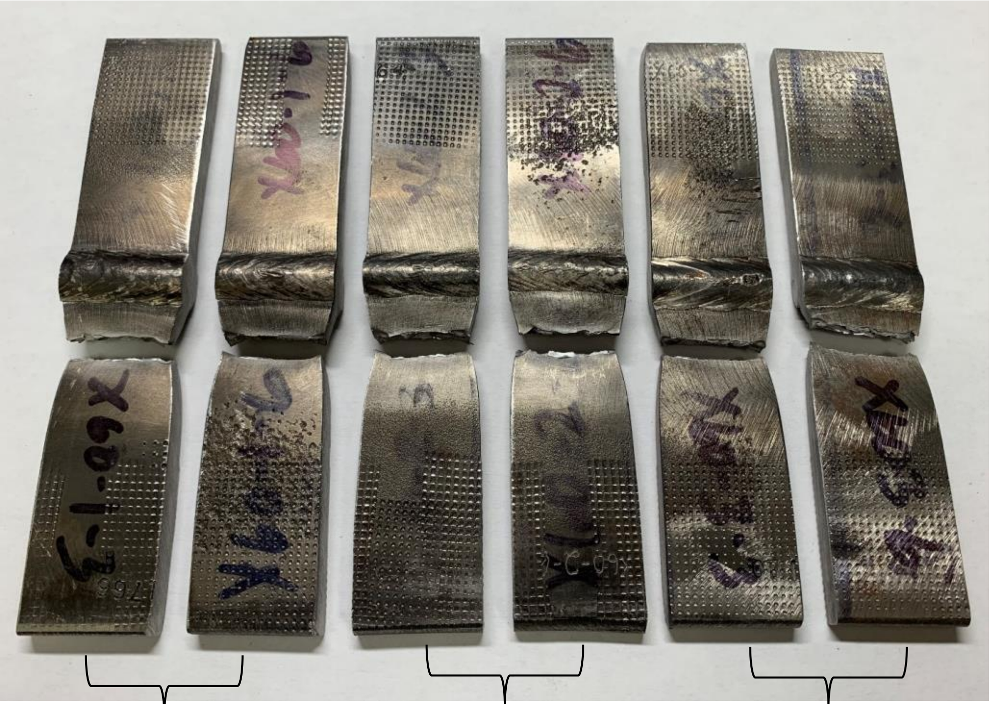
X-Ray NDE



X60-1 **X60-2** **X60-3**

Cross-weld tensile test results

	YS of X60 (SMYS)*	Average YS of X60 weld	qualification	TS of X60 (SMTS)*	Average TS of X60 weld	qualification
X60-1	60.20 ksi	62.15 ksi	Average YS = 103% SMYS	75.40 ksi	88.72 ksi	Average TS = 117.7% SMTS
X60-2	60.20 ksi	61.47 ksi	Average YS = 102% SMYS	75.40 ksi	87.12 ksi	Average TS = 115.5% SMTS
X60-3	60.20 ksi	58.18 ksi	Average YS = 96.6% SMYS	75.40 ksi	81.50 ksi	Average TS = 108.1% SMTS

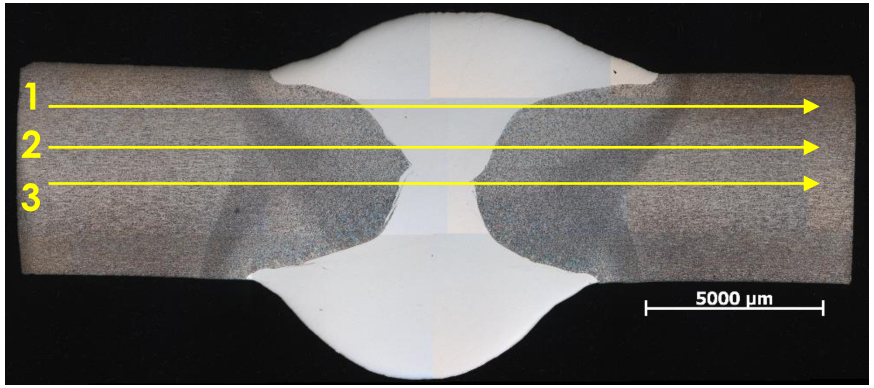


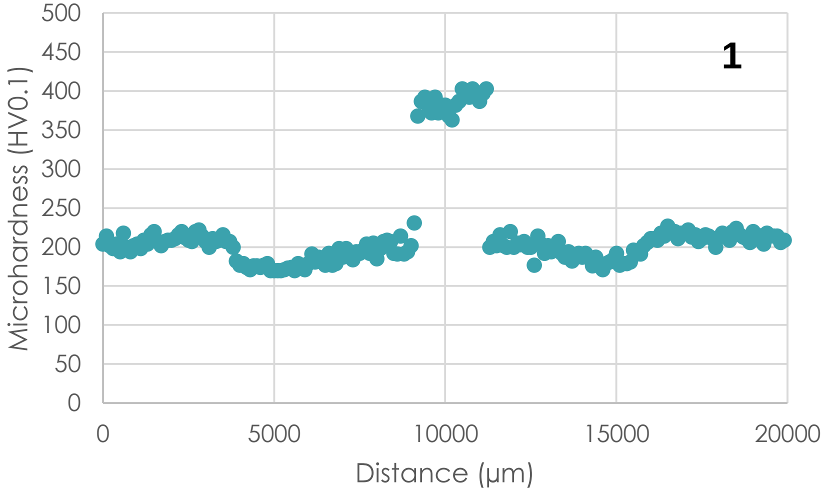
X60-1 X60-2 X60-3

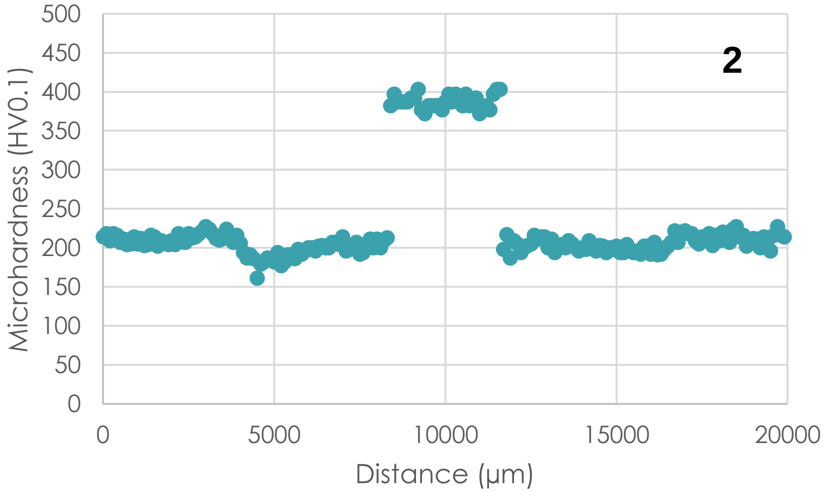
All welds failed outside the weld region, in the base metal or heat affected zone (HAZ) in the cross-weld tensile tests

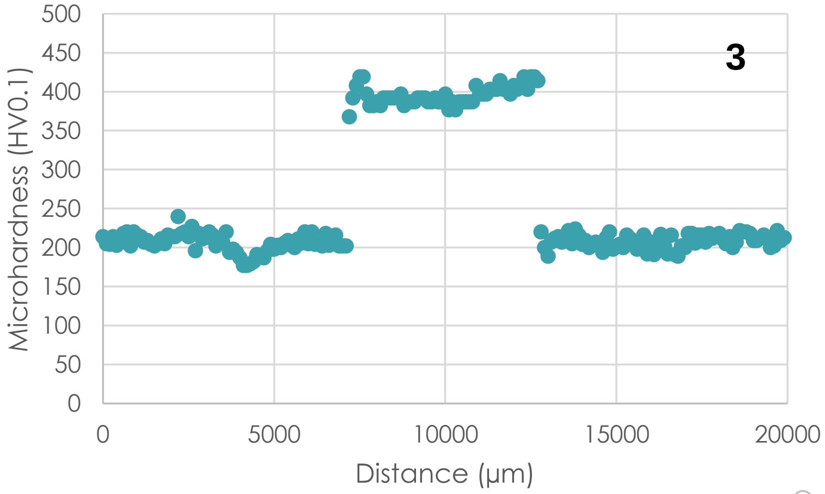
Microhardness profiles

- Very high microhardness in weld metal: weld metal overmatched based metal strength
- X60 pipe & L1766 weld wire



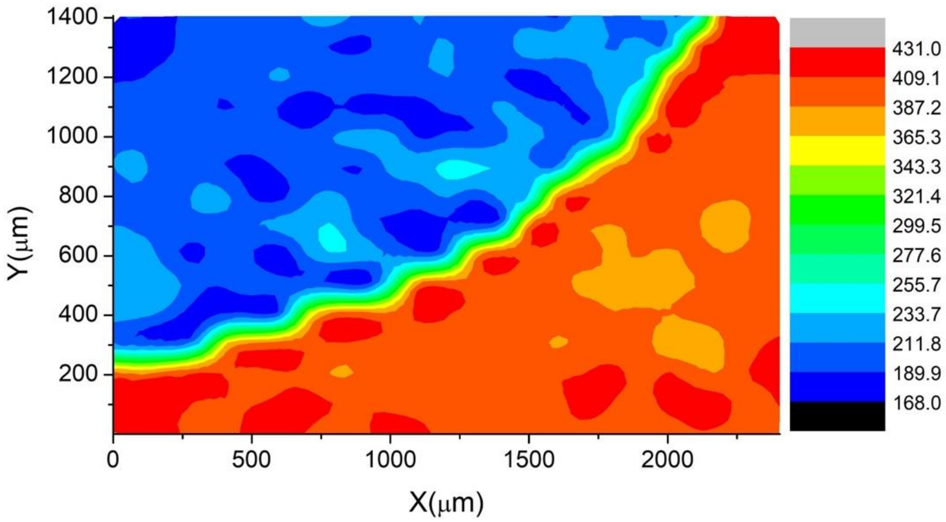


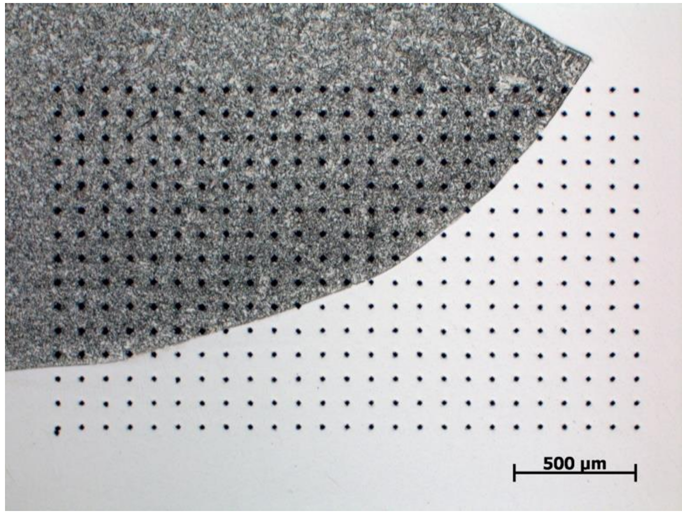


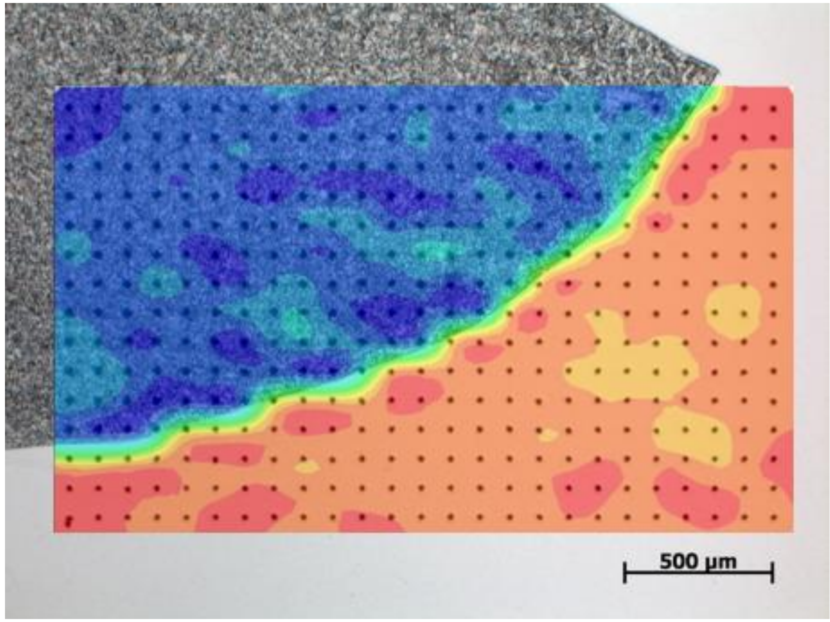


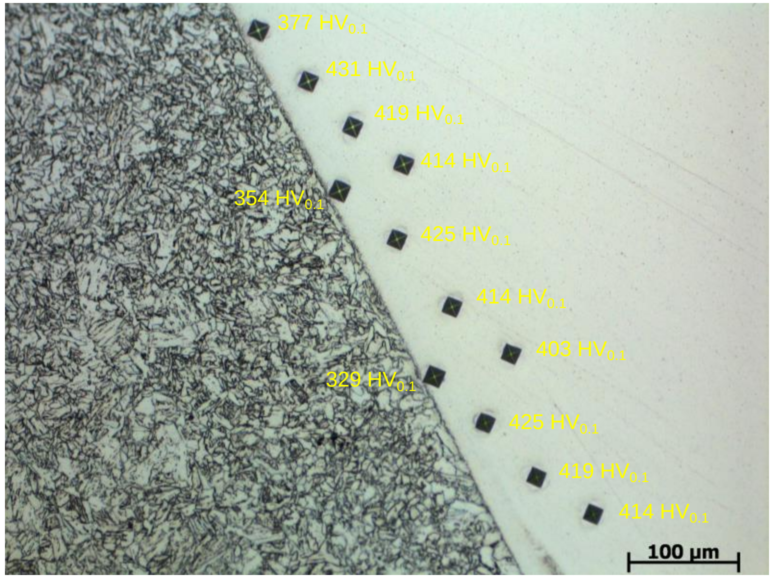
No evidence of hardened partial melting zone

- X60 pipe with L1766 weld wire



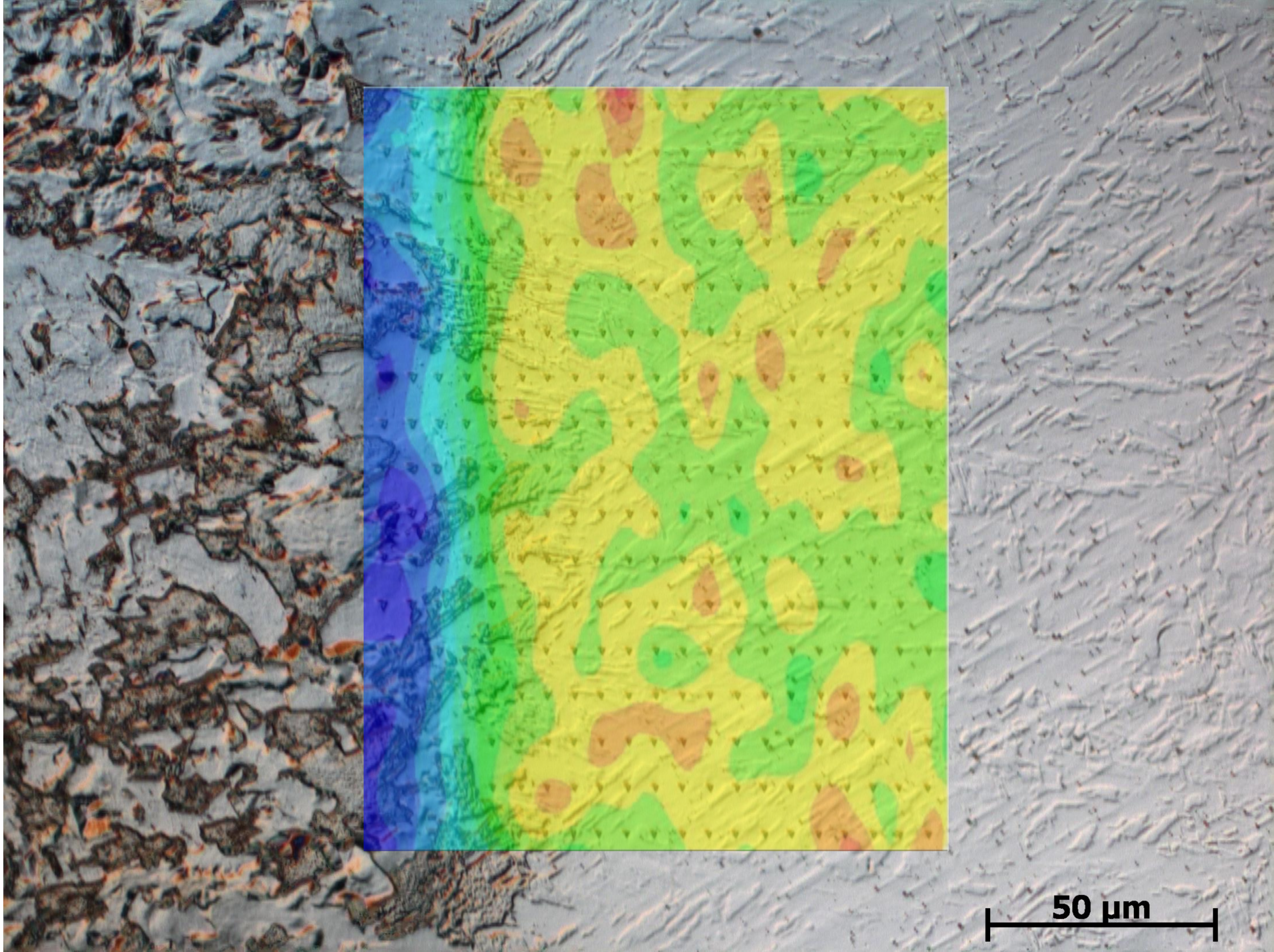




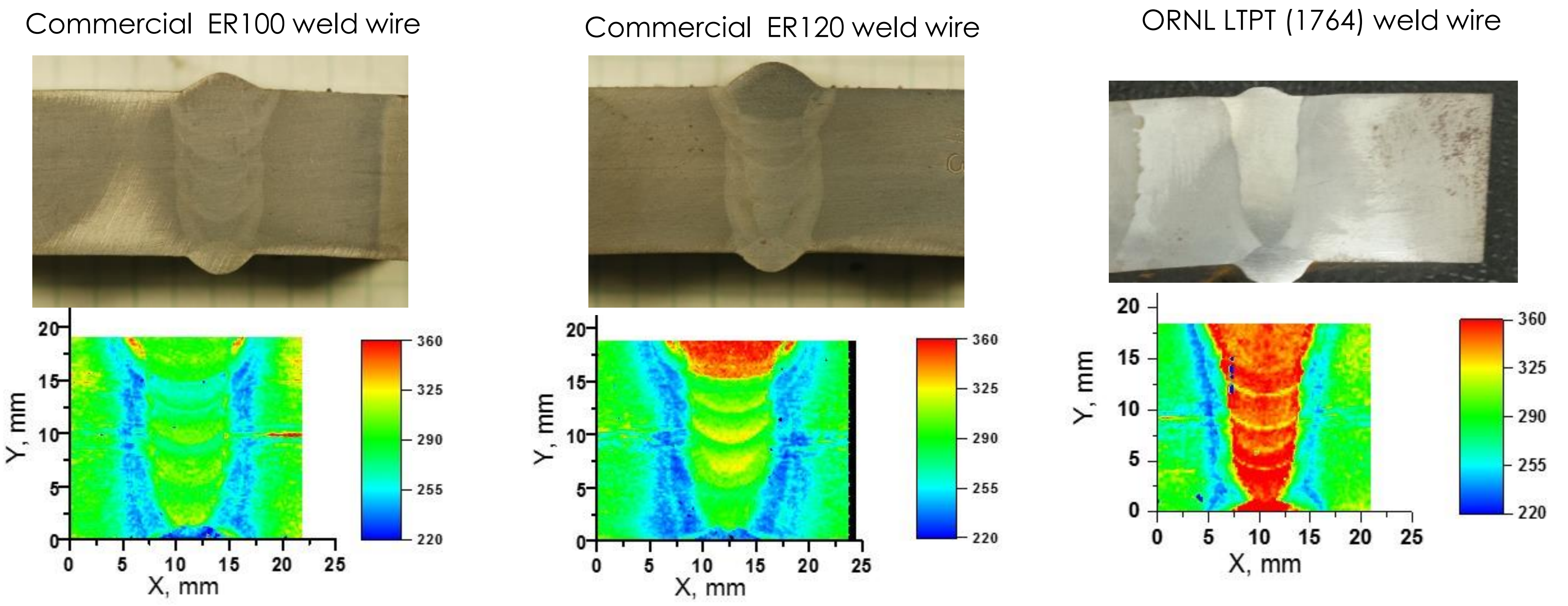


Nanohardness mapping

- No hardened partial melting zone
- Hardness range: 3-6GPa
- X60-1764 weld

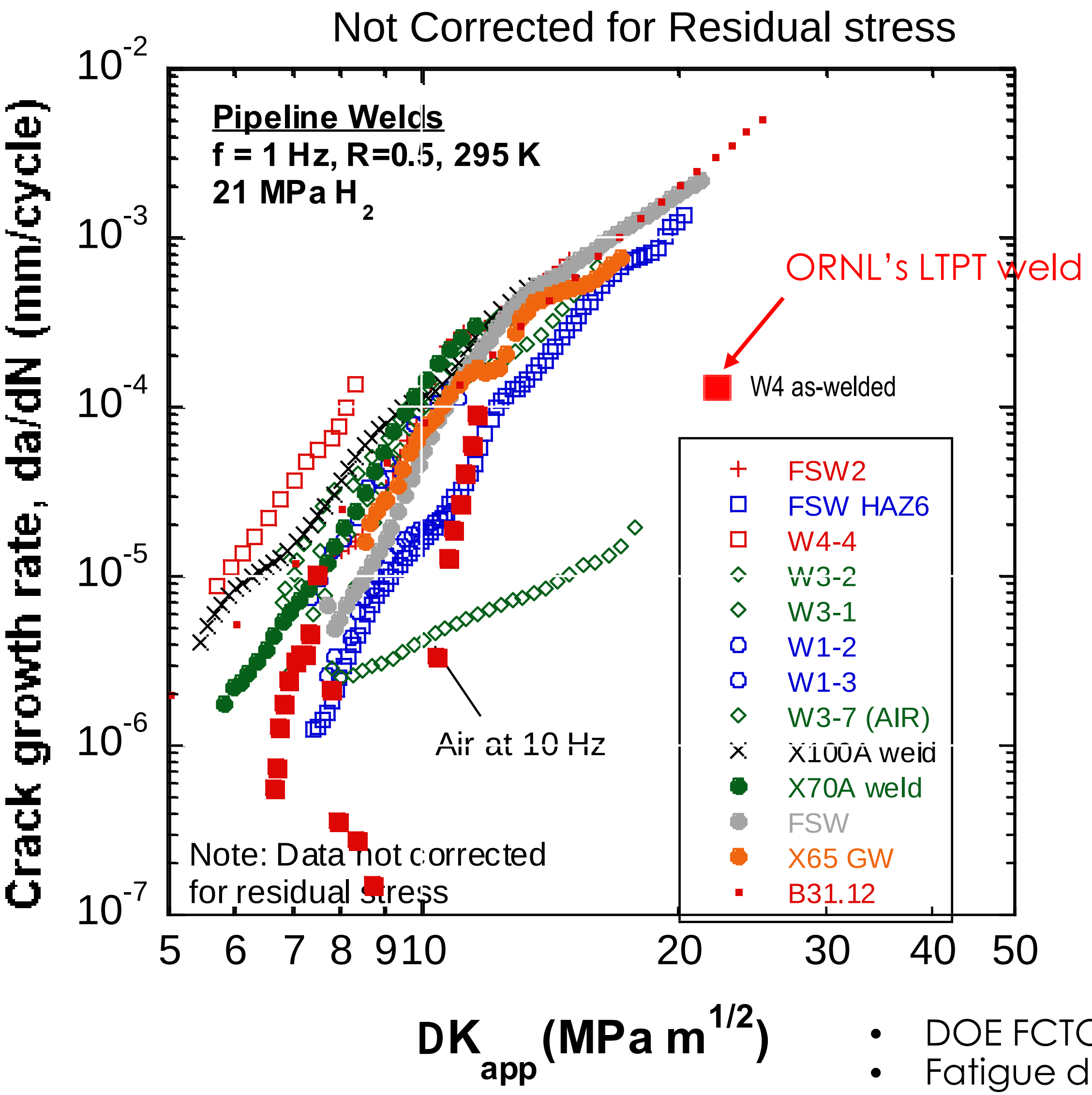


Welding of X100 pipeline steel



- **ORNL's weld wire**
  - Capable of maintaining strength in multi-pass weld. Very stable microstructure; no appreciable inter-pass tempering effects; retaining high strength
  - **No preheating is needed (major cost savings)**
- **Commercial weld wires (ER100, and ER120)**
  - **Requiring 150C pre-heating**
  - Show considerable microstructure instability in multi-pass weld

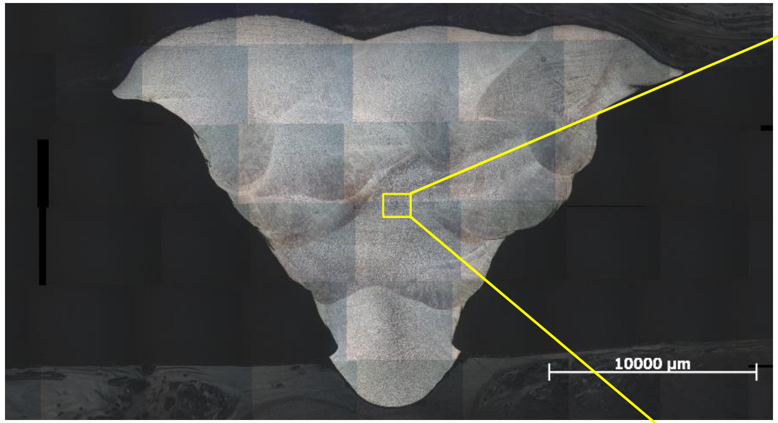
Significantly improves resistance of fatigue cracking propagation in high pressure hydrogen (21 MPa H_2 pressure)

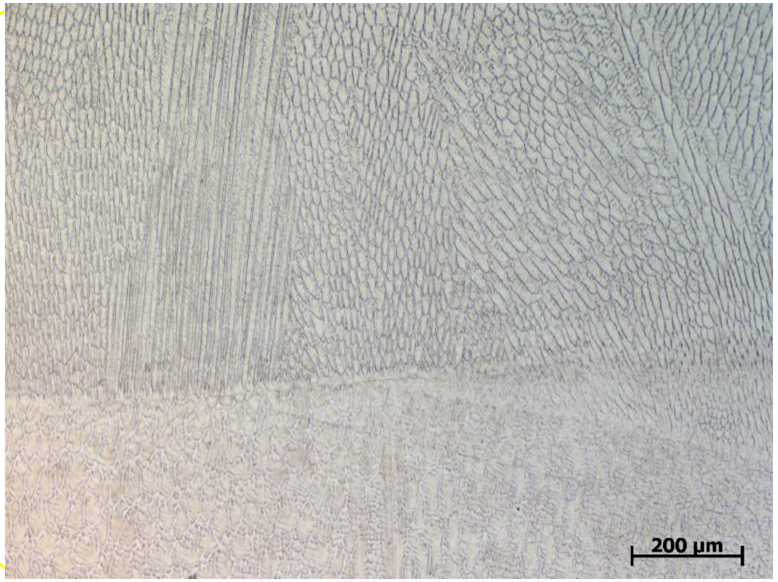


- DOE FCTO Hydrogen Pipeline Project
- Fatigue data from Sandia National Lab

X65 Weld: HIC free, but relatively low Charpy toughness

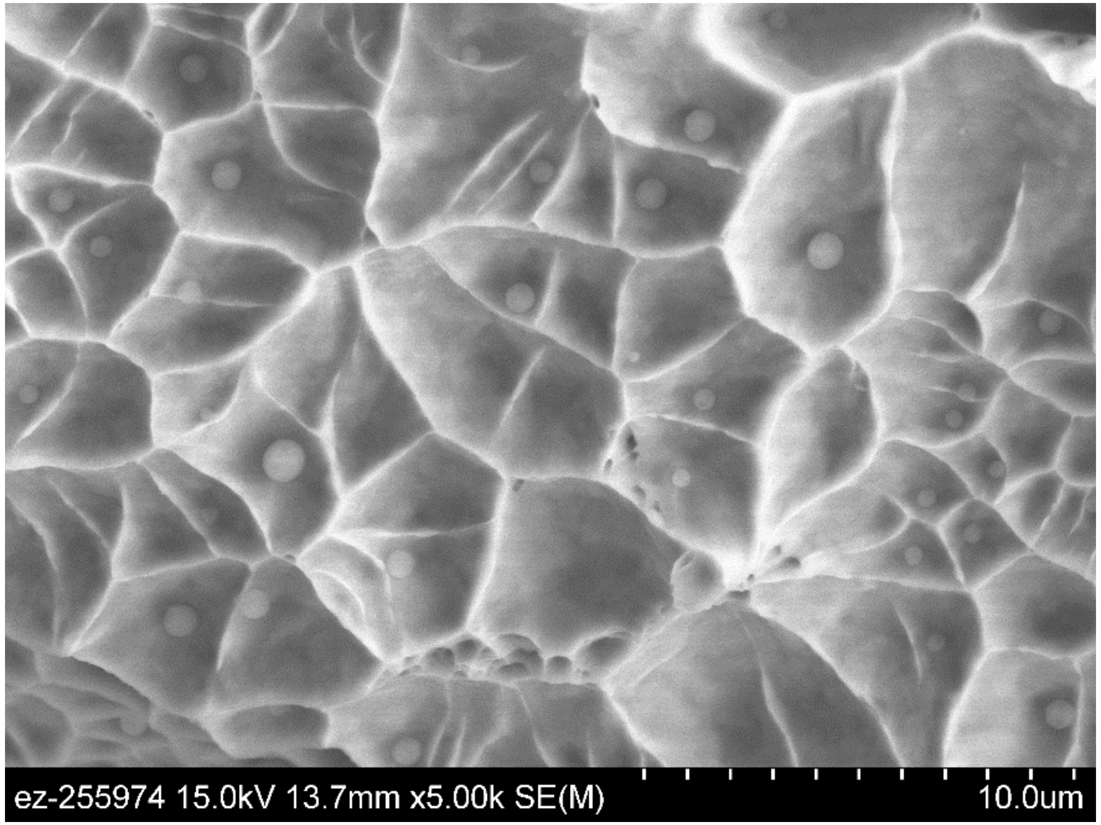
(US Steel, API 5L-X65Q/PSL-2, 8.625" OD, 0.12%C, 0.37Ceq)

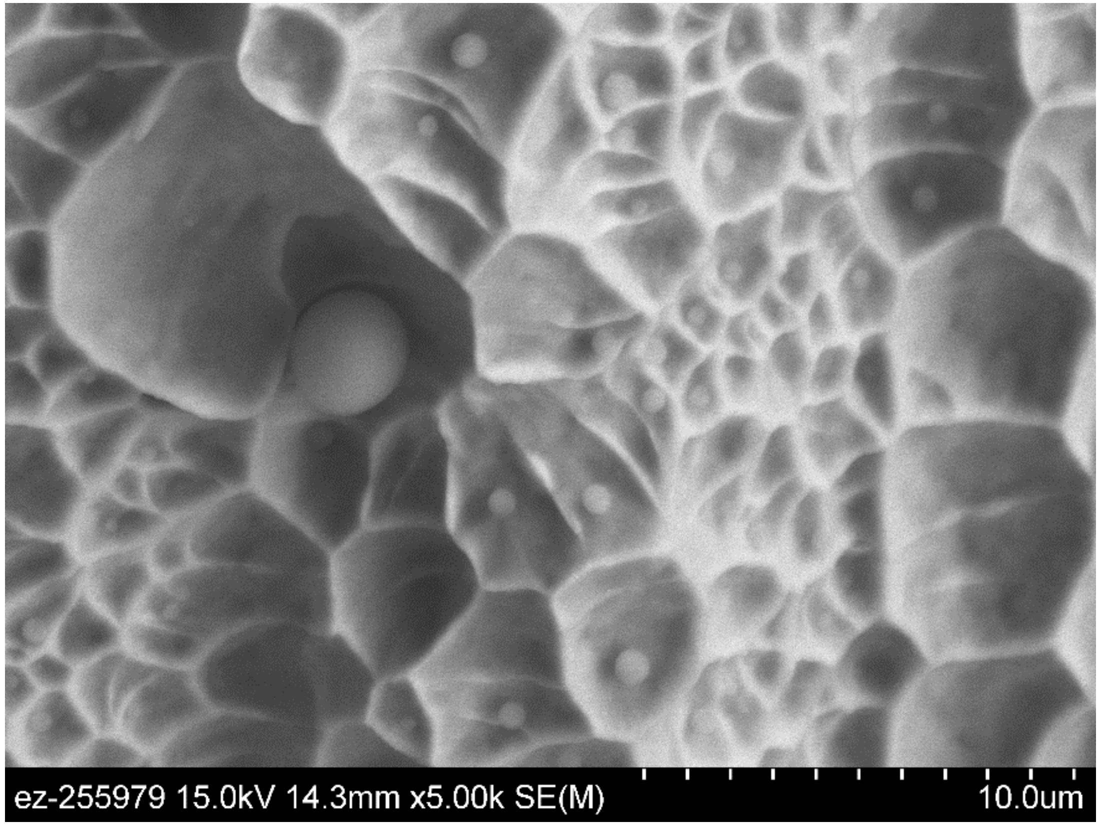




Weld	Notch location	Notch orientation	Abs. energy, J (ft-lb)	Lateral expansion (mm)	Shear area (%)
X65-1764	WCL	TL	35.7 (26.3)	0.42 0.017 (in)	55
X65-1766	WCL	TL	27.7 (20.0)	0.28 0.011 (in)	48.3

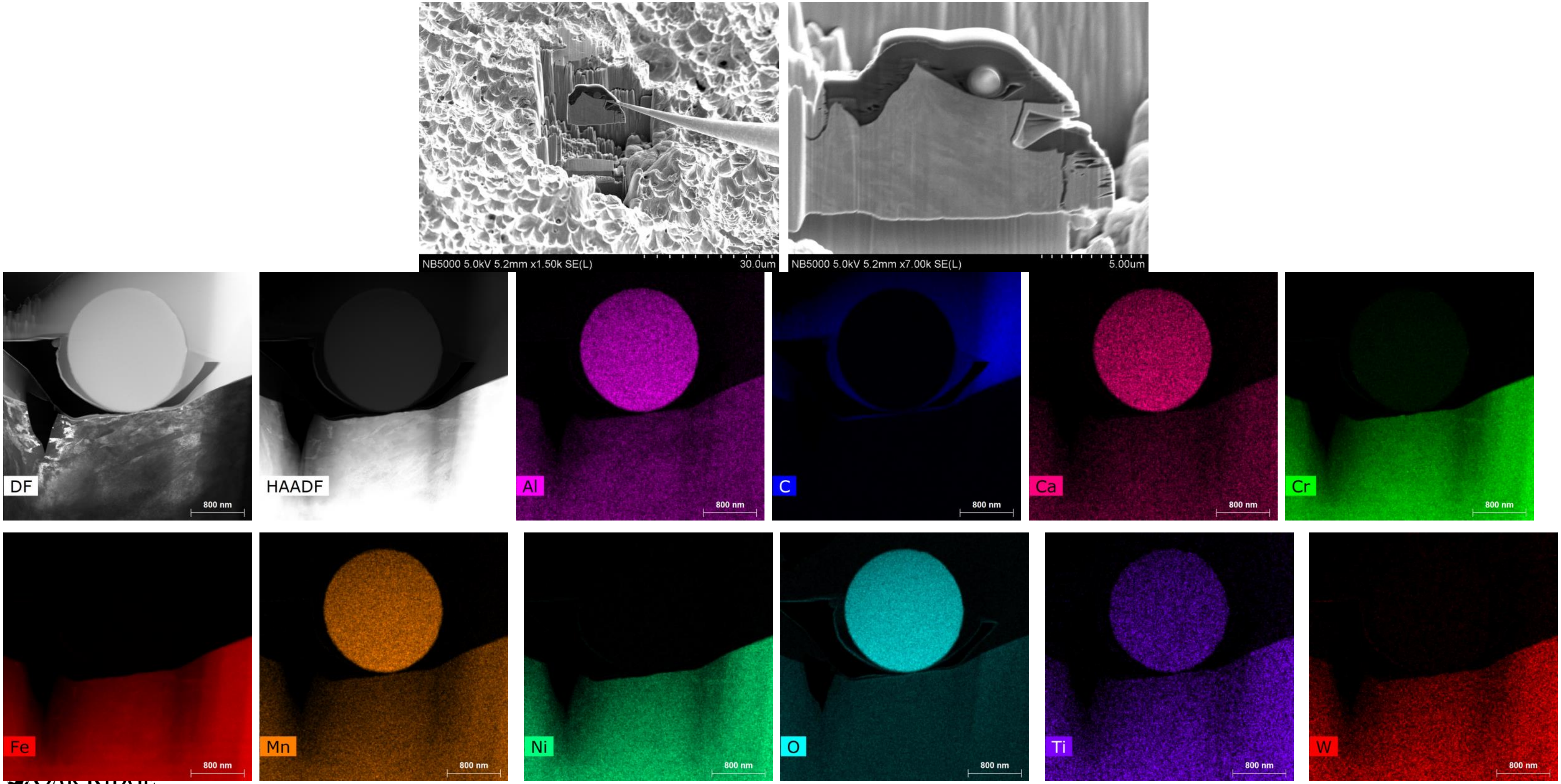
Fracture surface shows ductile fracture but many micron sized inclusions in the dimples (X65-1764 weld metal)





Similar observations for armored steels – inclusions reduce the toughness

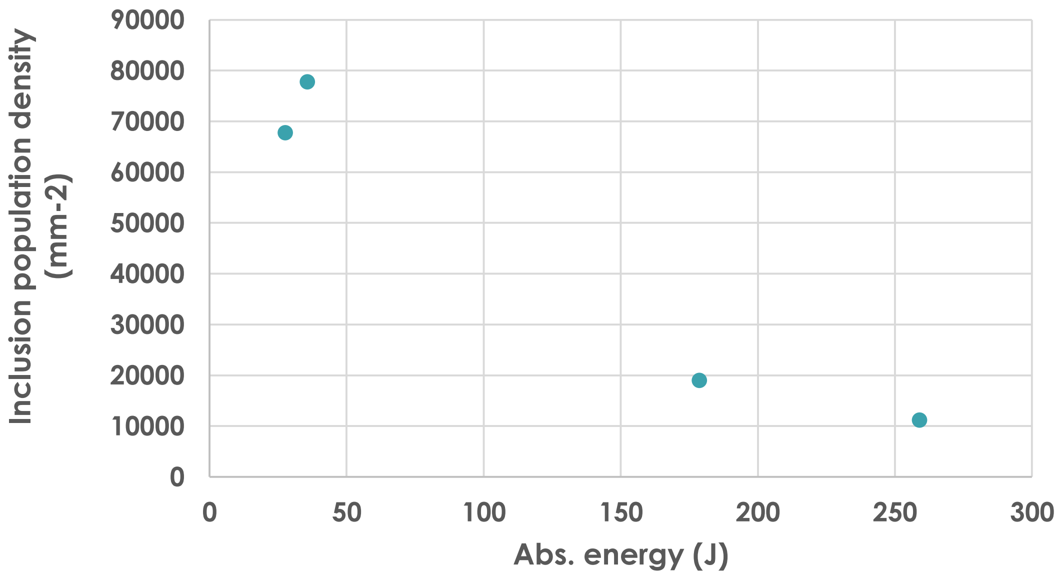
TEM analysis confirmed the inclusions are Mn and Al rich oxides



Second round development: Improving Weld Metal CVN Toughness

- Approach: reduce oxidation during welding by refining welding process conditions and shielding gas chemistries

Welding Conditions	Abs. energy J (ft-lb)	Lateral expansion (mm)	Shear area (%)
X65-1, L1764, Baseline Conditions	**35.7 (26.3)**	0.42 0.017 (in)	55
X65-2, L1766, Baseline Conditions	**27.7 (20.0)**	0.28 0.011 (in)	48.3
X65-3, LNi10, Improved Conditions	**259 (191.3)**	1.81 0.071 (in)	100
X65-4, L1764, Improved Conditions	**178.7 (132)**	1.52 0.06 (in)	100



Successfully solved the low toughness issue of first round weld wires

- Round 2: two of the weld wires yielded weld metal Charpy impact value of **259 J and 178 J** respectively, far exceeding the CVN requirement for highest steel grade (X120) of 108 J per API Specification 5L.

Table 8 — CVN absorbed energy requirements for pipe body of PSL 2 pipe

Specified outside diameter D mm (in)	Full-size CVN absorbed energy, minimum K_V J (ft·lbf)						
	Grade						
	≤ L415 or X60	> L415 or X60 to ≤ L450 or X65	> L450 or X65 to ≤ L485 or X70	> L485 or X70 to ≤ L555 or X80	> L555 or X80 to ≤ L625 or X90	> L625 or X90 to ≤ L690 or X100	> L690 or X100 to ≤ L830 or X120
≤ 508 (20.000)	27 (20)	27 (20)	27 (20)	40 (30)	40 (30)	40 (30)	40 (30)
> 508 (20.000) to 762 (30.000)	27 (20)	27 (20)	27 (20)	40 (30)	40 (30)	40 (30)	40 (30)
> 762 (30.000) to 914 (36.000)	40 (30)	40 (30)	40 (30)	40 (30)	40 (30)	54 (40)	54 (40)
> 914 (36.000) to 1 219 (48.000)	40 (30)	40 (30)	40 (30)	40 (30)	40 (30)	54 (40)	68 (50)
> 1 219 (48.000) to 1 422 (56.000)	40 (30)	54 (40)	54 (40)	54 (40)	54 (40)	68 (50)	81 (60)
> 1 422 (56.000) to 2 134 (84.000)	40 (30)	54 (40)	68 (50)	68 (50)	81 (60)	95 (70)	108 (80)

Summary

- Phase I development of LTPT weld wires has been successful and achieved its objectives:
  - No pre-heat and post weld heat treatment
  - No HIC and other weld defects
  - Met or exceeded all API specification requirement for weld metal
  - Superior weld metal Charpy toughness
  - Over-matched weld metal strength
- Strong industry support and participation
  - Oil/gas companies: ExxonMobil, Shell
  - Weld consumable companies: Lincoln Electric, ESAB
  - Steel suppliers: JFE, ArcelorMittal
  - PRCI

Plan for Phase II: Complete lab R&D and transition to field test by industry

- Refine the weld wire chemistry to reduce the strength for better matching with X80-X100 pipelines
  - Perform additional welding and testing on X65 and other pipeline steels with learn and rich chemistry.
  - In-depth study of the microstructure of the partial melting region and microhardness
- Provide welded samples to industry partner for corrosion and stress corrosion test for sour service conditions
- Work with Industry such as ExxonMobil for field test
  - On full scale pipeline selected by industry
  - Welding and testing will be done at an industry site to simulate/mimic real-world welding construction and repair on the field
- Scale-up LTPT weld wire production and commercialization

Example of field welding for illustration only (Courtesy of ExxonMobil)

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Thank you!

- Comments, Questions, Recommendations