Impact of Weld Microstructures on Fracture Toughness in Gaseous Hydrogen for X-Series Pipeline Steels

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Background and Motivation

Industrial Problem: The current building code for hydrogen pipelines (ASME B31.12) does not consider the microstructural aspects in the weldments and their influence on hydrogen embrittlement (HE).

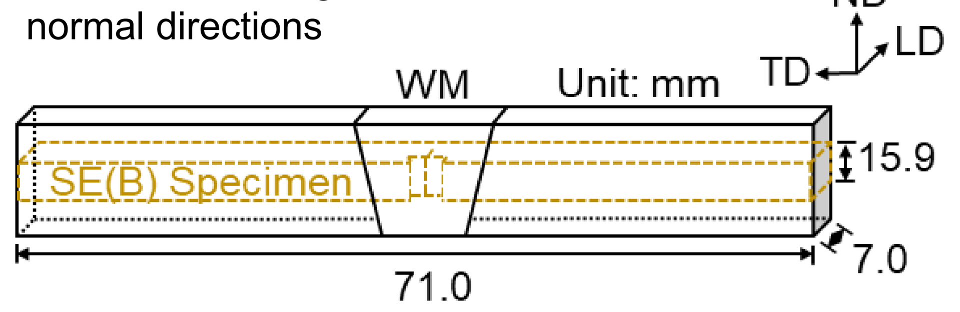
Project Goal: Provide a microstructure-based weld pathway for testing H2 pipeline weldments in air and gaseous hydrogen to support industry with a correlation among welding parameters, filler chemistry, microstructure and mechanical performance to reduce the risk of hydrogen-related degradation.

Methods

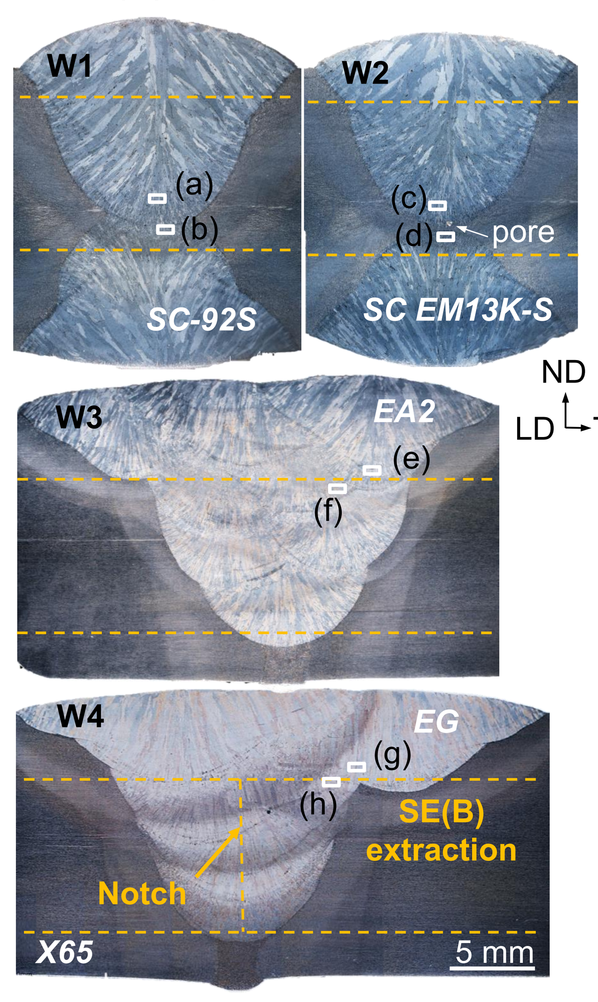
- This project initiated with physical simulation of HAZ subzone microstructures via Gleeble thermal cycling guided by finite element modeling of welding processes [1].
- This study focused on weld metal (WM) evaluation, which was extracted from a matrix of over thirty welds with varying filler chemistries and welding parameters to evaluate the fracture toughness and crack behavior.
- **Mechanical Testing**: Single-edge bend tests (SE(B)) in-situ gaseous hydrogen to determine the plane-strain fracture toughness
- **Fractography and Metallurgical Analysis**: Optical and scanning electron microscopy (SEM) with electron backscatter diffraction (EBSD) of select conditions.

SE(B) Geometry and Welding Parameters

LD, TD, ND: Longitudinal, transverse, and normal directions



SE(B) Specimen Extraction

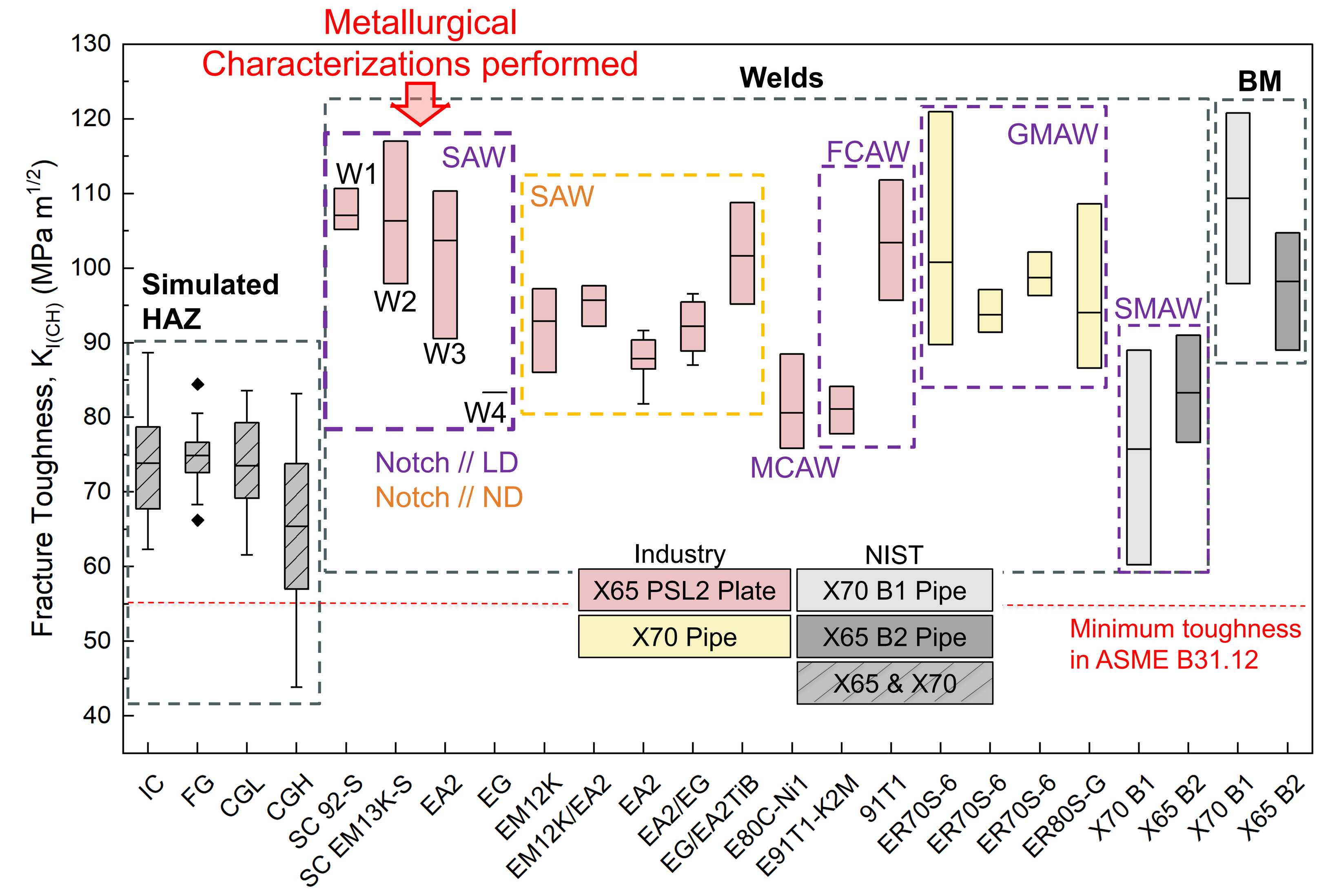


Welding Conditions for SAW Conditions W1-4

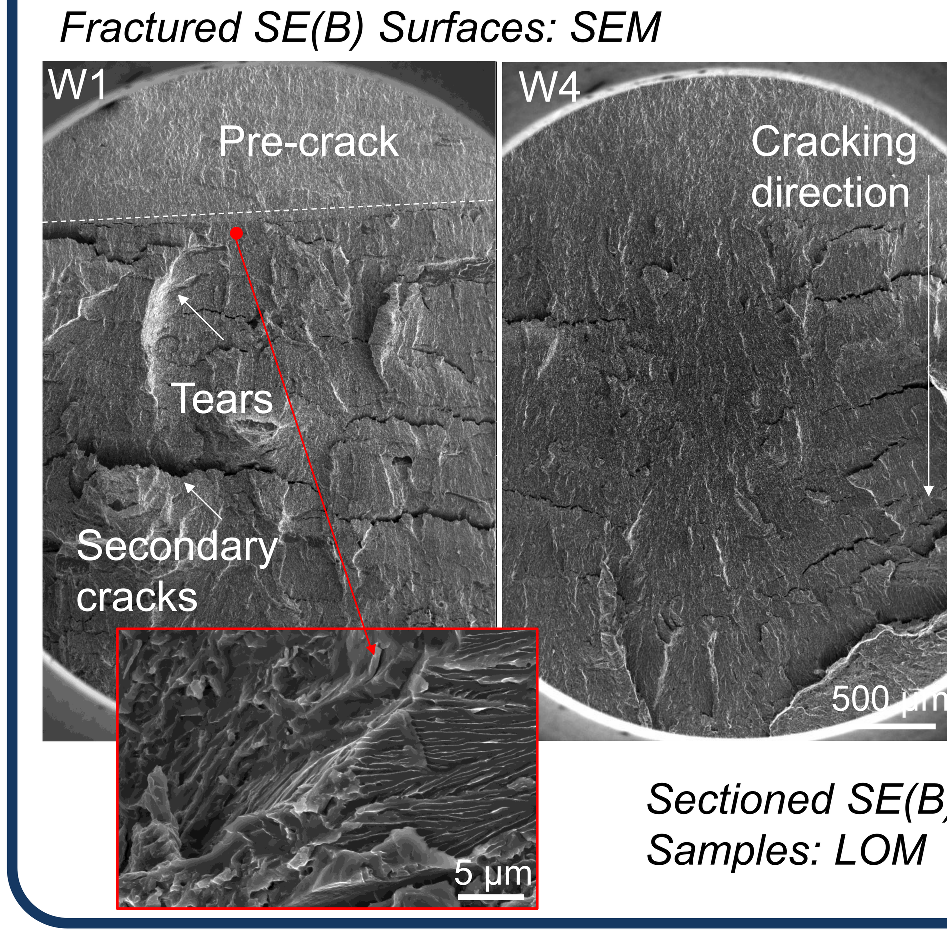
Specimen #	Filler Metal (AWS)	Joint Design	Pass Sequence	Heat Input (kJ/mm)
W1	SC 92-S	Double-V	Root + cap	2.2–2.8
W2	EM13K-S	Double-V	Root + cap	2.2–2.8
W3	EA2	Single-V	1 root + 9 fill/cap	1.8–2.0
W4	EG	Single-V	1 root + 7 fill/cap	2.3–2.5

- W3-4 SE(B) specimens contain more reheated fusion zone (FZ) area than W1-2.
- Filler chemistry of W4 promotes acicular ferrite (**AF**) by including carbide formers such as Ti, suppressing the formation of carbon-rich microstructure constituents.

SE(B) Test in H_2 Atmosphere

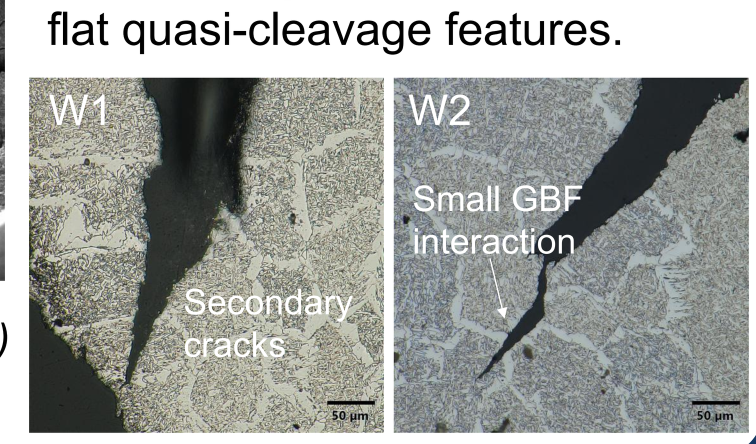


Fractured SE(B) Surfaces: SEM



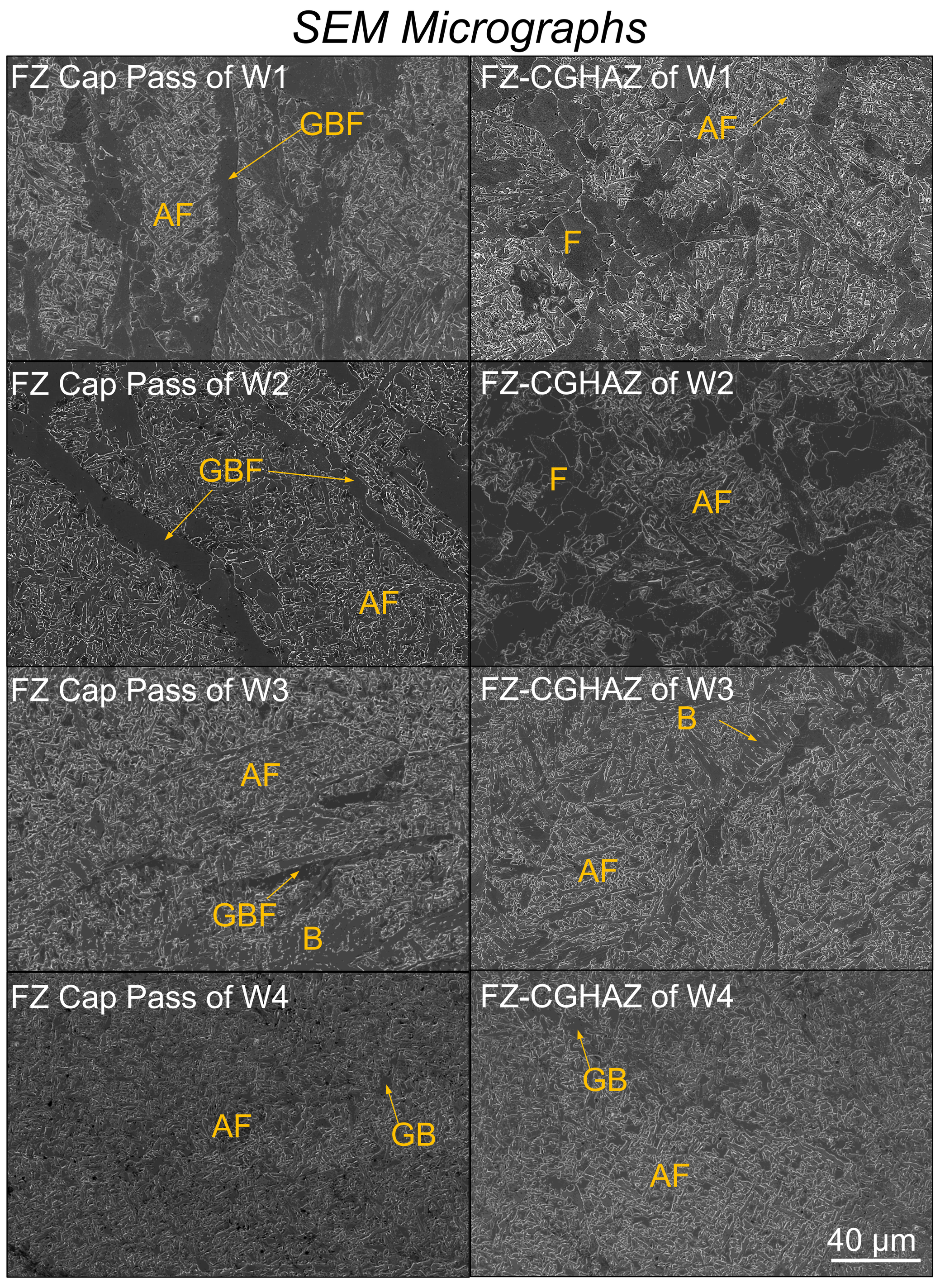
- W1-4 all showed secondary cracking and tearing, but W1-2 exhibited a coarser fracture surface, promoted by the columnar microstructure and thick GBF.
- Higher-magnification SEM showed that all conditions cracked via brittle transgranular fracture with flat quasi-cleavage features.

Sectioned SE(B) Samples: LOM



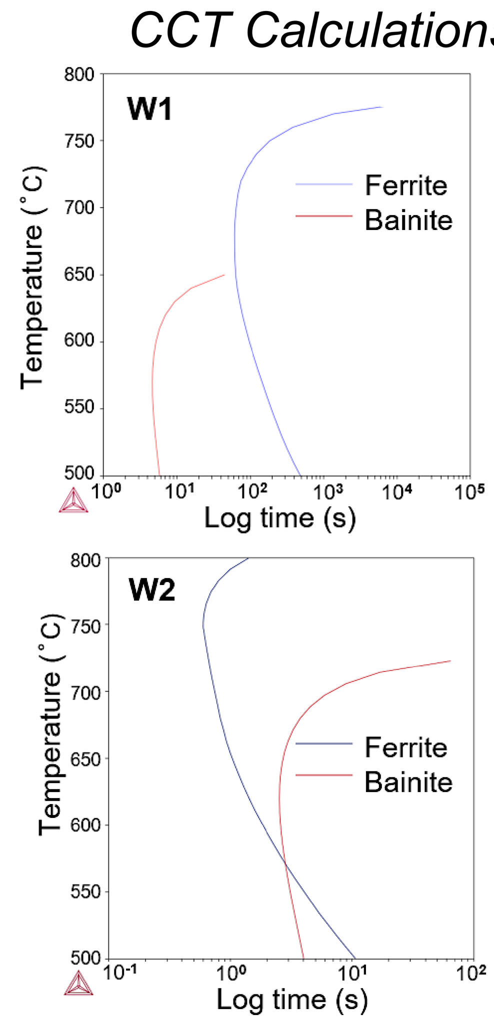
Metallurgical Characterization: Microstructure Impact on Toughness, $K_{IC(H)}$

SEM Micrographs



F: ferrite; **AF**: acicular ferrite; **GBF**: grain boundary ferrite; **B**: bainite; **GB**: granular bainite; **UB**: upper bainite

CCT Calculations

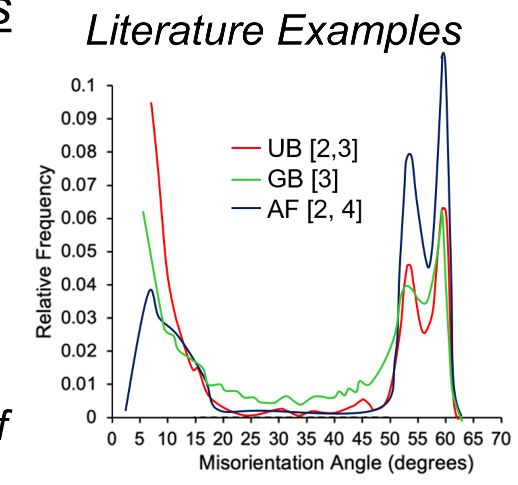


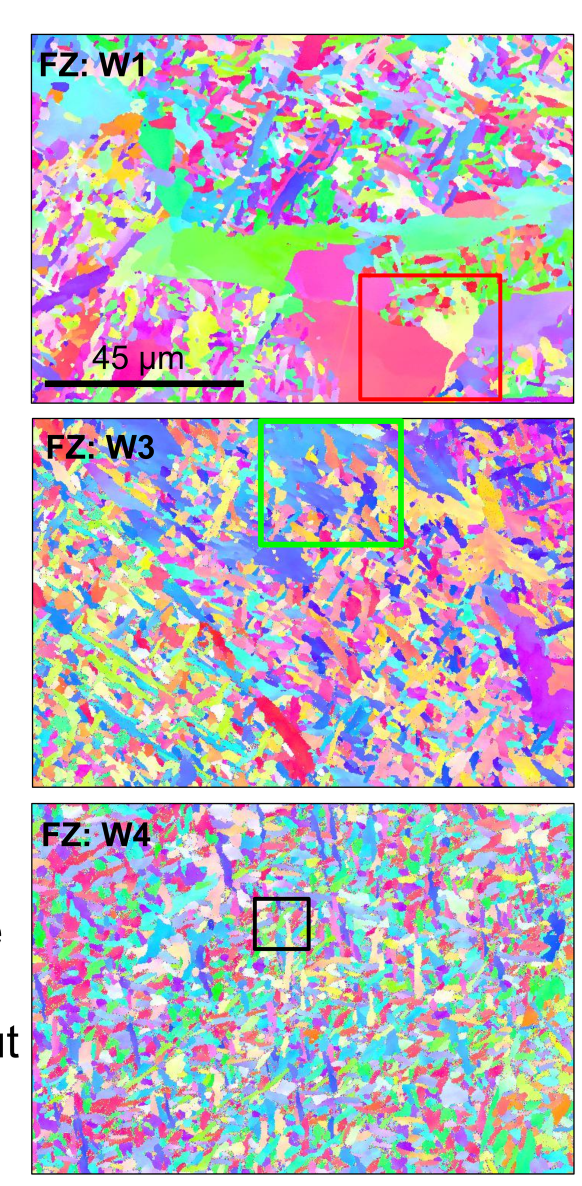
- W2 with fewer austenite stabilizers exhibits thicker GBF than W1.
- W3 with smaller pass size exhibits thinner GBF.
- W4, with higher heat input but an AF promoting filler, exhibits little to no GBF.

EBSD Identification of Microstructural Constituents

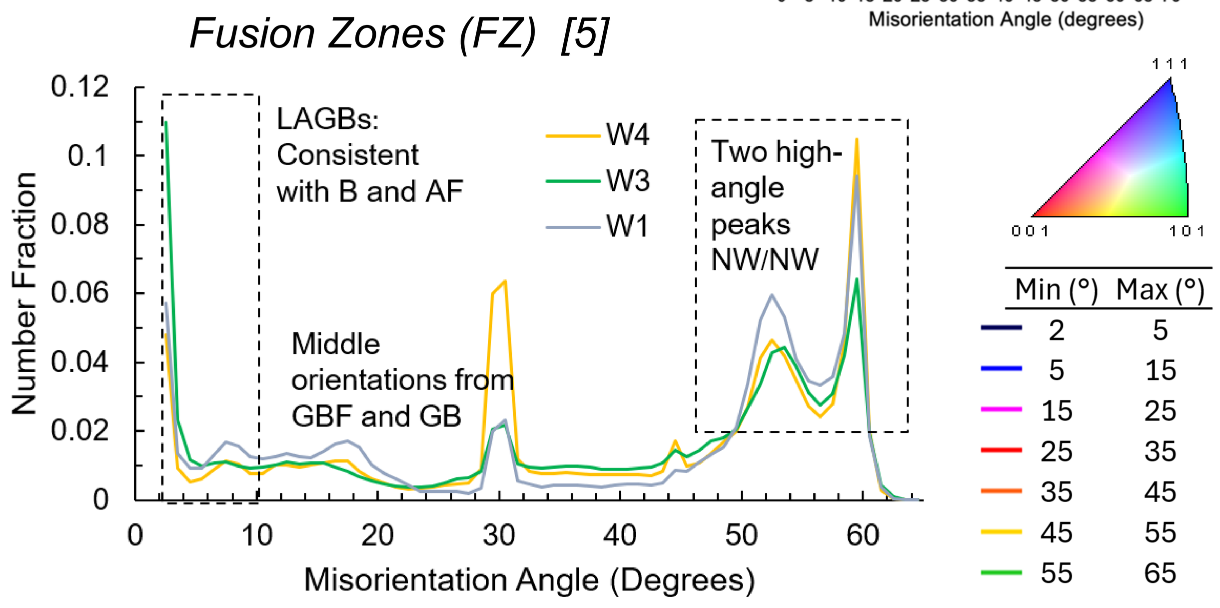
- The misorientation angle distributions from the weld subregions further confirmed the microstructural constituents identified from morphological analysis.

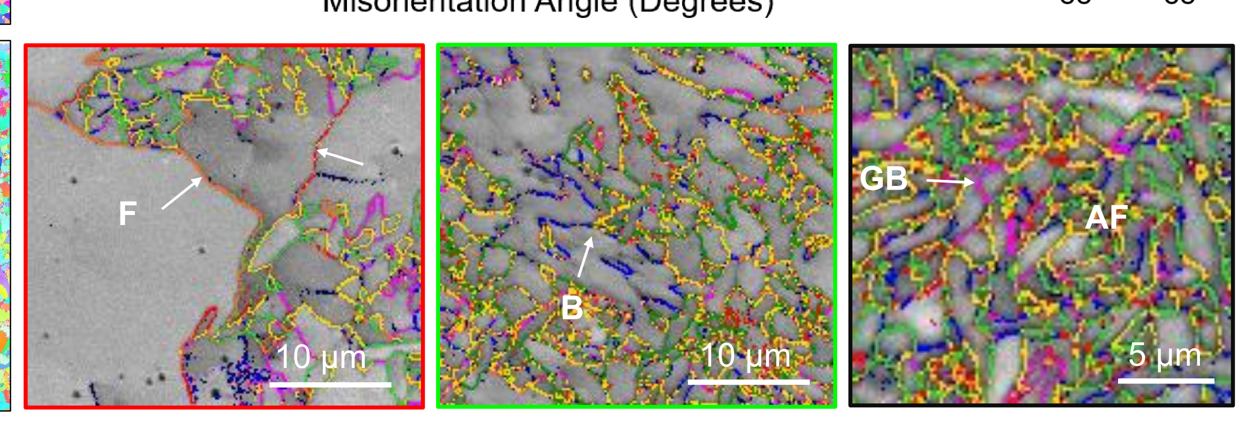
Literature Examples





Misorientation Distributions of Fusion Zones (FZ) [5]





Conclusions and Future Work

- The simulated HAZ subzones average the lowest fracture toughness, while the weld metals showing comparable toughness to the base metals in gaseous hydrogen.
- The lower fracture toughness of W3 and W4 can be attributed to a larger area fraction of reheated fusion zones and minimal to no grain boundary ferrite (GBF).
- The fracture mode is predominantly brittle transgranular fracture, with W1-2 having large secondary cracks that propagate through the GBF into the surrounding AF within the grain interior. W3 and W4 exhibit brittle transgranular fracture through the AF but have finer secondary cracks and fewer large flat facet features.
- W4, with primarily acicular ferrite (AF), exhibited the lowest average fracture toughness in hydrogen of the SAW conditions with the notch along the welding direction.
- **Future Work:** Complete metallurgical analysis; and tailor the weld metal microstructure of the pipe to maximize local fracture toughness as a function of crack path.

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References: [1] J. McCloskey et al., *Pressure Vessels and Piping Conference,* PVP2025-154282, July 2025 [2] H. M. Flower and T. C. Lindley, *Materials Science and Technology*, vol. 16, no. 1, pp. 26–40, Jan. 2000 [3] S. Zajac, V. Schwinn, and K. H. Tacke, *MSF*, vol. 500–501, pp. 387–394, Nov. 2005 [4] A. Church, et al., *Metall. Mater. Trans. A*, vol. 56, Dec. 2024 [5] L. Hines et al., *Pressure Vessels and Piping Conference,* PVP2026-179172, July 2026