# Effect of Substrate Composition on Liquid Metal Embrittlement Susceptibility in 3rd Gen AHSS

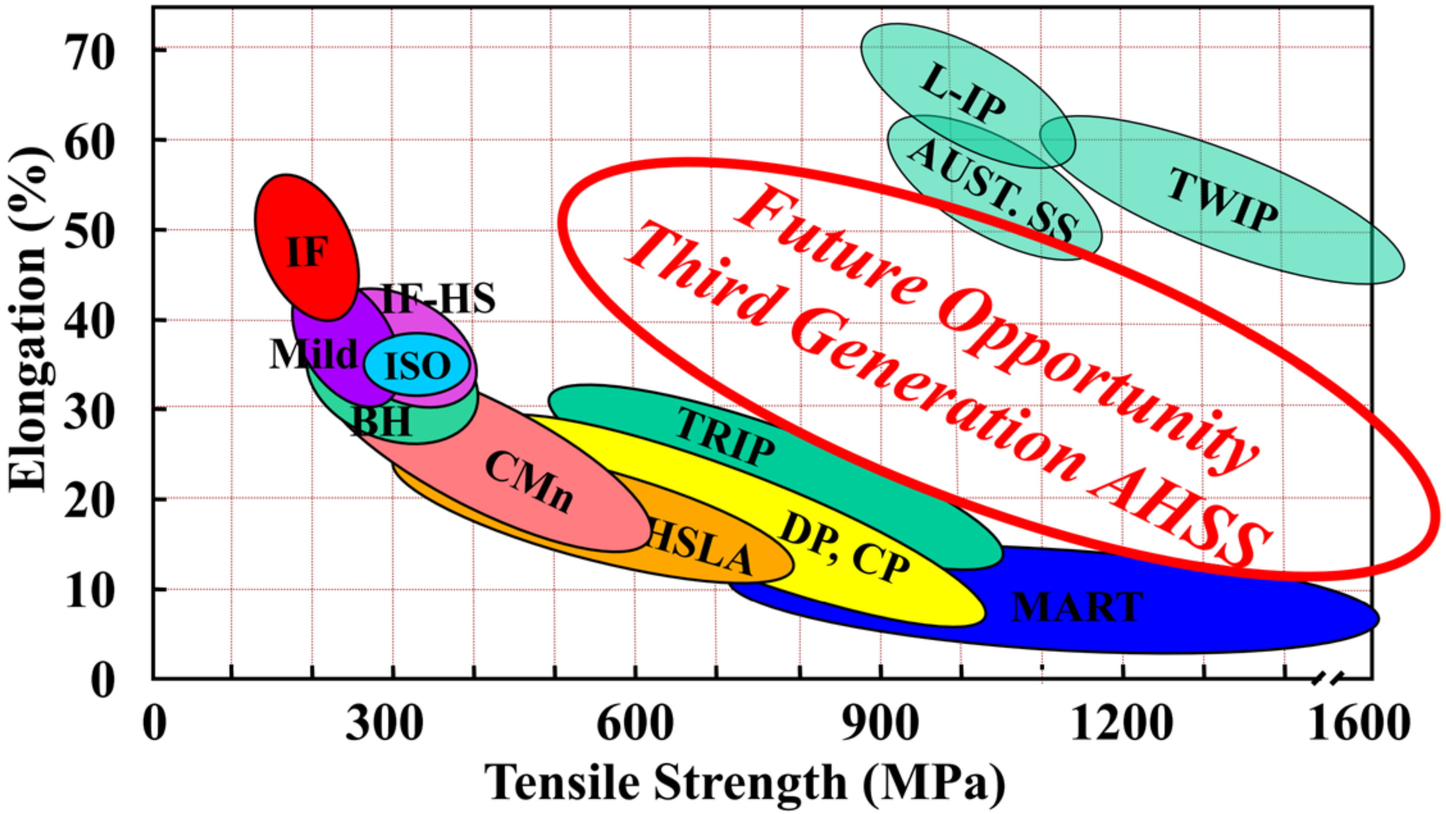
Jake Colburn

*Advanced Steel Processing and Products Research Center*

*Colorado School of Mines*

Advanced Steel Processing & Products Research Center

# 3rd Gen AHSS

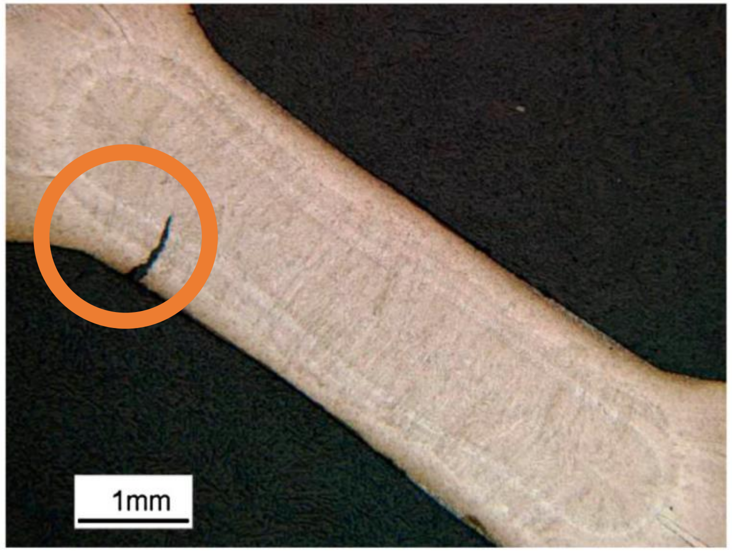


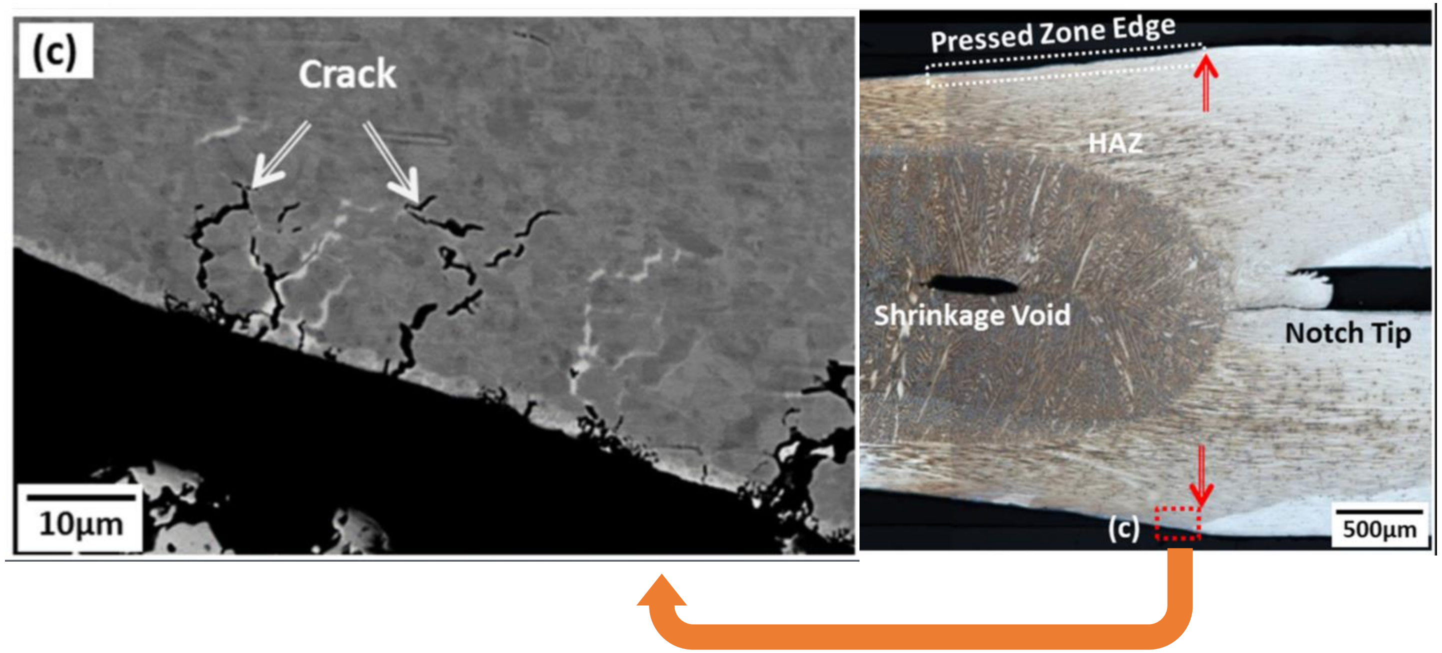

**Desire for lighter, stronger automotive bodies**

→ ***3rd Generation advanced high strength steels***

D. K. Matlock and J. G. Speer, "Processing Opportunities for New Advanced High-Strength Sheet Steels," *Materials and Manufacturing Processes*, vol. 25, no. 1–3, pp. 7–13, Mar. 2010.

# Cracking During RSW



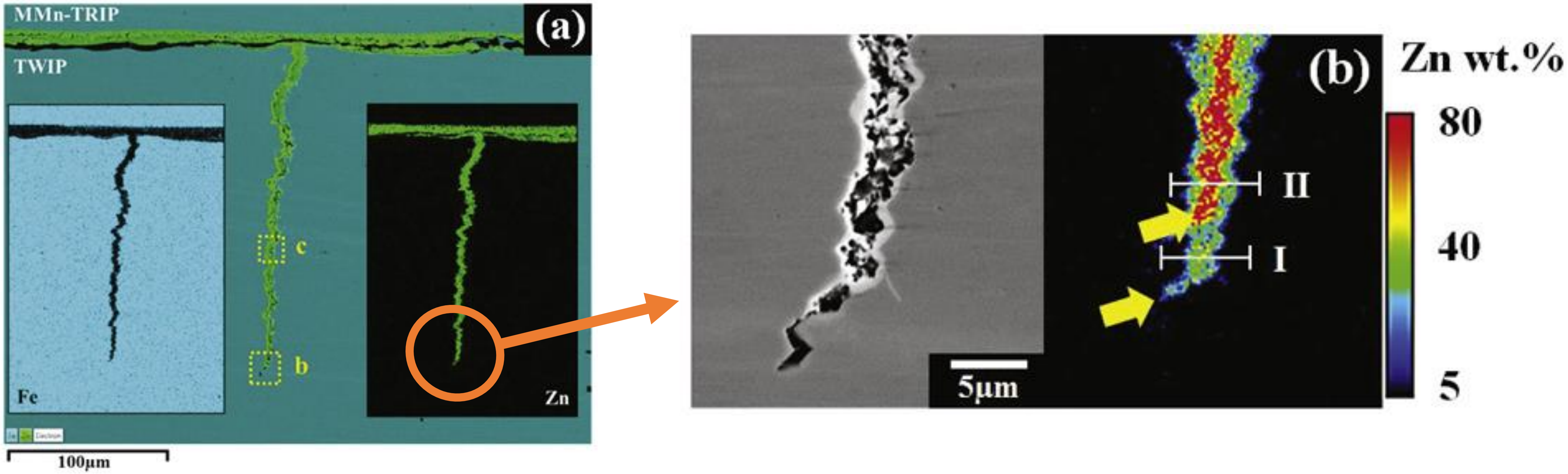

**Liquid metal embrittlement causes *cracking* in resistance spot welds of 3rd Gen AHSS**

**→ *Difficulty in implementation of 3rd Gen AHSS***

C. Beal, et al., "Embrittlement of a Zinc Coated High Manganese TWIP Steel," *Materials Science and Engineering*, vol. 543, pp. 76-83, May 2012.

Lee et al., "Microstructural evolution of liquid metal embrittlement in resistance-spot-welded galvanized TWinning-Induced Plasticity (TWIP) steel sheets," *Materials Characterization,* vol. 148, pp. 233-241, Jan 2019.

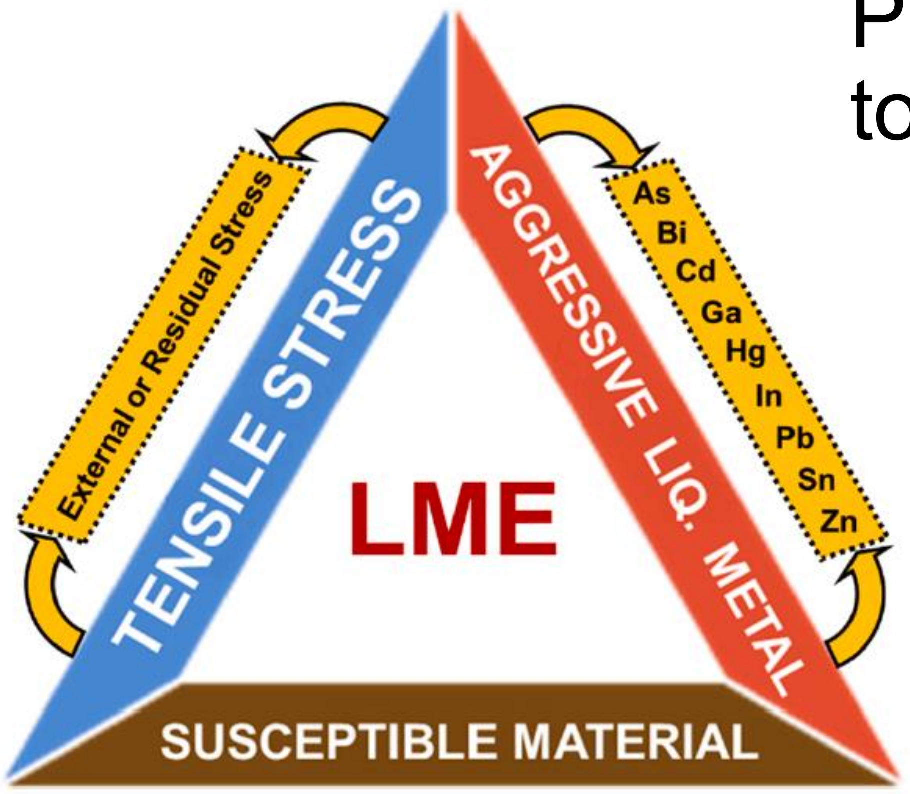
# Liquid Zinc and Crack Path




**LME *crack path* coincides with <u>presence of Zn</u> from galvanized coating**

M. H. Razmpoosh, E. Biro, D. L. Chen, F. Goodwin, and Y. Zhou, "Liquid metal embrittlement in laser lap joining of TWIP and medium-manganese TRIP steel: The role of stress and grain boundaries," *Materials Characterization*, vol. 145, pp. 627–633, Nov. 2018.

# What is LME?




Presence of **three components** leads to **<u>LME</u>**

↓

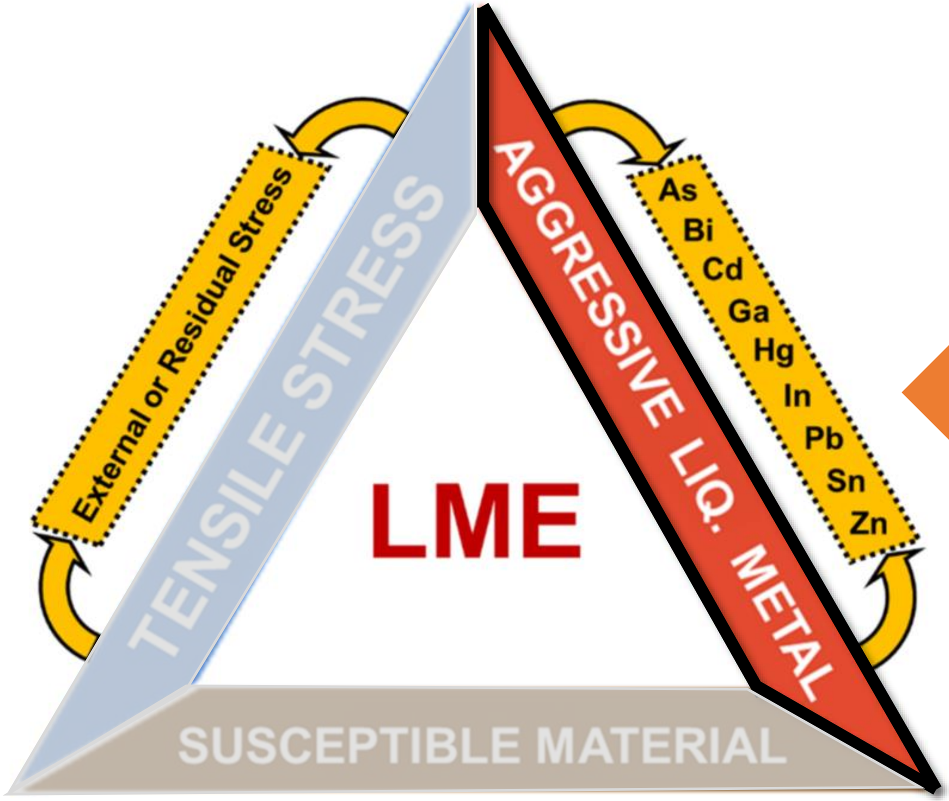
*Decrease in energy for **grain boundary decohesion** due to **grain boundary penetration** of liquid embrittler*

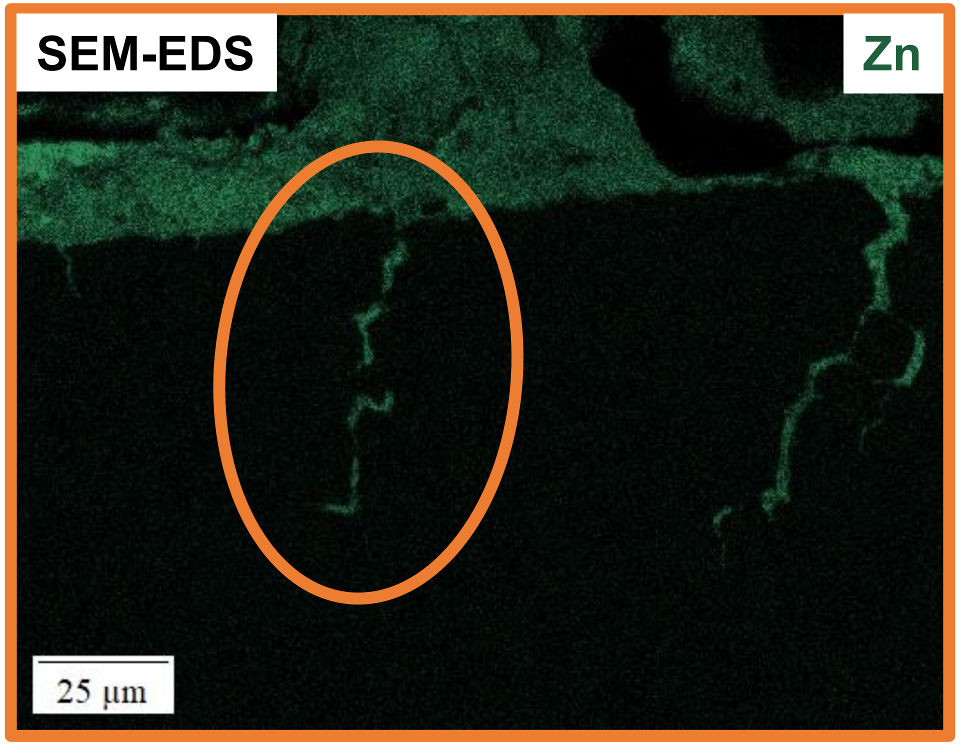
↓

***<u>Crack formation</u>***

M. Razmpoosh, et al., "Pathway to Understand Liquid Metal Embrittlement (LME) in Fe-Zn Couple: From Fundamentals toward Application," *Progress in Materials Science*, vol. 121, pp. 1-29, Aug. 2021.

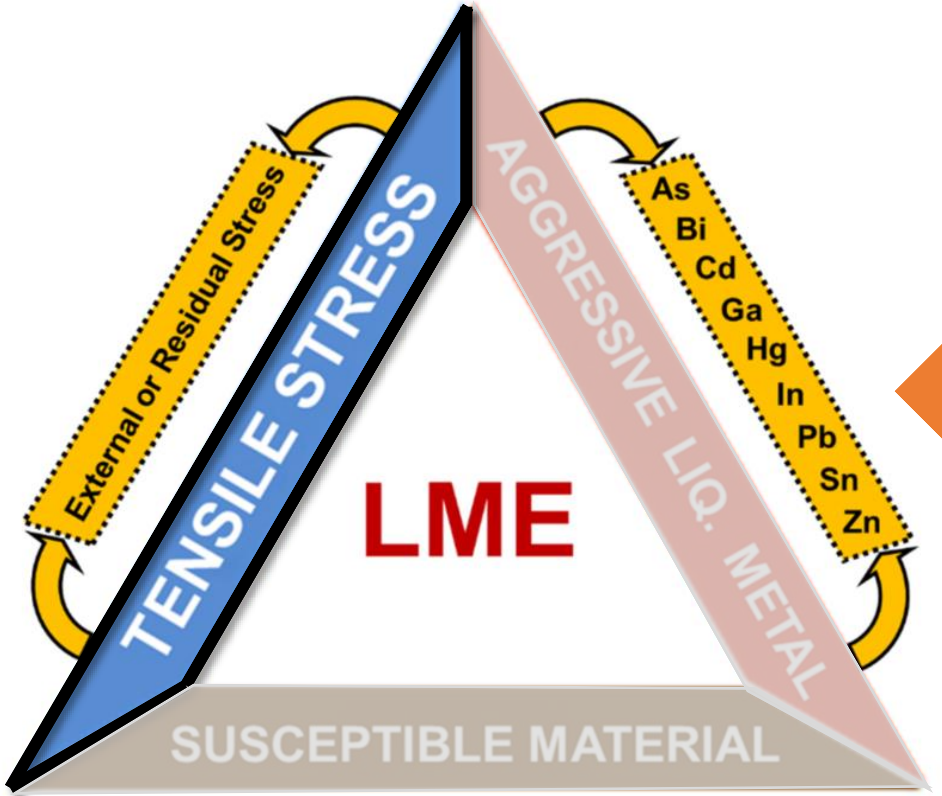
# What is LME?

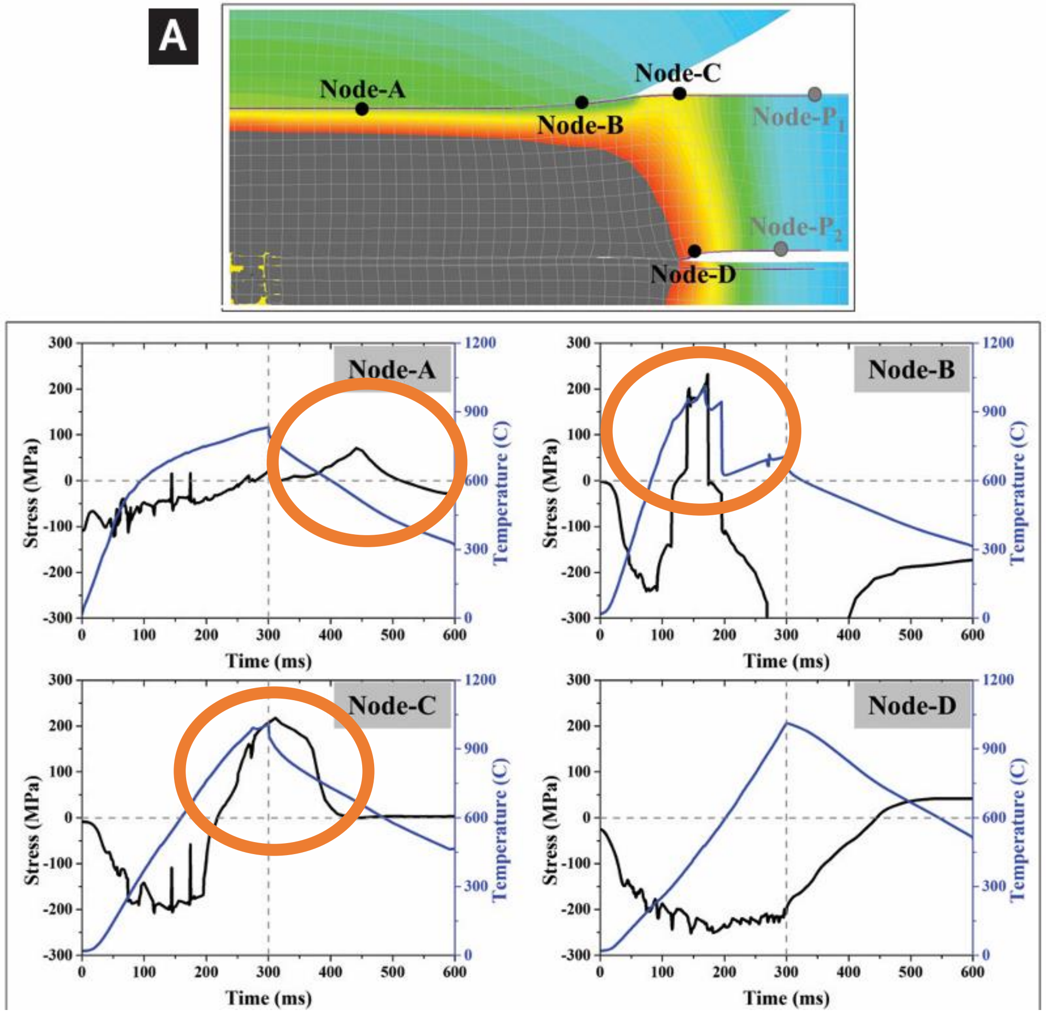



***Liquid zinc*** **($T_m$ = 420 °C) forms during the weld cycle**

# What is LME?

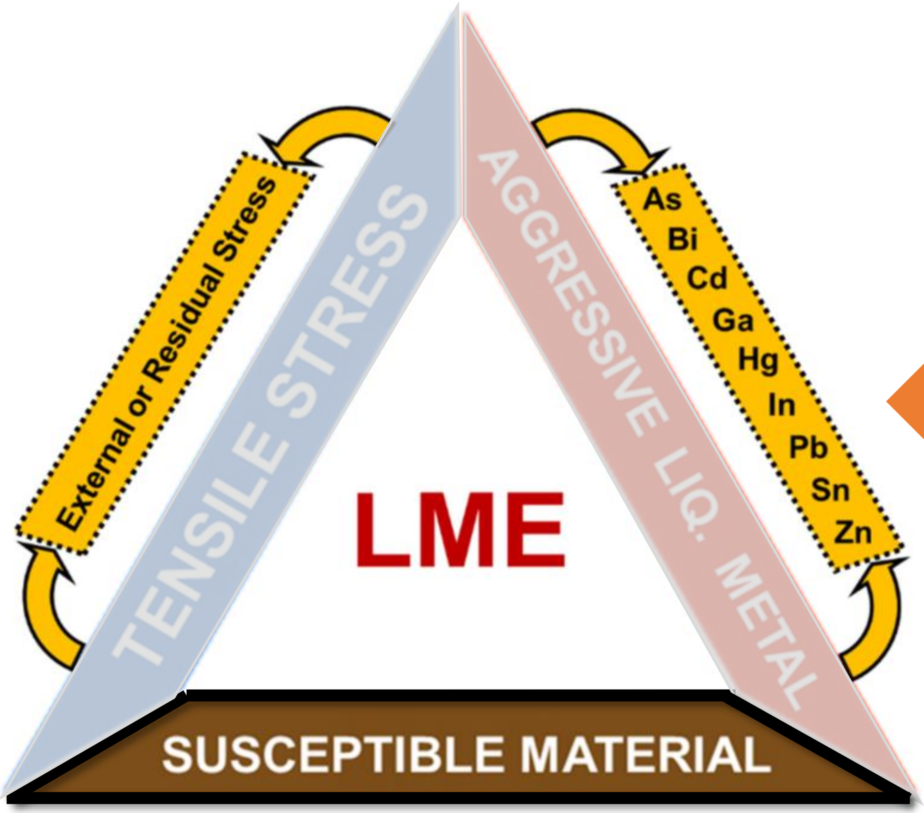


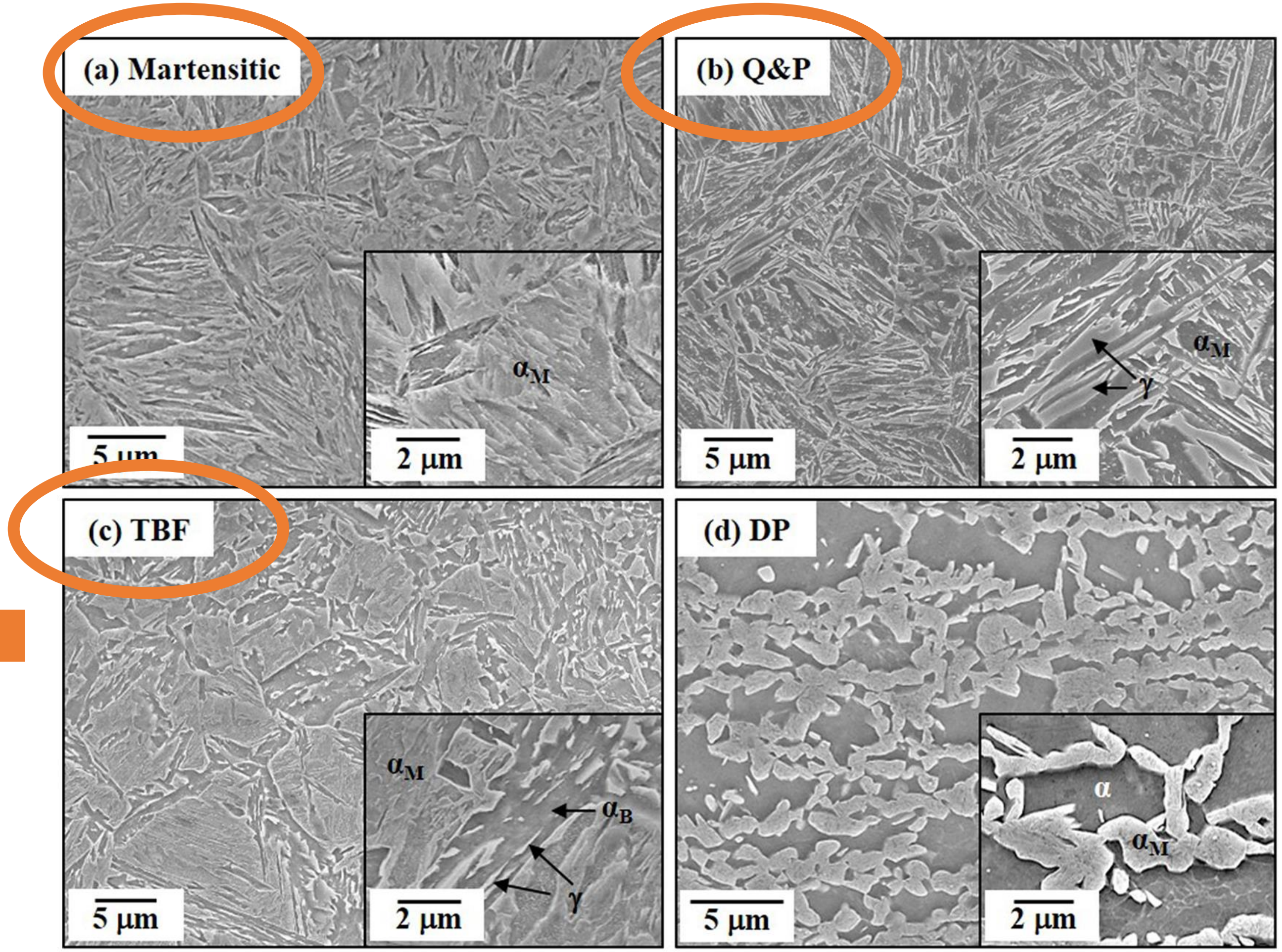




***Tensile stresses*** **form as substrate heated, compressed, and cooled**

S. Murugan, V. Vijayan, C. Ji, and Y. D. Park, "Four Types of LME Cracks in RSW of Zn-Coated AHSS," *Welding Journal*, vol. 99, pp. 75–92, Mar. 2020.

# What is LME?

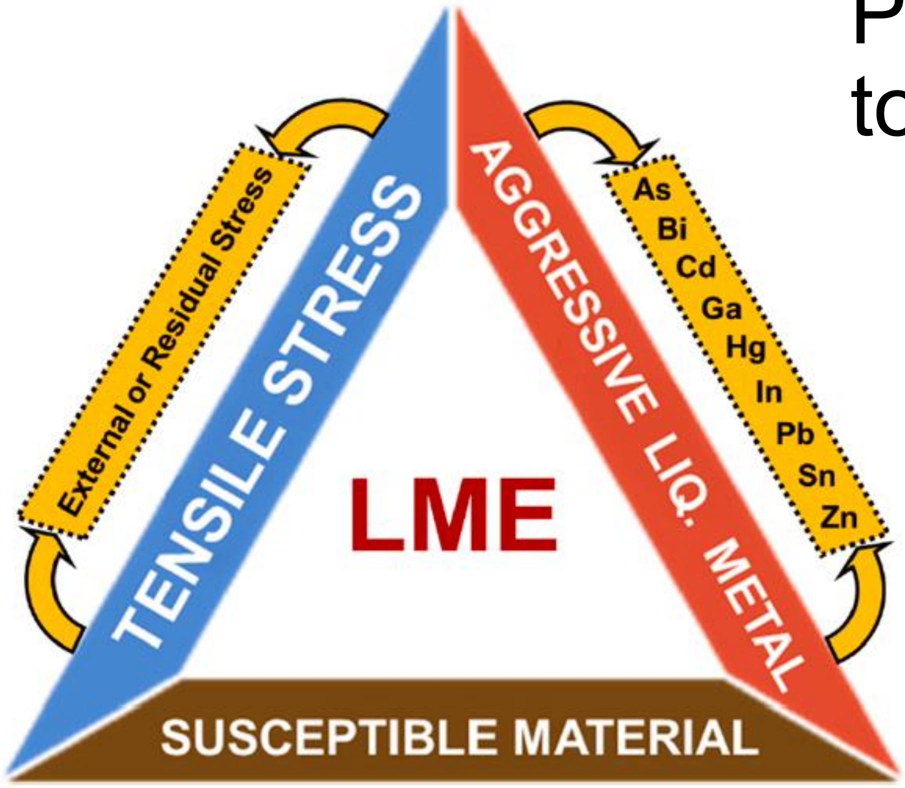



**Generally, *higher strength* (>900 MPa) with *austenite/martensite***

D. Bhattacharya *et al.*, "Influence of the starting microstructure of an advanced high strength steel on the characteristics of Zn-Assisted liquid metal embrittlement," *Materials Science and Engineering: A*, vol. 804, art. 140391, Feb. 2021.

# What is LME?




Presence of **three components** leads to **<u>LME</u>**

↓

*Decrease in energy for **grain boundary decohesion** due to **grain boundary penetration** of liquid embrittler*

→ ***Crack formation***

*Remove a leg of the triangle*

→ ***Mitigate/Prevent LME***

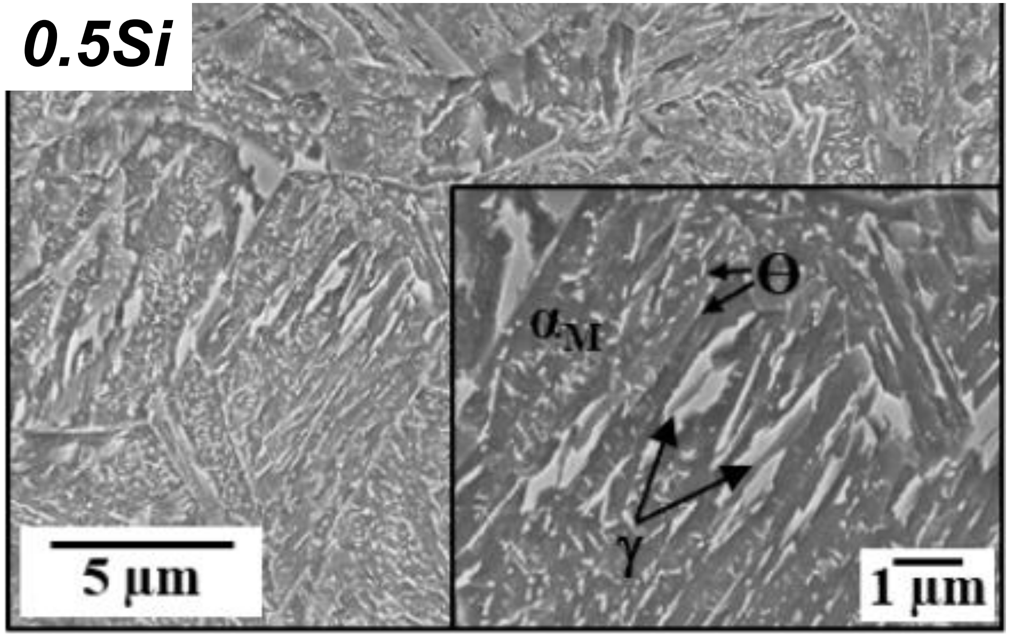
# Example Case: Effect of Substrate Silicon and Aluminum Content on LME Susceptibility

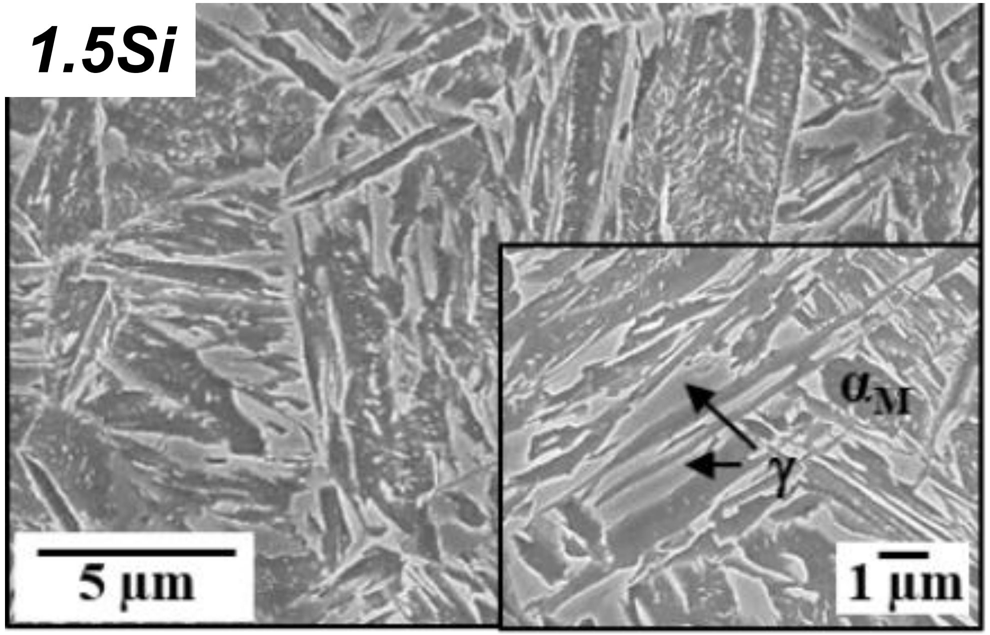
# Example Case: Effect of Substrate Silicon and Aluminum Content on LME Susceptibility

# Si Effect on LME: Material

| Alloy | Si | Al | C | Mn |
|---|---|---|---|---|
| Low Si | 0.5 | 0.05 | 0.25 | 2.67 |
| High Si | 1.5 | 0.05 | 0.25 | 2.67 |

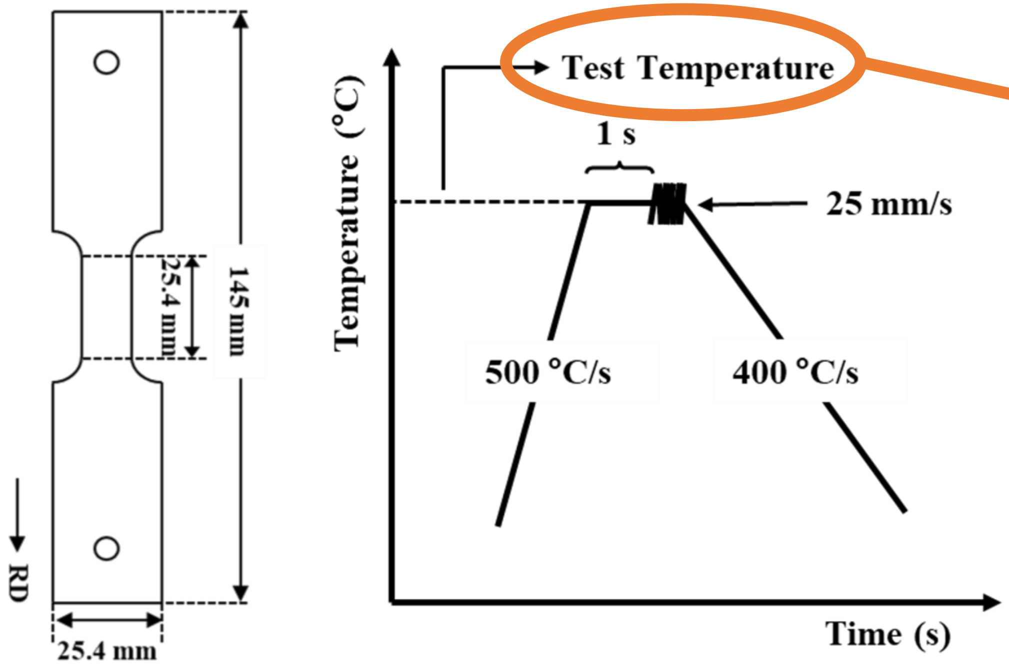
- Laboratory produced
- Hot rolled, cold rolled, continuous annealed
- Electrogalvanized

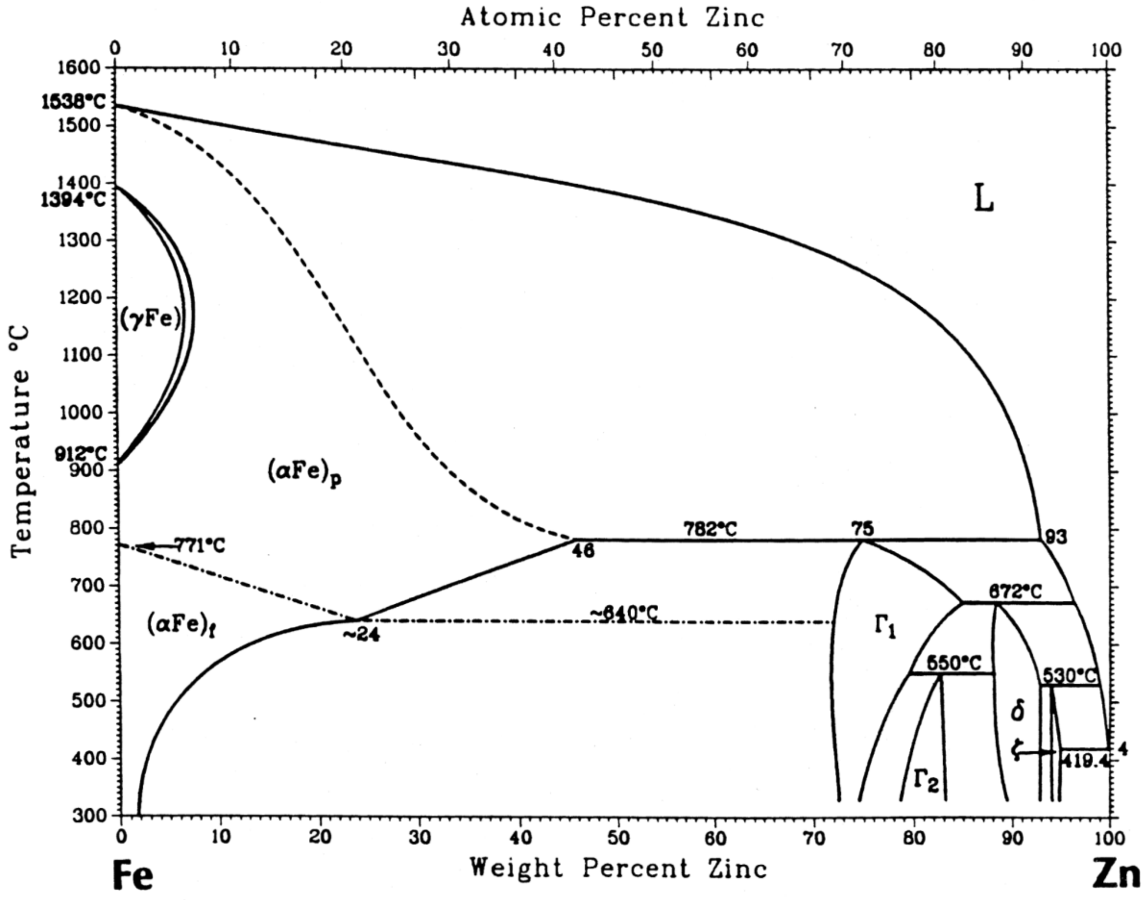


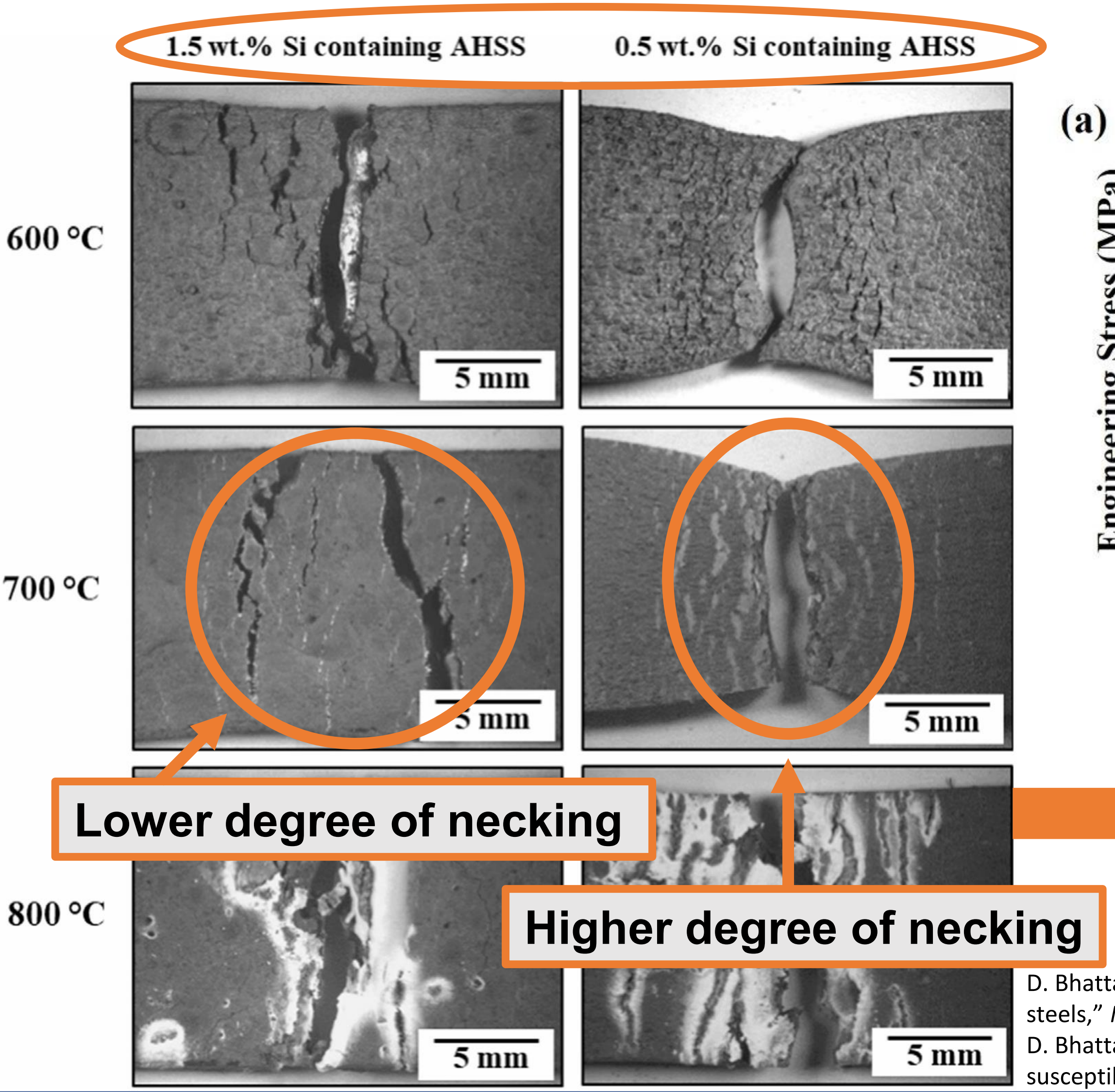
# Hot Tension Testing

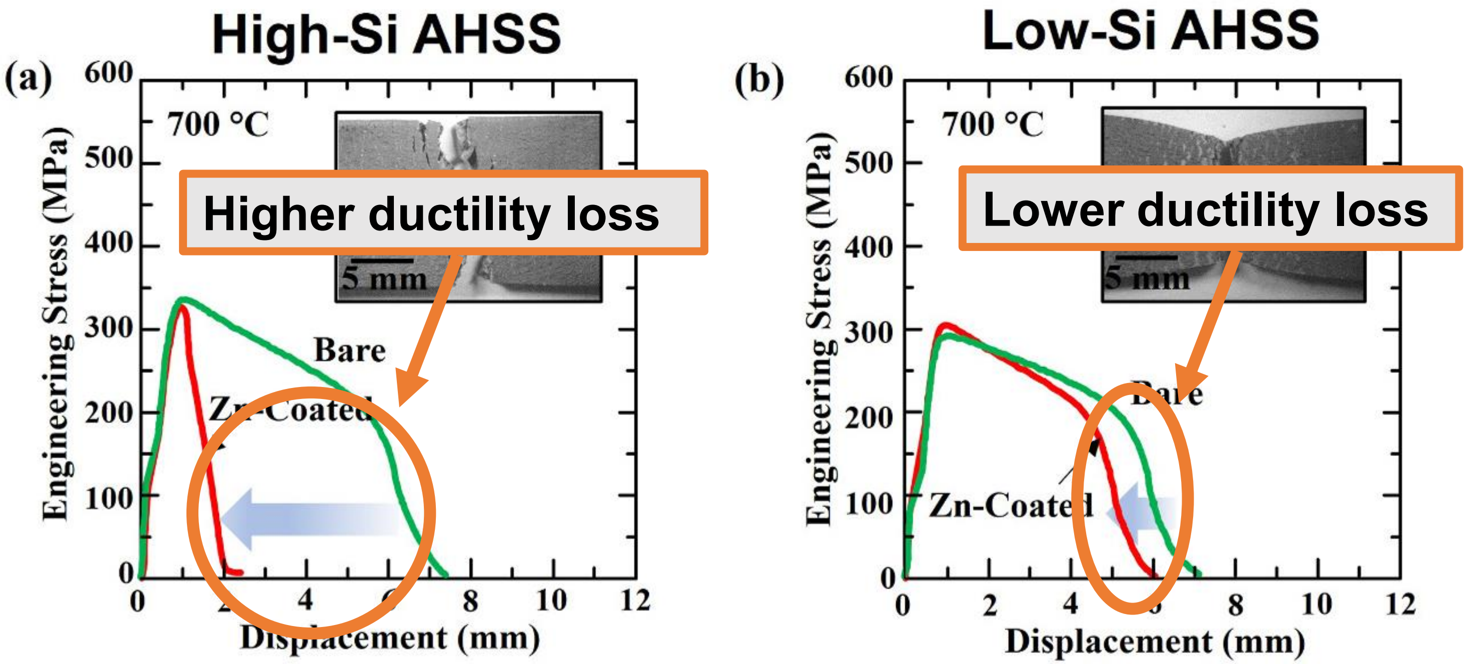
**<u>Thermomechanical simulations</u> of (simplified) RSW *stress and thermal* conditions**



# Si Effect on LME: Hot Tension Testing

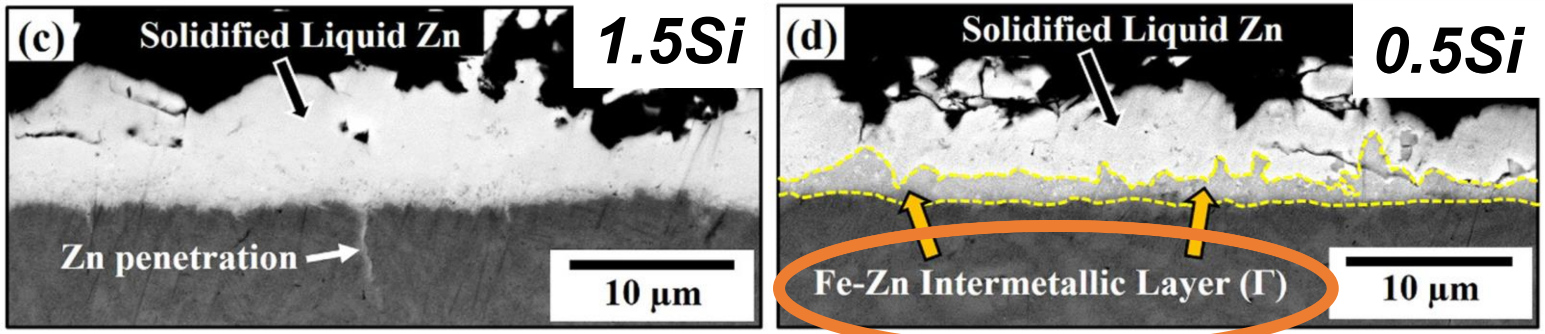


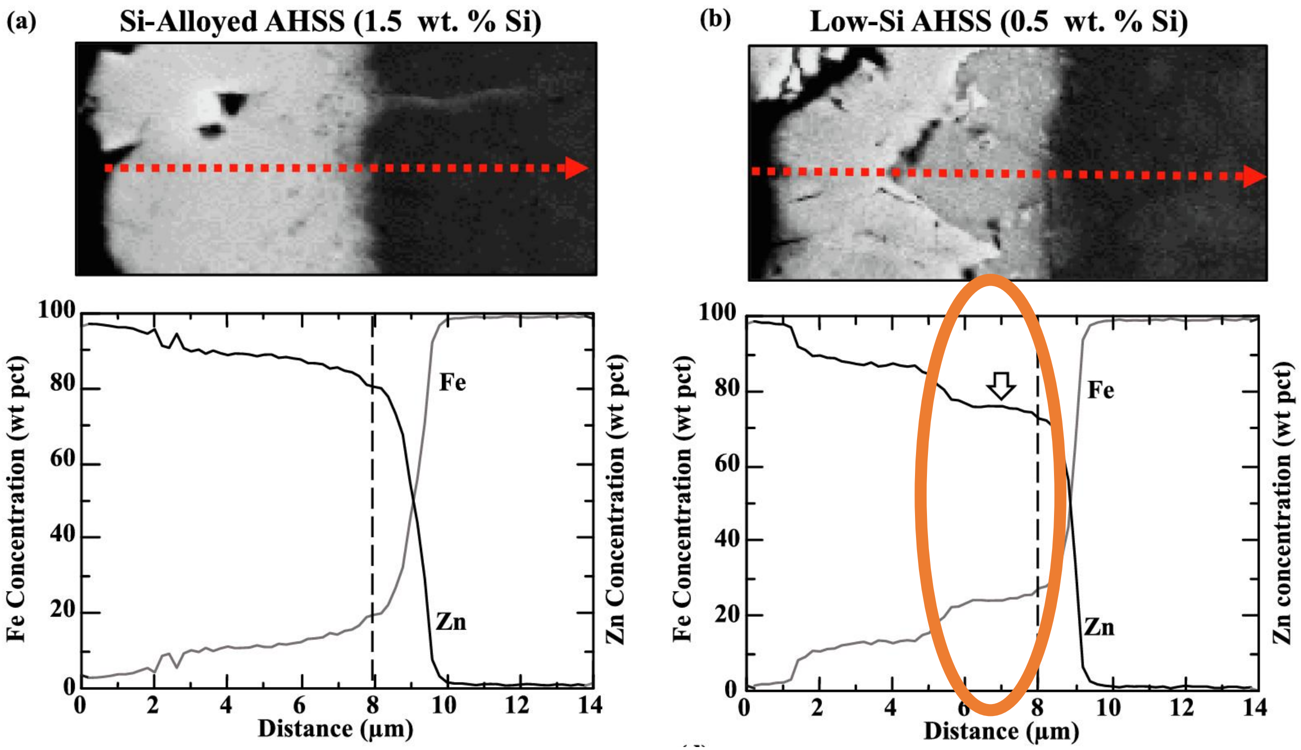




**_1.5Si_ AHSS showed <u>greater ductility loss</u> than _0.5Si_ AHSS**


D. Bhattacharya *et al.*, “Influence of selected alloying variations on liquid metal embrittlement susceptibility of quenched and partitioned steels,” *Materials & Design*, vol. 224, pp. 1–20, Dec. 2022.
D. Bhattacharya *et al.*, “Silicon effect on retardation of Fe-Zn alloying behavior: Towards an explanation of liquid zinc embrittlement susceptibility of third generation advanced high strength steels,” *Corrosion Science*, vol. 235, art. 112161, July 2024.

# Si Effect on LME: SEM Observations



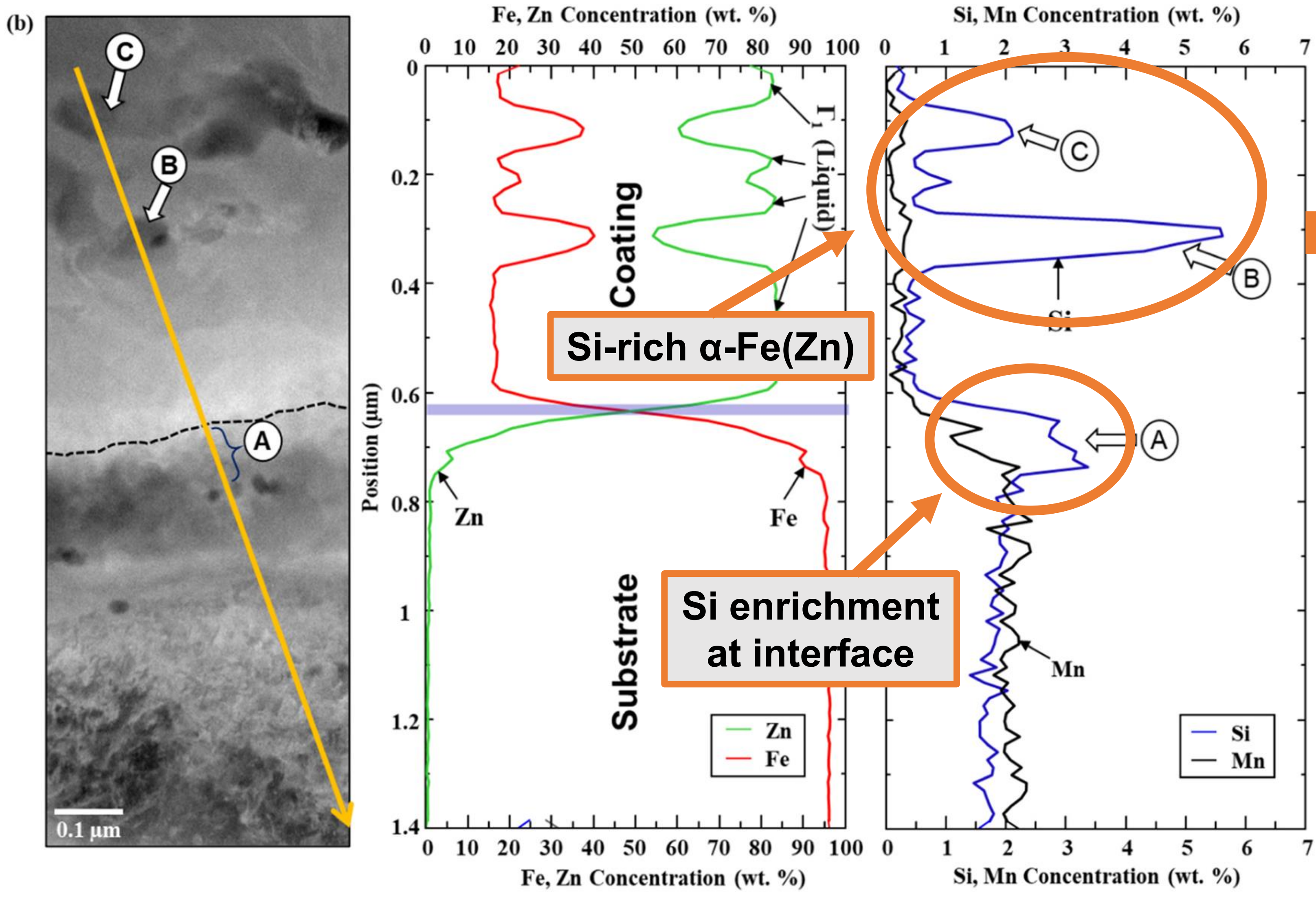




Formation of Γ can *consume liquid Zn* and act as a *physical barrier* for Zn penetration

**<u>Less Fe-Zn intermetallics</u>**
**present in *higher Si* AHSS**

D. Bhattacharya *et al.*, "Influence of selected alloying variations on liquid metal embrittlement susceptibility of quenched and partitioned steels," *Materials & Design*, vol. 224, pp. 1–20, Dec. 2022.

# Si Effect on LME: STEM-EDS Observations

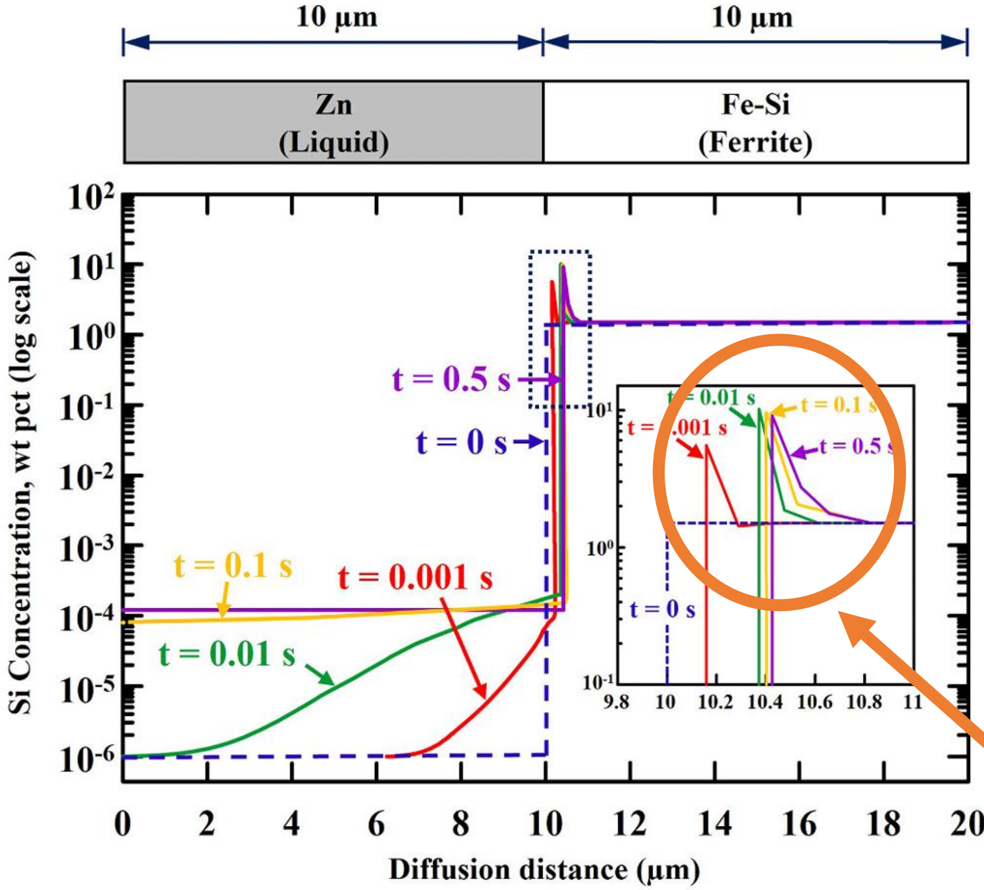



**1.5Si AHSS:**

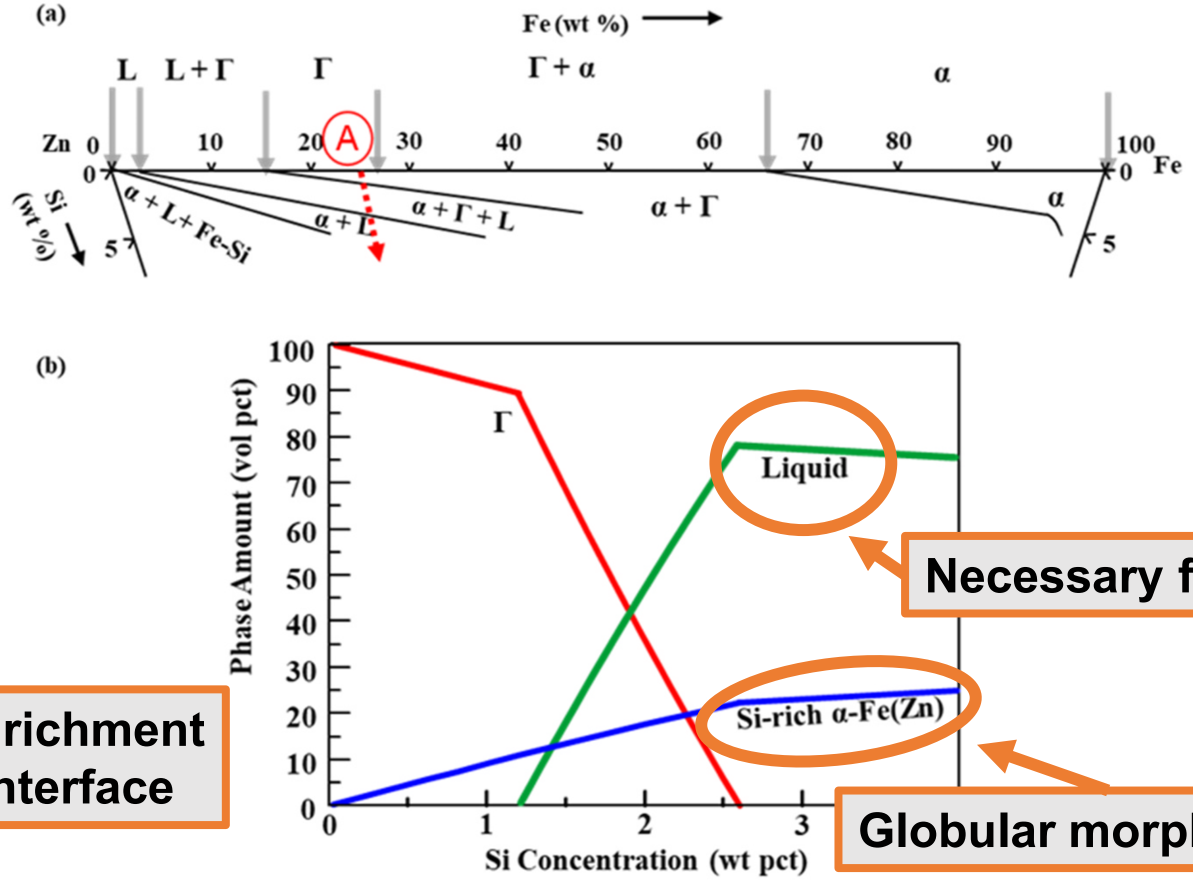
**Si enrichment at coating-substrate interface and presence of *Si-rich α-Fe(Zn)***

D. Bhattacharya *et al.*, "Silicon effect on retardation of Fe-Zn alloying behavior: Towards an explanation of liquid zinc embrittlement susceptibility of third generation advanced high strength steels," *Corrosion Science*, vol. 235, art. 112161, July 2024.

# Si Effect on LME: Ther. and Diff. Modeling




Si enrichment at interface




Necessary for LME

Globular morphology

**<u>Si enrichment</u> predicted *at interface***
**→ *Stabilization* of <u>liquid</u> and <u>α-Fe(Zn)</u> phases**

D. Bhattacharya *et al.*, "Silicon effect on retardation of Fe-Zn alloying behavior: Towards an explanation of liquid zinc embrittlement susceptibility of third generation advanced high strength steels," *Corrosion Science*, vol. 235, art. 112161, July 2024.

# Effect of Si on LME Susceptibility

***1.5Si*** **AHSS exhibited** **<u>higher LME susceptibility</u>** **than** ***0.5Si*** **AHSS**

***Increasing Si*** **content in the substrate:**

**→ Lead to <u>Si enrichment</u> at interface**

**→ <u>Suppressed Fe-Zn</u> intermetallic reactions**

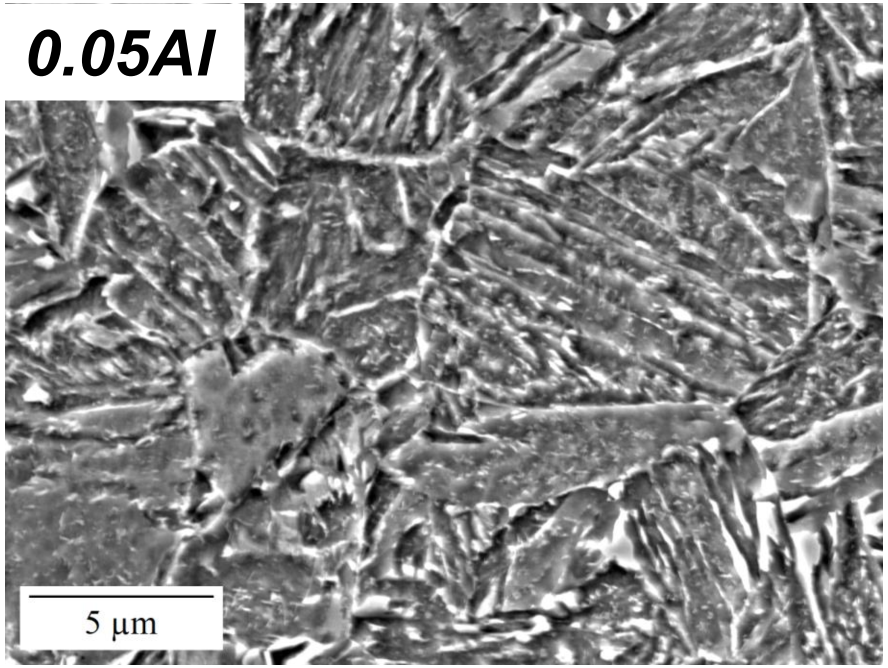
**→ *<u>Increased liquid</u>* fractions at interface**

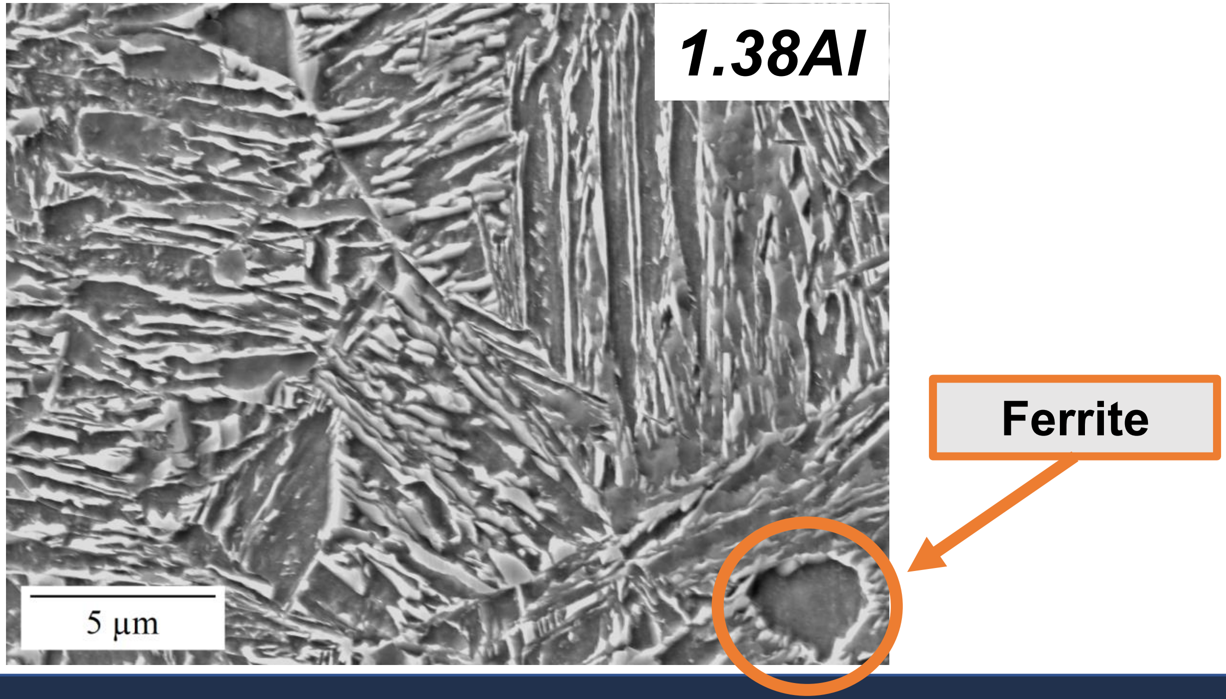
# Example Case: Effect of Substrate Silicon and <u>Aluminum</u> Content on LME Susceptibility

# Al Effect on LME: Material

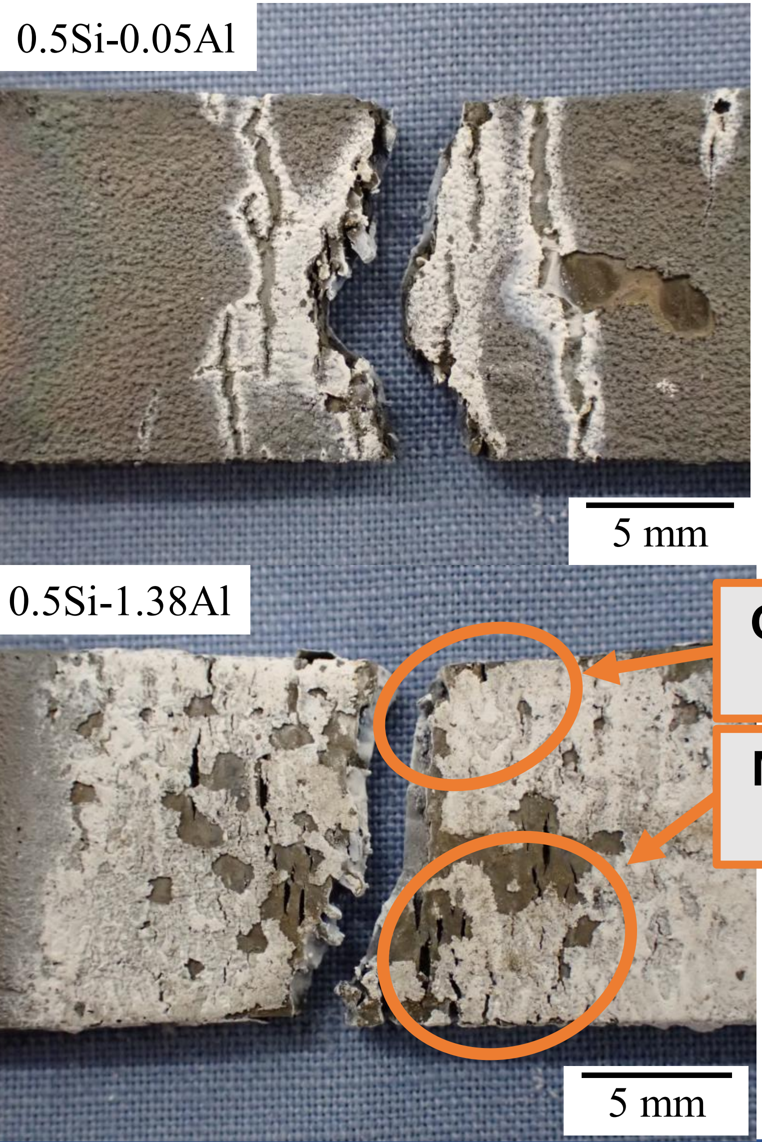
| Alloy | Si | Al | C | Mn |
|---|---|---|---|---|
| Low Al | 0.5 | 0.05 | 0.25 | 2.67 |
| High Al | 0.5 | 1.38 | 0.25 | 2.67 |

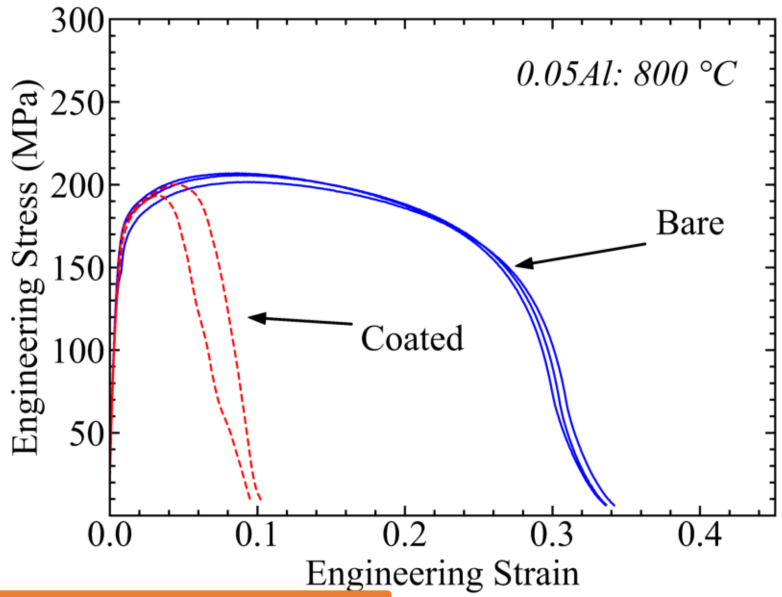
- Laboratory produced
- Hot rolled, cold rolled, continuous annealed
- Electrogalvanized

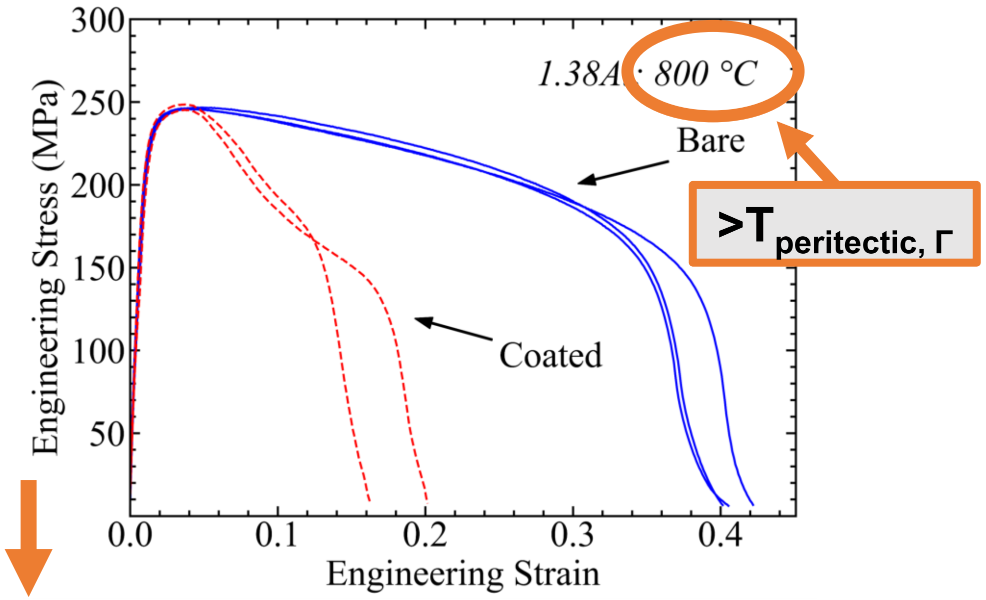


# Al Effect on LME: Hot Tension Testing




**Greater reduced area**

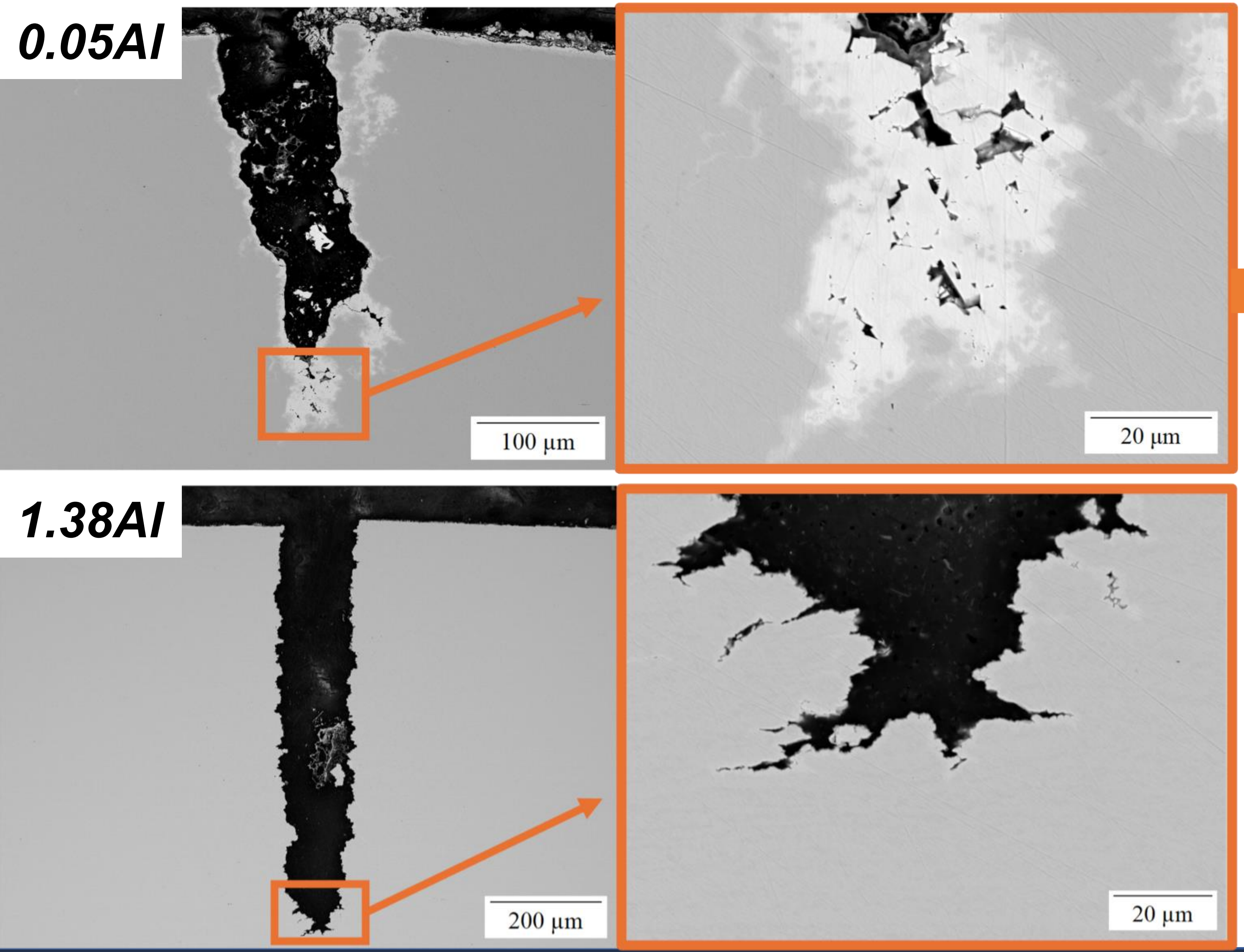
**More secondary cracking**

| Alloy | Ductility Loss (%) |
|---|---|
| Low Al | 74 |
| High Al | 58 |

**<u>Lower ductility loss</u> in *1.38Al* AHSS as compared to 0.05Al**

J. Colburn, J. G. Speer, and J. Klemm-Toole, "Effect of substrate Al content on liquid metal embrittlement susceptibility in quench and partitioned steels," *Materials Science and Engineering: A*, vol. 922, art. 147636, Feb. 2025.

# Al Effect on LME: SEM-BSE

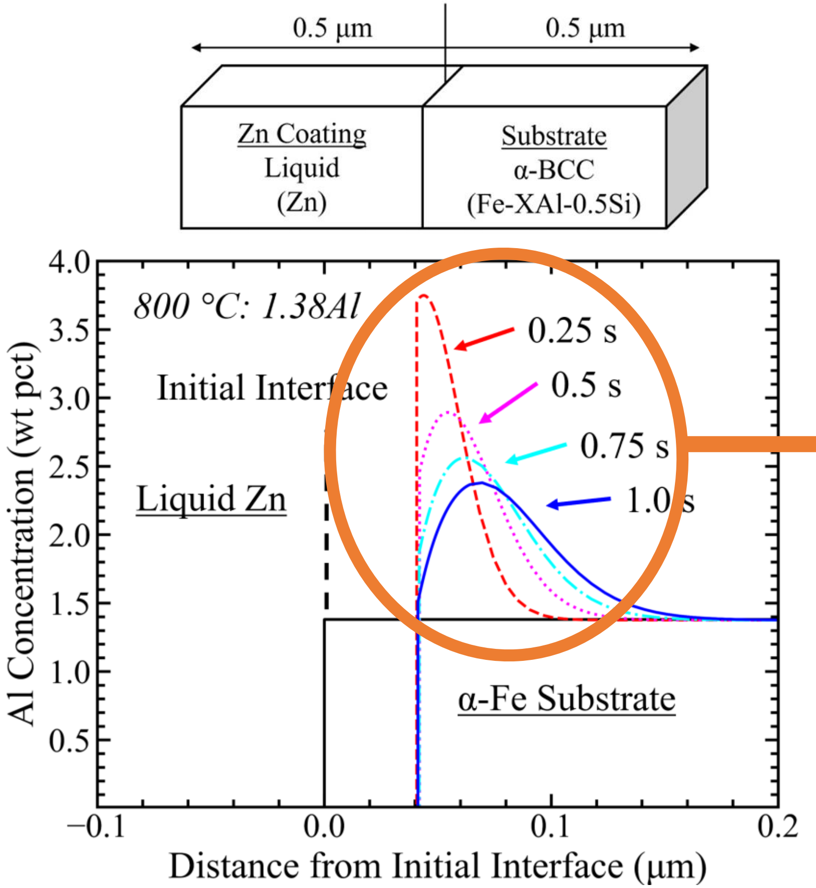


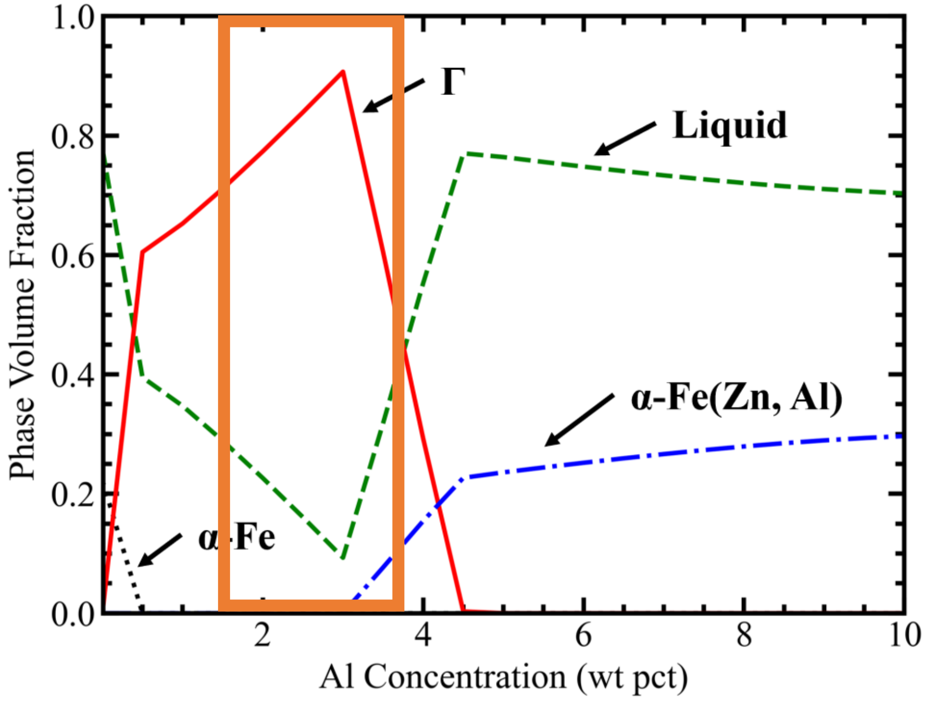

***1.38Al AHSS:***

**Less Zn (*high contrast regions*) penetration and enrichment around and ahead of LME crack**

J. Colburn, J. G. Speer, and J. Klemm-Toole, “Effect of substrate Al content on liquid metal embrittlement susceptibility in quench and partitioned steels,” *Materials Science and Engineering: A*, vol. 922, art. 147636, Feb. 2025.

# Al Effect on LME: Ther. and Diff. Modeling




***Low Al solubility*** **in liquid Zn → Predicted** **<u>enrichment of Al</u>**

***Increasing Al*** **at interface** **<u>decreases phase fraction of liquid</u>**

J. Colburn, J. G. Speer, and J. Klemm-Toole, "Effect of substrate Al content on liquid metal embrittlement susceptibility in quench and partitioned steels," *Materials Science and Engineering: A*, vol. 922, art. 147636, Feb. 2025.

# Al Effect on LME: Ther. and Diff. Modeling

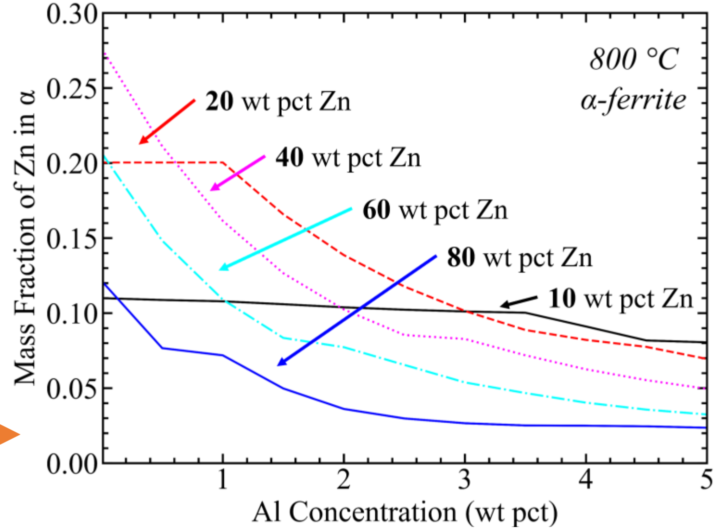
***Increasing Al decreases:***

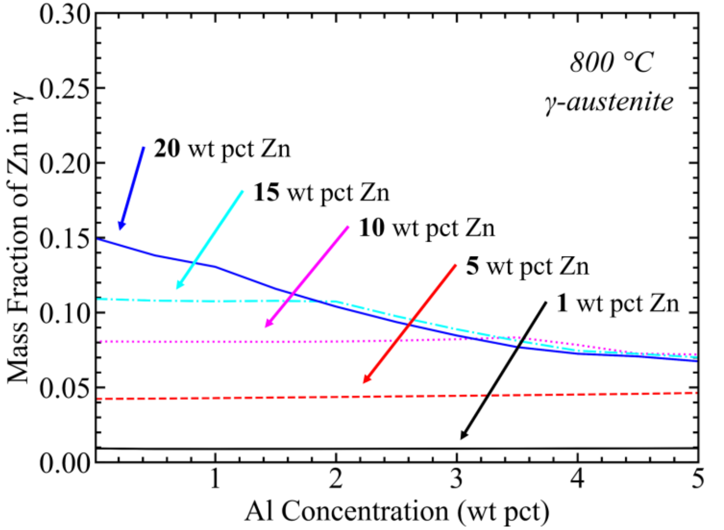
**<u>Equilibrium fraction of Zn</u>**

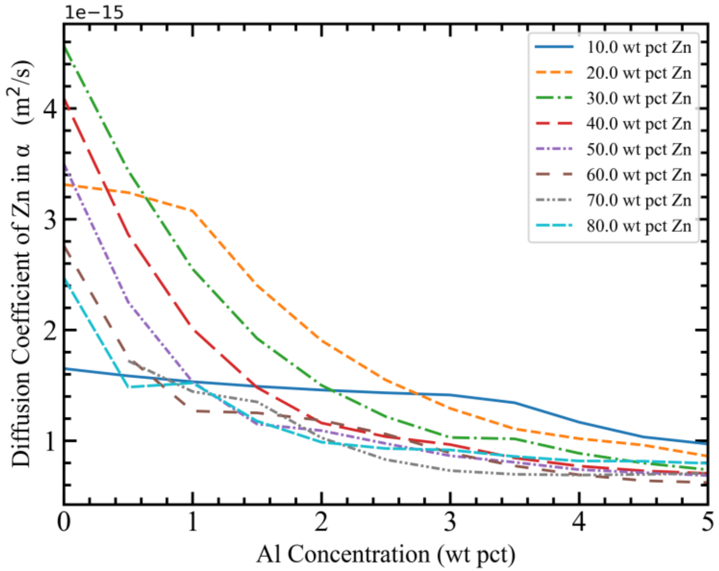
***and***

**<u>Diffusivity of Zn</u>**

**in substrate**




J. Colburn, J. G. Speer, and J. Klemm-Toole, “Effect of substrate Al content on liquid metal embrittlement susceptibility in quench and partitioned steels,” *Materials Science and Engineering: A*, vol. 922, art. 147636, Feb. 2025.

# Al Effect on LME: Ther. and Diff. Modeling

***Increasing Al decreases*:**

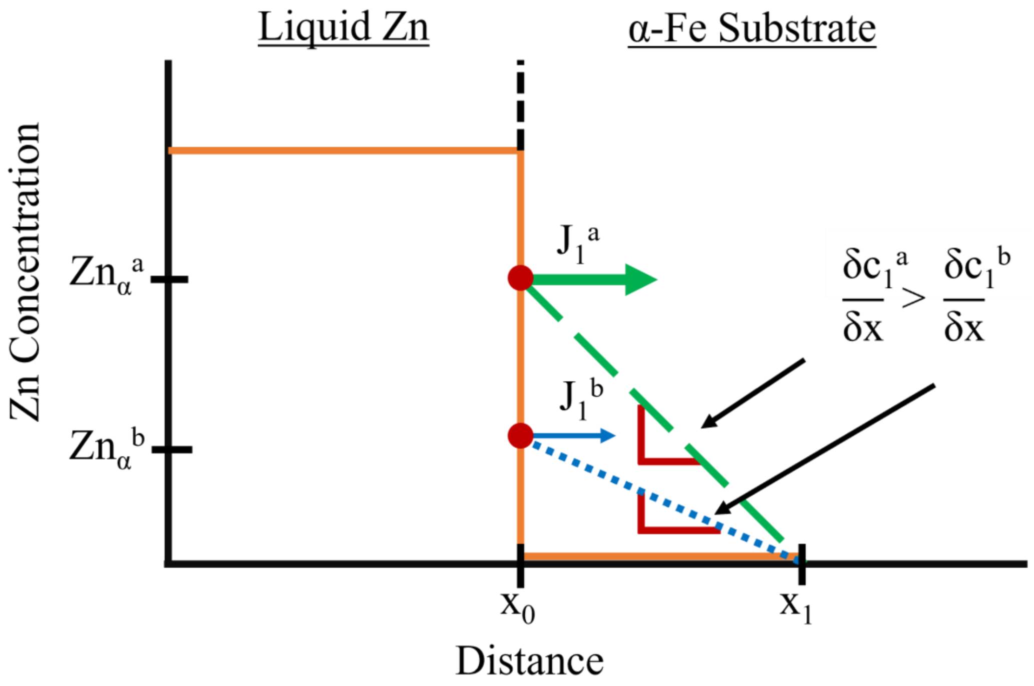
**Equilibrium fraction of Zn**

***and***

**Diffusivity of Zn in substrate**

**Decrease flux of Zn in substrate *(F.F.L.)***

$$J_1 = -D_1 \frac{\delta c_1}{\delta x}$$




J. Colburn, J. G. Speer, and J. Klemm-Toole, "Effect of substrate Al content on liquid metal embrittlement susceptibility in quench and partitioned steels," *Materials Science and Engineering: A*, vol. 922, art. 147636, Feb. 2025.

# Effect of Al on LME Susceptibility, Pt 1

*1.38Al* AHSS exhibited lower LME susceptibility and less Zn penetration and enrichment ahead and around LME cracks than *0.05Al* AHSS when hot tension tested at 800 °C

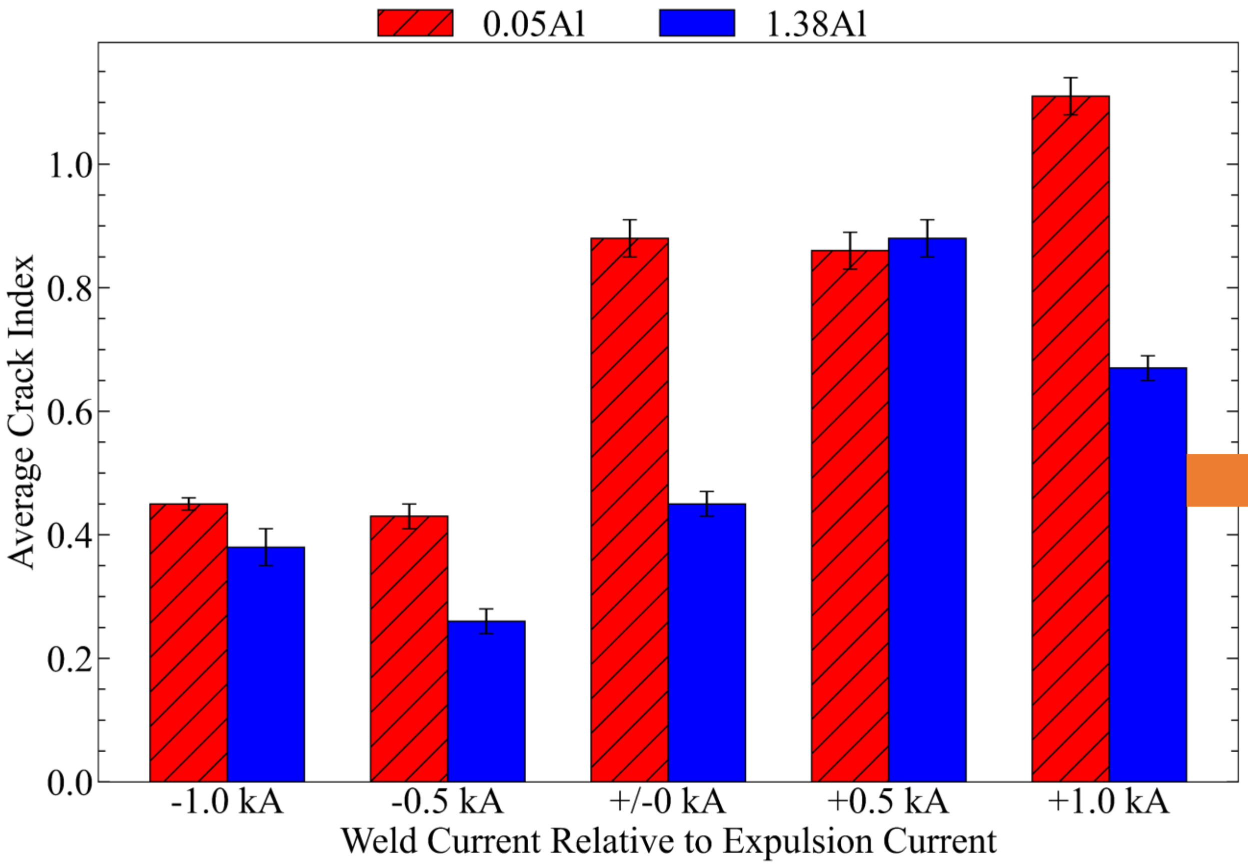
Thermodynamic and diffusion calculations predict:

- Al enrichment at coating-substrate *interface*
- Decreasing equilibrium mass fraction and diffusivity of *Zn in substrate*
- *Stabilization* of Γ phase at expense of liquid phase with *increasing Al* at interface (up to 3 wt pct Al)

# Al Effect on LME: RSW Testing

Table 2 – RSW Parameters

| Parameter | Force (kN) | Squeeze (ms) | **Current (kA)** | **Weld Time (ms)** | Pulse Count | Hold Time (ms) | $H_2O$ Flow Rate (gpm) |
|---|---|---|---|---|---|---|---|
| Value | 4.0 | 1500 | **6.0-9.5** | **600** | 1 | 250 | 1.0 |




**LME Metric:** $$\text{Crack Index} = \frac{nL}{t}$$

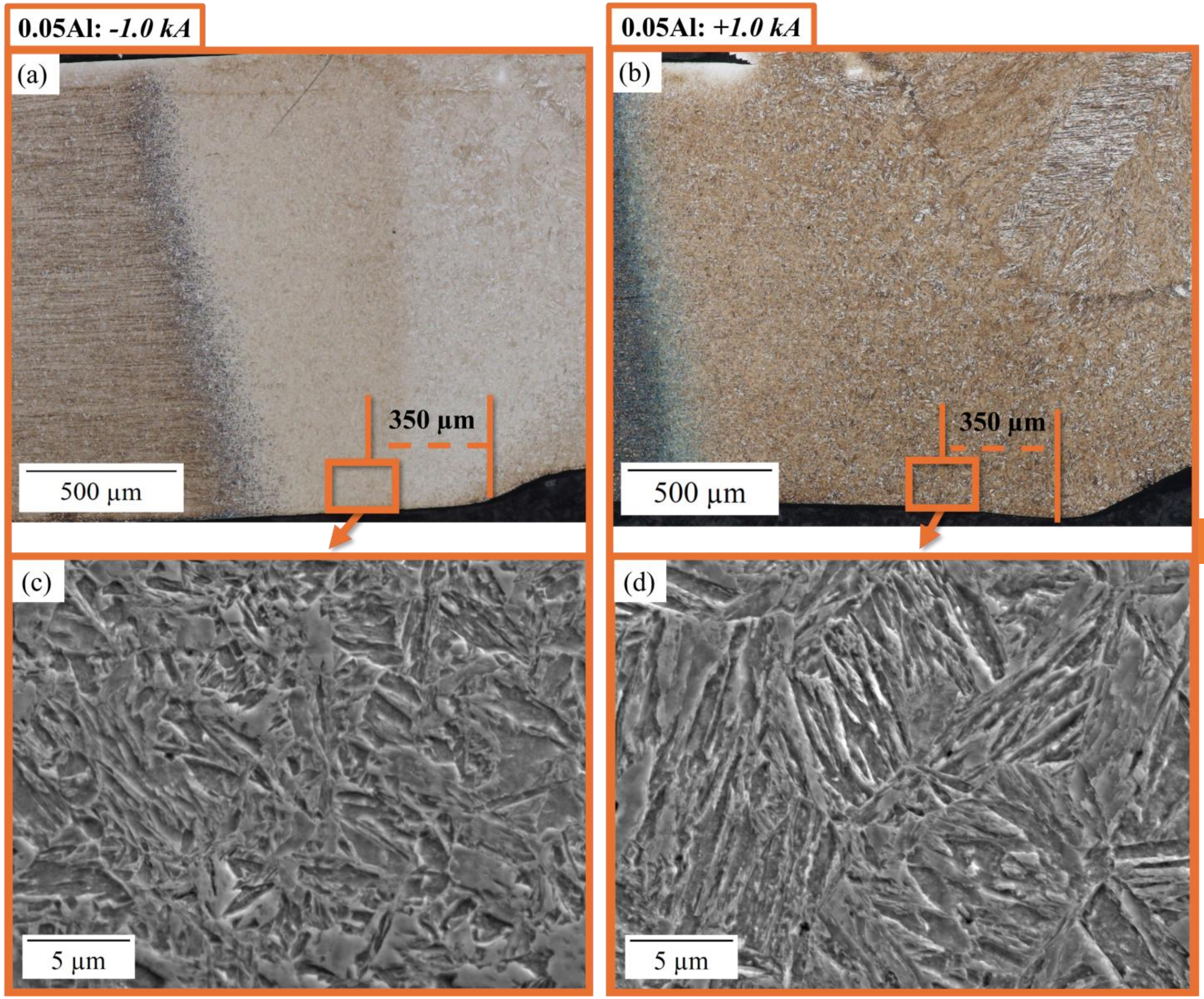
***n*** **: number of cracks**

***L*** **: lognormal median crack length**

***t*** **: sheet thickness**

***Higher Al (1.38Al)*** **AHSS exhibited <u>lower crack index</u> (LME susceptibility) at all but one current level**

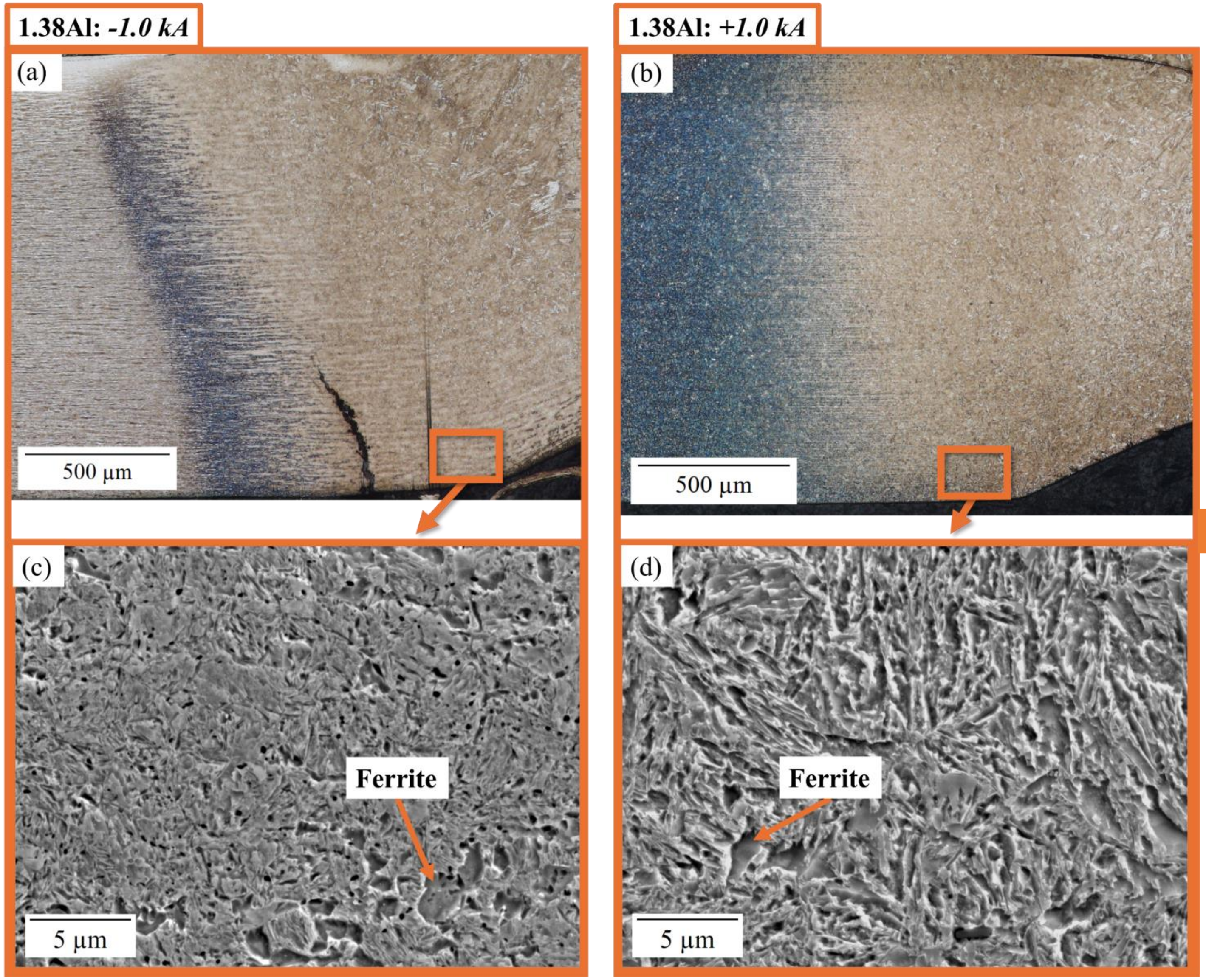
# Al Effect on LME: 0.05Al LOM and SEM




***Low Al (0.05Al)*:**

**<u>Super-critical HAZ</u> extends to *weld periphery* at all weld currents**

# Al Effect on LME: 1.38Al LOM and SEM




***High Al (1.38Al)*:**

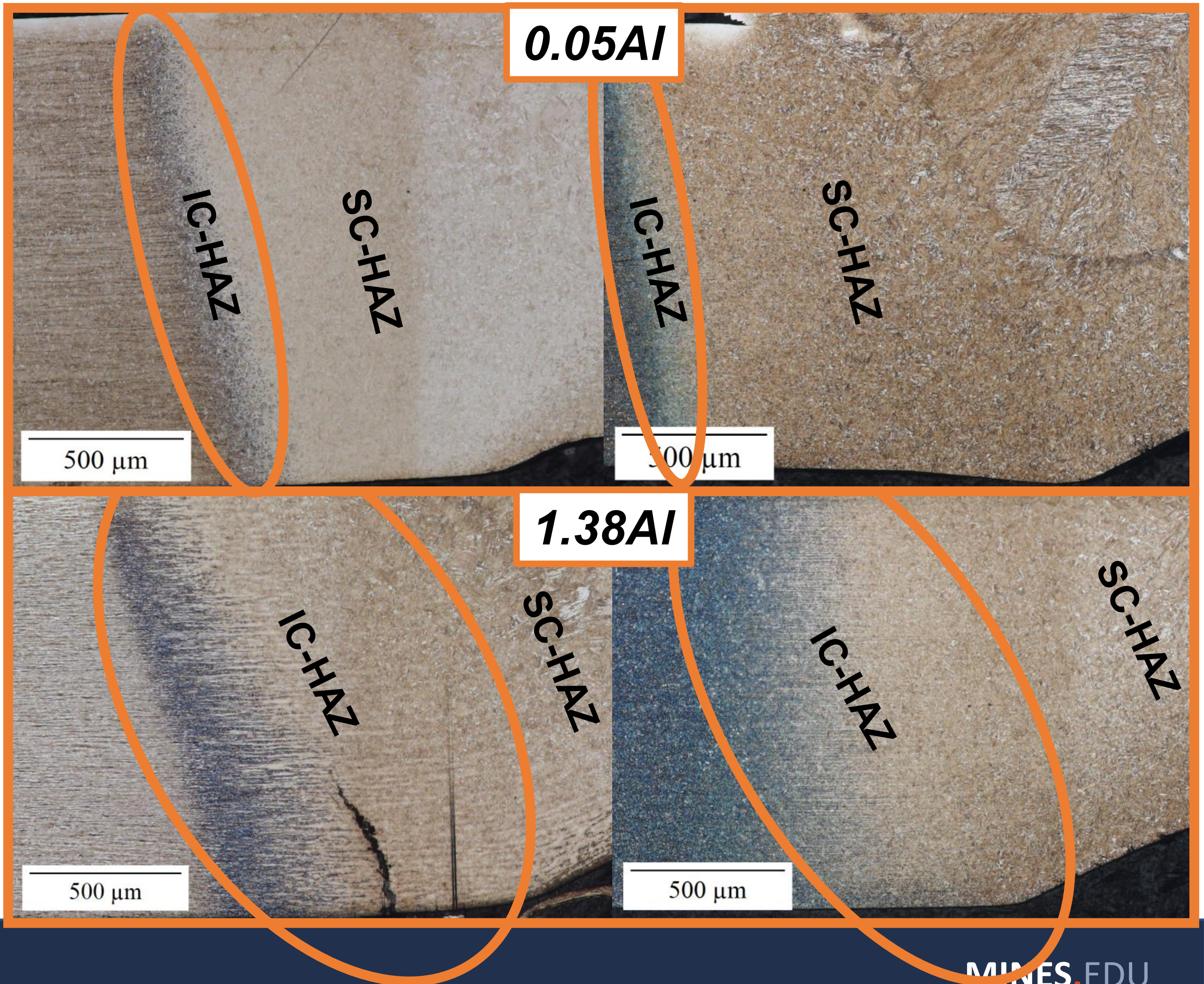
**<u>Inter-critical HAZ</u> present at *weld periphery* at all weld currents**

# Al Effect on LME: Transformation Temps.

| Alloy | $A_{c1}$ (°C) | $A_{c3}$ (°C) | ($A_{c3}$ - $A_{c1}$) (°C) |
|---|---|---|---|
| 0.05 Al | 740 | 850 | 110 |
| 1.38 Al | 740 | 970 | 230 |

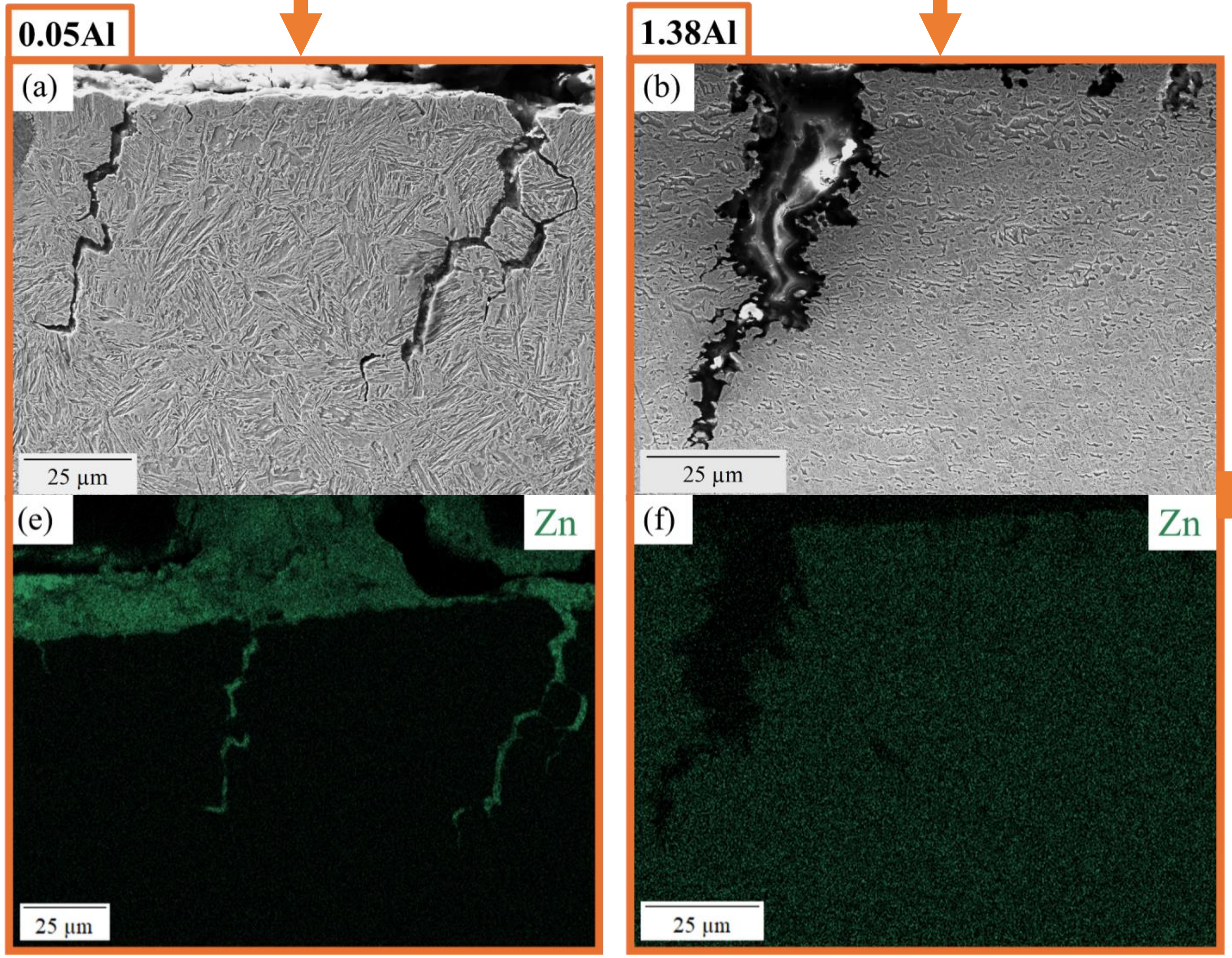
*Transformation temperatures determined via dilatometry
(Heating rate: 5 °C/s, Cooling rate: 50 °C/s)

**<u>Higher $A_{c3}$</u> temperature and *wider inter-critical* range in *1.38Al* AHSS**



# Al Effect on LME: SE- and EDS-SEM

**SE- and EDS-SEM at weld shoulder**

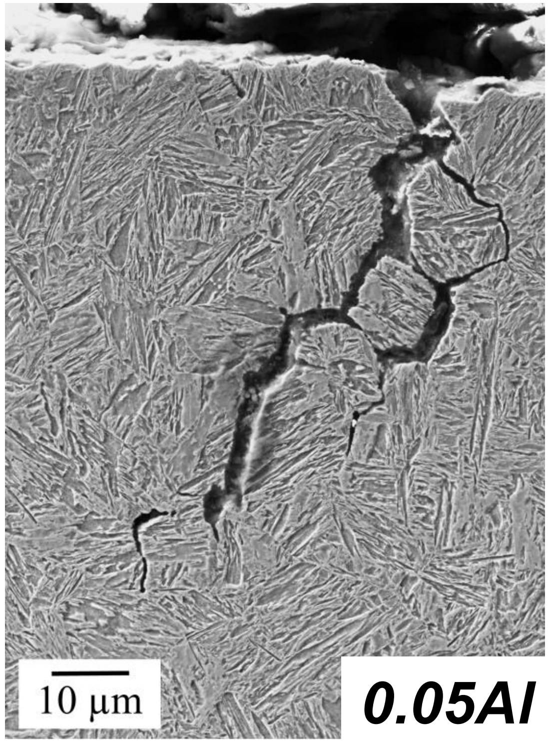



***High Al*** **AHSS(inter-critical HAZ) exhibits <u>less Zn enrichment and penetration</u> than *Low Al AHSS* (super-critical HAZ)**

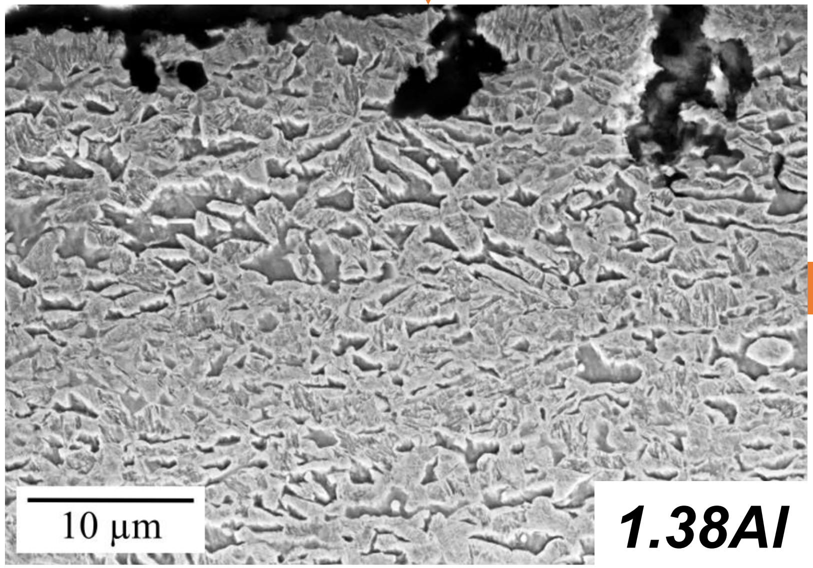
# Al Effect on LME: HAZ Microstructure

***At peak temperature:***

***<u>Austenite</u>*** ***<u>Austenite + ferrite</u>***




***0.05Al***




***1.38Al***

***Inter-critical microstructure***

**→ <u>Finer effective microstructure</u> and <u>more tortuous</u> crack path**

# Effect of Al on LME Susceptibility, Pt 2

*1.38Al* AHSS exhibited lower crack index than *0.05Al* AHSS during RSW testing

The 1.38Al AHSS spot welds also exhibited:

- An inter-critical HAZ extended into the *weld periphery* (as compared to super-critical HAZ for the 0.05Al welds)
- *Less* Zn enrichment and penetration around and ahead of LME cracks
- Finer effective (inter-critical) microstructure in the *weld shoulders and periphery*

# Substrate Compositional Factors that Affect LME Susceptibility

# How Does Composition Affect LME?

**How does the alloying addition affect:**

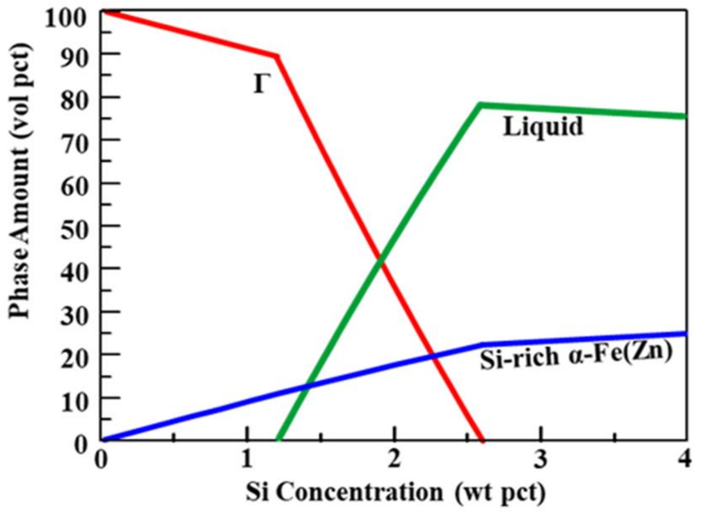
1. **Stability of *Fe-Zn intermetallics* versus *liquid phase?***
2. **Substrate *microstructure* at elevated (susceptible) temperatures?**
3. **Zn *diffusion* and *penetration?***

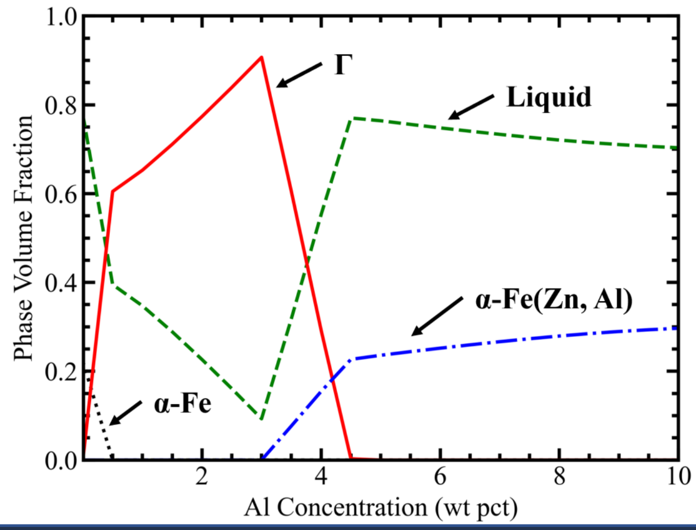
# How Does Composition Affect LME?

1. **Stabilization of *Fe-Zn intermetallics* versus *liquid phase***

***Alloying addition increases phase fraction of:***

| | **Liquid** | **Fe-Zn intermetallics** |
|---|---|---|
| **Availability of liquid Zn** | ***Increase*** | ***Decrease*** |
| **Formation of potential barrier to Zn penetration** | ***Decrease*** | ***Increase*** |



# How Does Composition Affect LME?

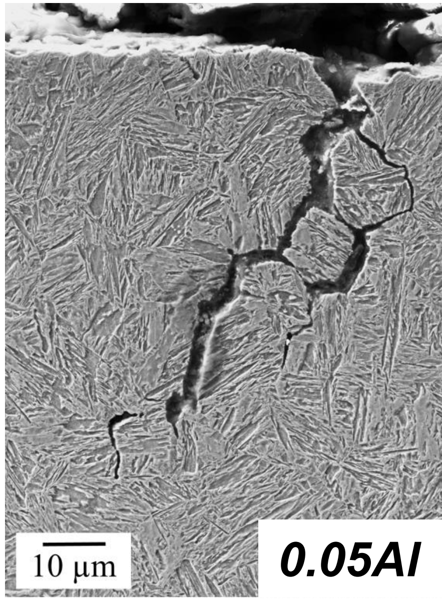
2. Substrate *microstructure* at elevated (susceptible) temperatures

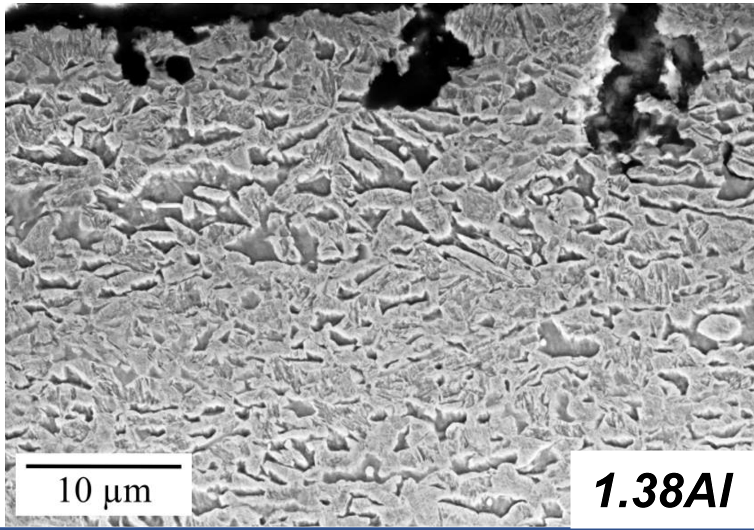
**How does the alloying addition affect:**

Effective microstructure size?

*Fraction* of a more susceptible microstructure?

Microstructure at *more susceptible* locations of weld?



# How Does Composition Affect LME?

3. Zn *diffusion* and *penetration*

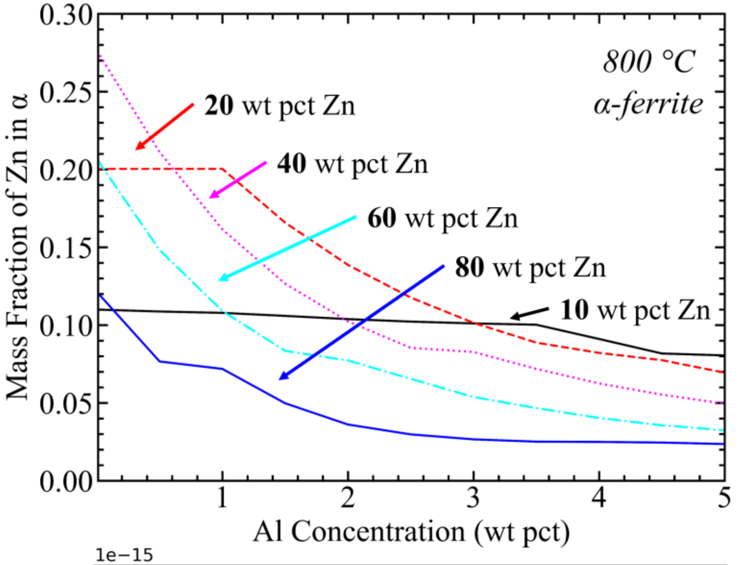
**Does alloying addition *increase* or *decrease* the *thermodynamic propensity and driving force* for <u>Zn diffusion and penetration</u>?**

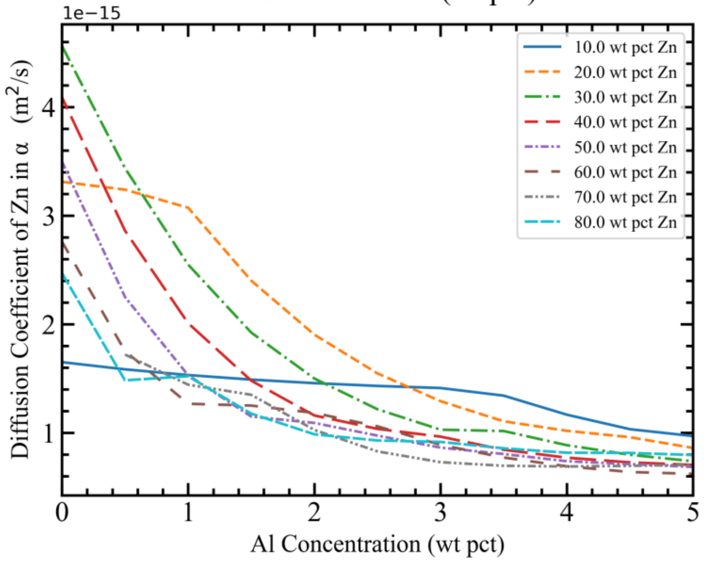
**Considerations:**

***Solubility of Zn*** **in substrate**

***Diffusivity of Zn*** **in substrate**

***Chemical potential difference*** **between Zn in liquid and in substrate**



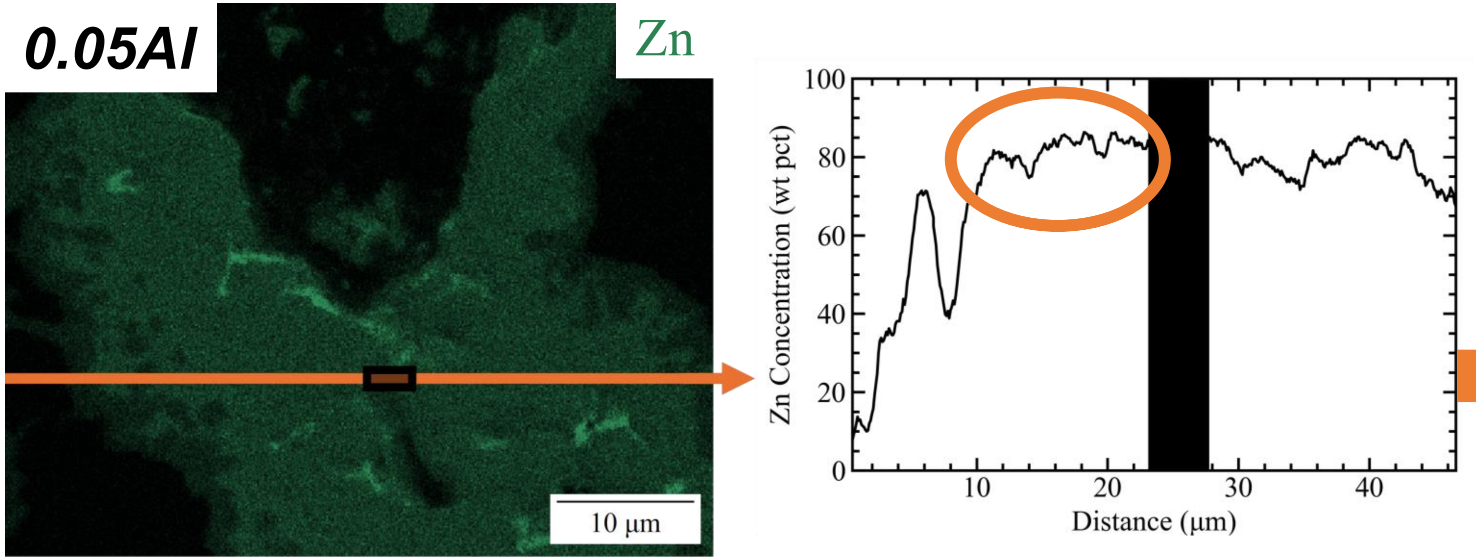



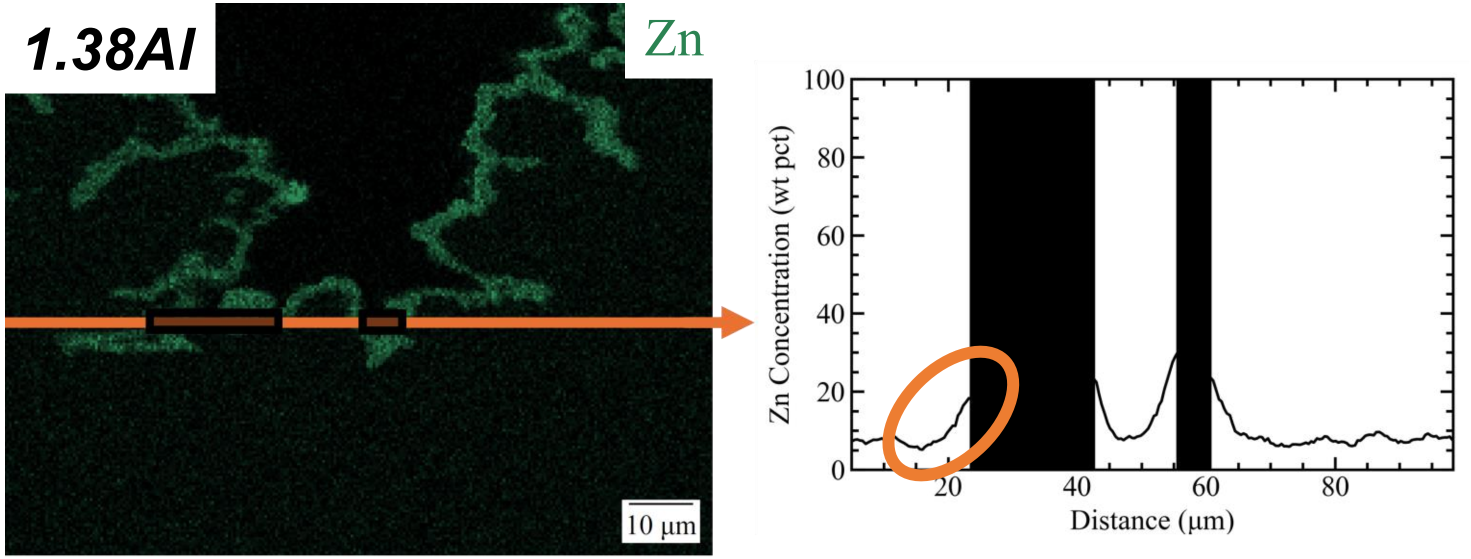
# Acknowledgments


- **ASPPRC Sponsors and Mentors**
  - Funding, material, and project guidance
- **University of Alabama College of Engineering and MTE Dept.**
  - Gleeble 3500 thermomechanical simulator access and assistance
- **Cleveland-Cliffs Research and Innovation Center**
  - Resistance spot welding access and assistance


*jcolburn@mines.edu*

# Al Effect on LME: SEM-EDS




***1.38Al AHSS:***

**<u>Less Zn penetration</u> and <u>enrichment</u> around and ahead of LME crack**


J. Colburn, J. G. Speer, and J. Klemm-Toole, "Effect of substrate Al content on liquid metal embrittlement susceptibility in quench and partitioned steels," *Materials Science and Engineering: A*, vol. 922, art. 147636, Feb. 2025.