# Comparative Study on Fracture Resistance of Ultra-High-Strength Press-Hardened Steels (UHS-PHSs)

**Jun Hu, PhD**
**Cleveland-Cliffs Inc.**

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# Acknowledgements

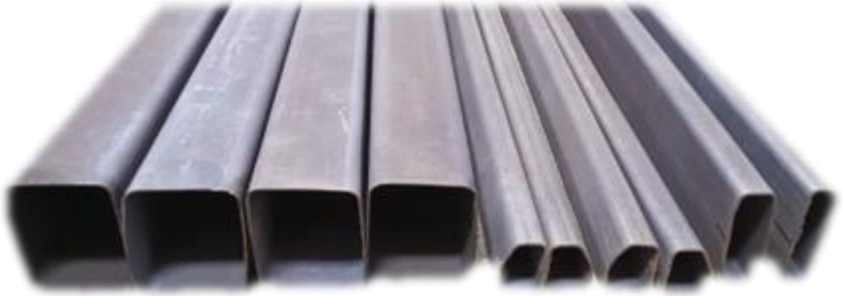

The presenter extends sincere gratitude to Eliseo Hernandez-Duran (co-author), Chris Copeland, Steven Walls, Matt Faulkner, Chris Walker, Jason Wymer, Koushik Balasubramanian, Laura Burroughs, Grant Thomas, Dana Lentz, and numerous colleagues for their efforts and discussions in this and previous studies. The support from Cleveland-Cliffs Inc. management is also deeply appreciated.

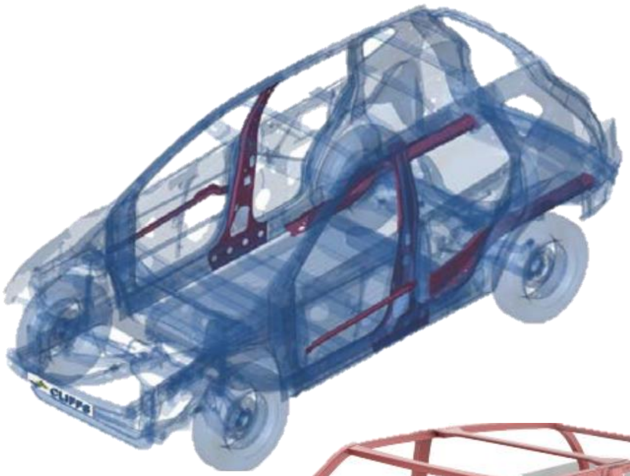
# CLIFFS Offers PH(Q)S500|1000*|1500|2000*



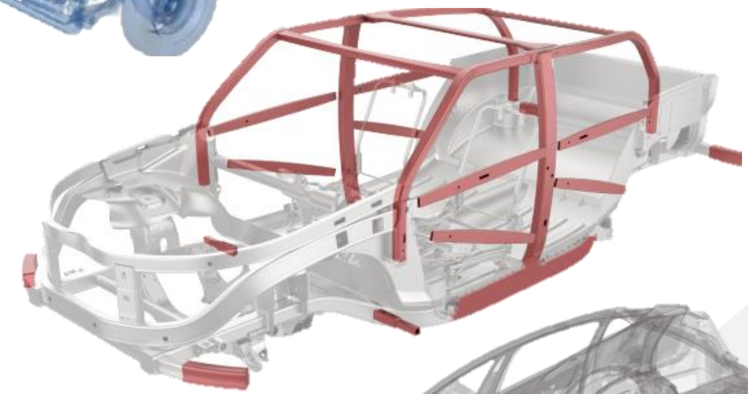
*In development







CLIFFS
ULTRALUME® PHS



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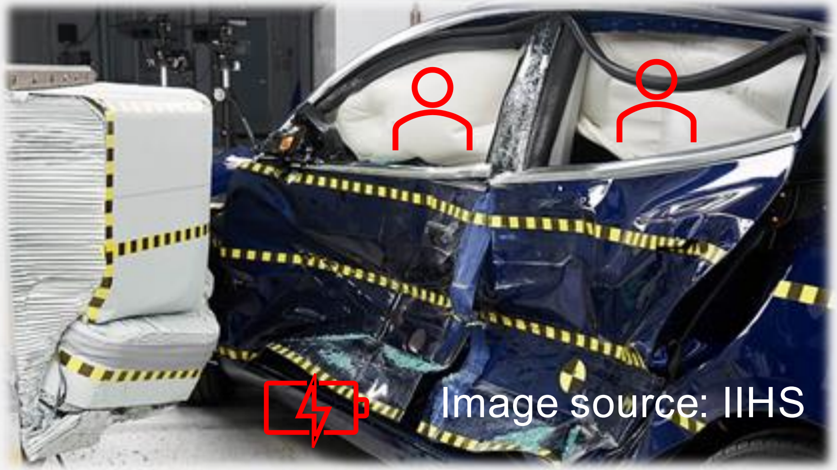
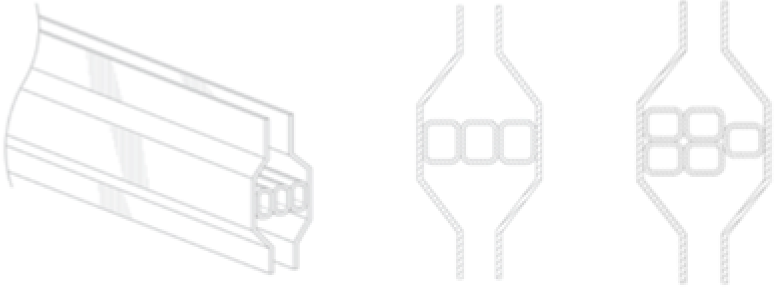
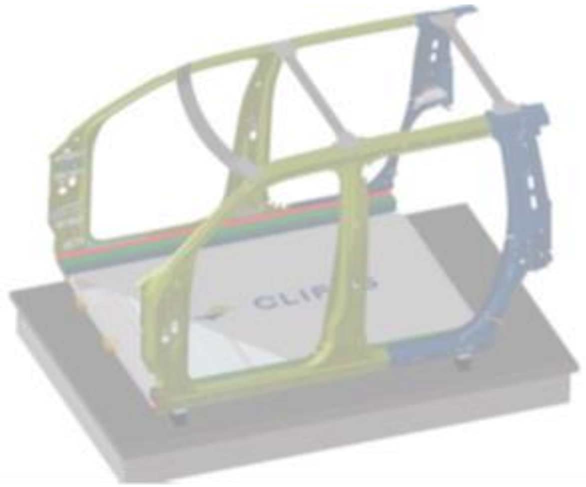


# More PH(Q)S Studies in Past GDIS

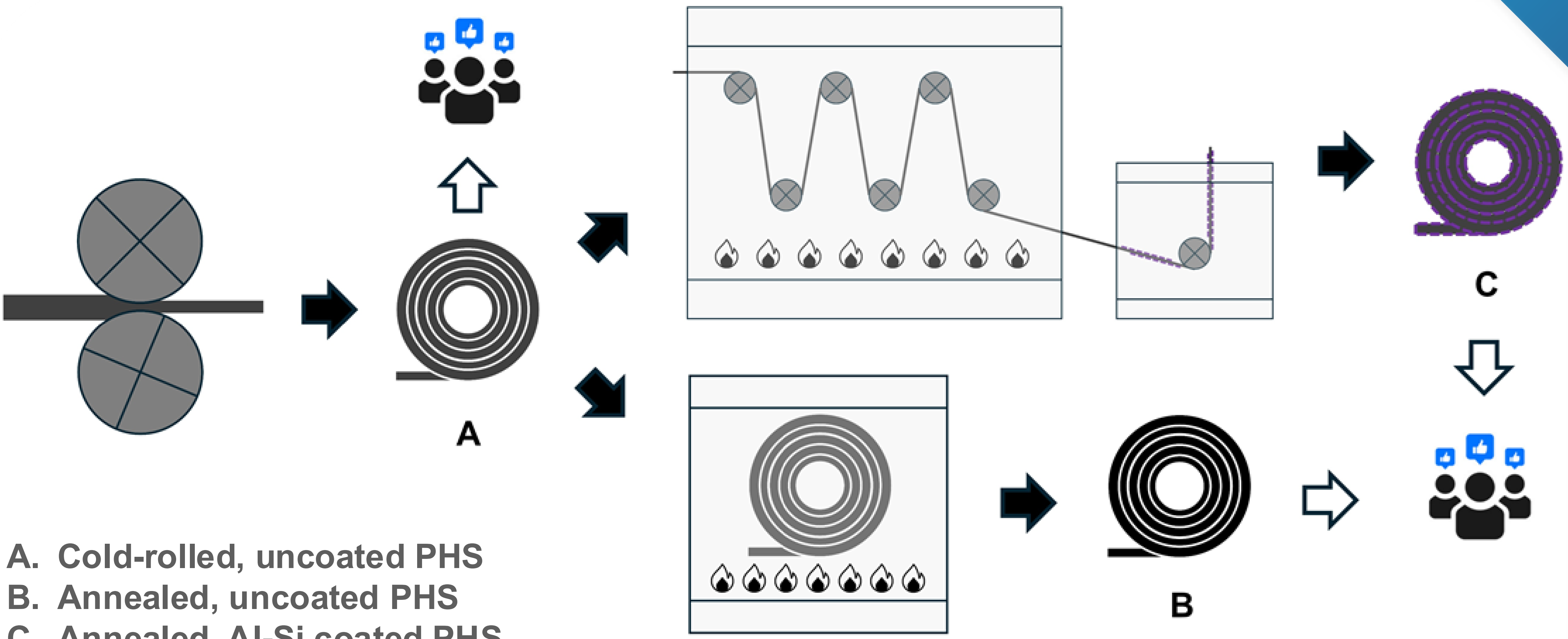


# CLIFFS Offers 3 Types of PHS1500|2000*

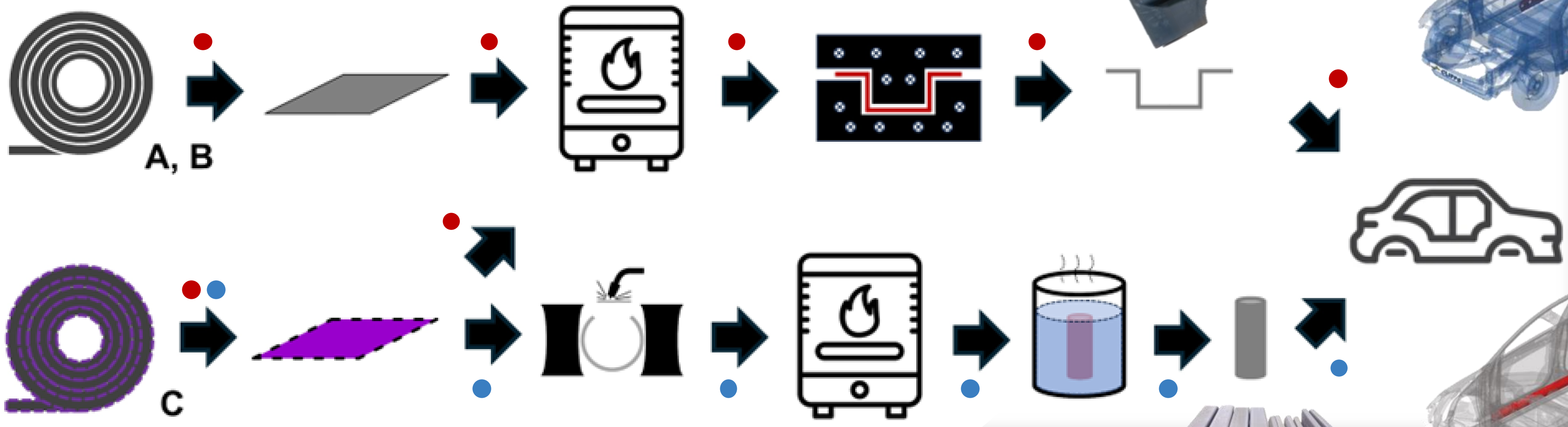
*In development

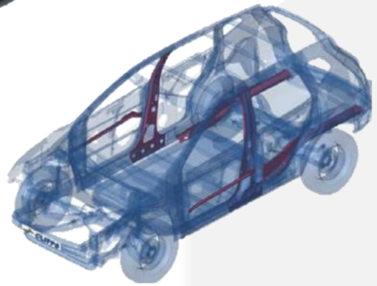


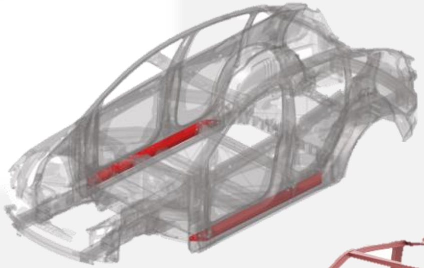

A. Cold-rolled, uncoated PHS
B. Annealed, uncoated PHS
C. Annealed, Al-Si coated PHS (most demanded type)

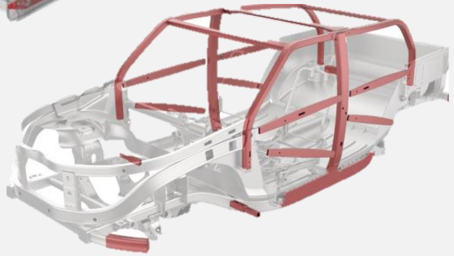
# 3 Types of PHS1500|2000 in Forming

**Hot-Stamped → Die-Quenched**







**Cold-Rolled → Annealed → Liquid-Quenched**

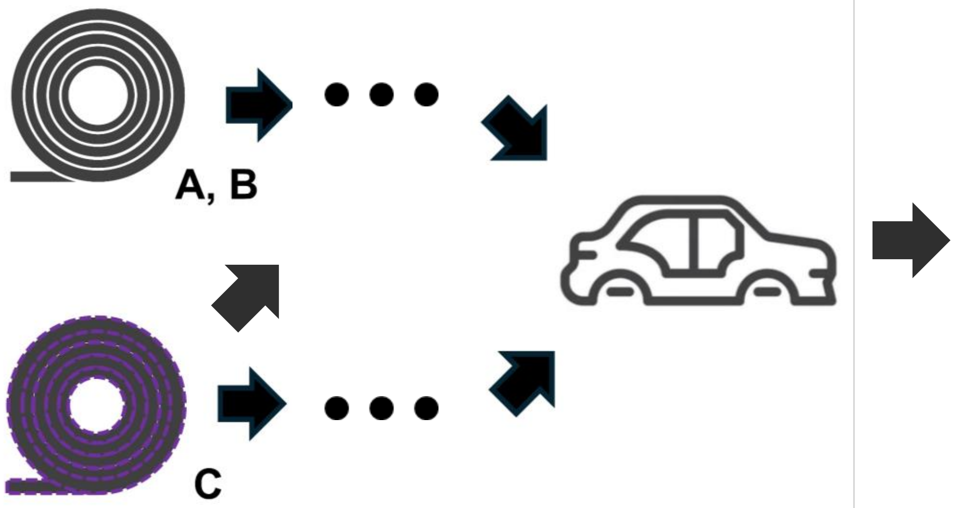
# 3 Types of PHS1500|2000 in Paint-Baking



A. Cold-rolled, uncoated PHS
B. Annealed, uncoated PHS
C. Annealed, Al-Si coated PHS

Microstructure evolution: ferritic → austenitic → fresh martensitic → tempered martensitic

**Hot-Stamped → Die-Quenched → Paint-Baked**




**Cold-Rolled → Annealed → Liquid-Quenched → Paint-Baked**

<u>Paint-baking = low-temperature-tempering (LTT)</u> can lower the micro-hardness of fresh martensite and eventually improve the fracture resistance of PHS1500|2000-AS (Type-C in this work) (CHS[2] 2024 and GDIS 2024)

# 3 Critical Stages & Research Motivation

A. Cold-rolled, uncoated PHS
B. Annealed, uncoated PHS
C. Annealed, Al-Si coated PHS

How does the fracture resistance evolve in the 3 stages?

Type-A/B → Hot-Stamped → Die-Quenched → Paint-Baked

Type-C → Cold-Rolled → Annealed → Liquid-Quenched → Paint-Baked

I. Untreated → II. As-Quenched → III. Low-Temp.-Tempered (LTT)

**Fracture resistance / fracture strain / local ductility ≠ global ductility / tensile elongation**

(SAE 2022, GDIS 2023, AIST Trans. 2024)

# Evolving Fracture Resistance of PHS1500|2000



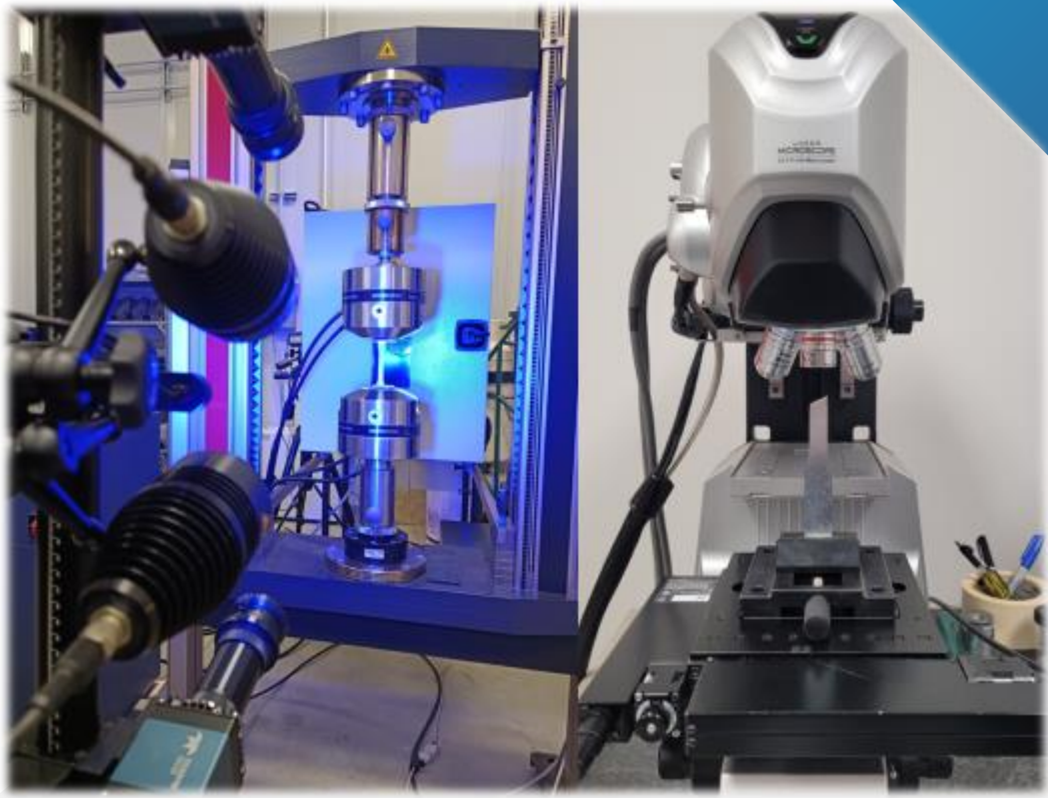
From Untreated to Quenched

LTT (Paint-Baking) Effects

Rate / Stress-State Effects (on Type-A)

# Tensile Testing Procedure



**Hot-stamping**: each blank was heat-treated in an oven at 930˚C for 5 min. → fully die-quenched at 300˚C/s

**Fracture strain measurement** based on the hybrid DIC-microscopic method (SAE 2022, GDIS 2023) of virtual strain gauge length (VSGL) 0.5 mm on longitudinal (L) ASTM E8 quasi-static tensile test samples

# Results: Tensile Strength & Elongation



A. Cold-rolled, uncoated PHS
B. Annealed, uncoated PHS
C. Annealed, Al-Si coated PHS

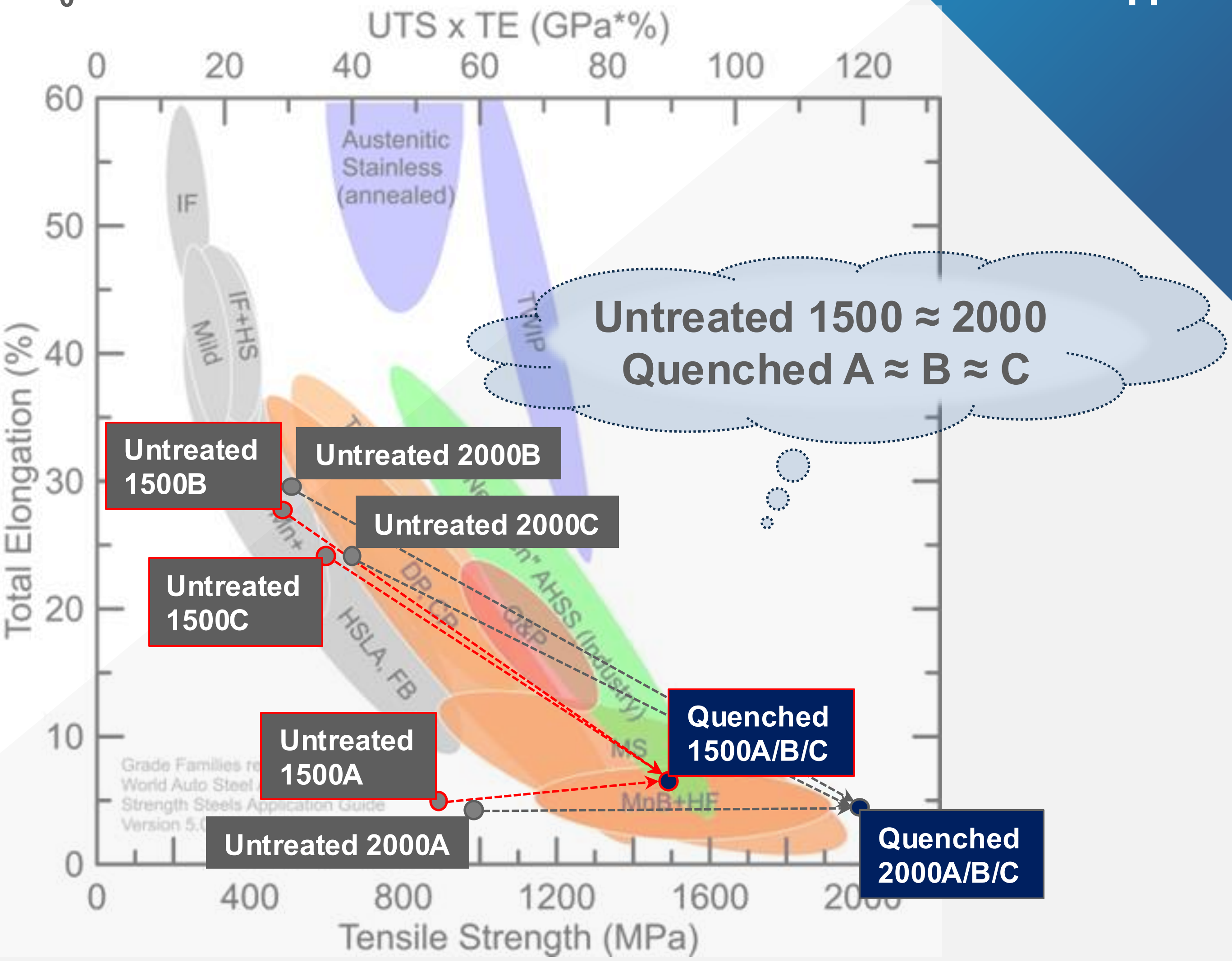
Same nominal $t_0$ = 1.8 mm

Only quenched properties matter

Type-A/B → Hot-Formed → Quenched

Type-C → Cold-Formed → Annealed → Quenched

Both untreated & quenched properties matter

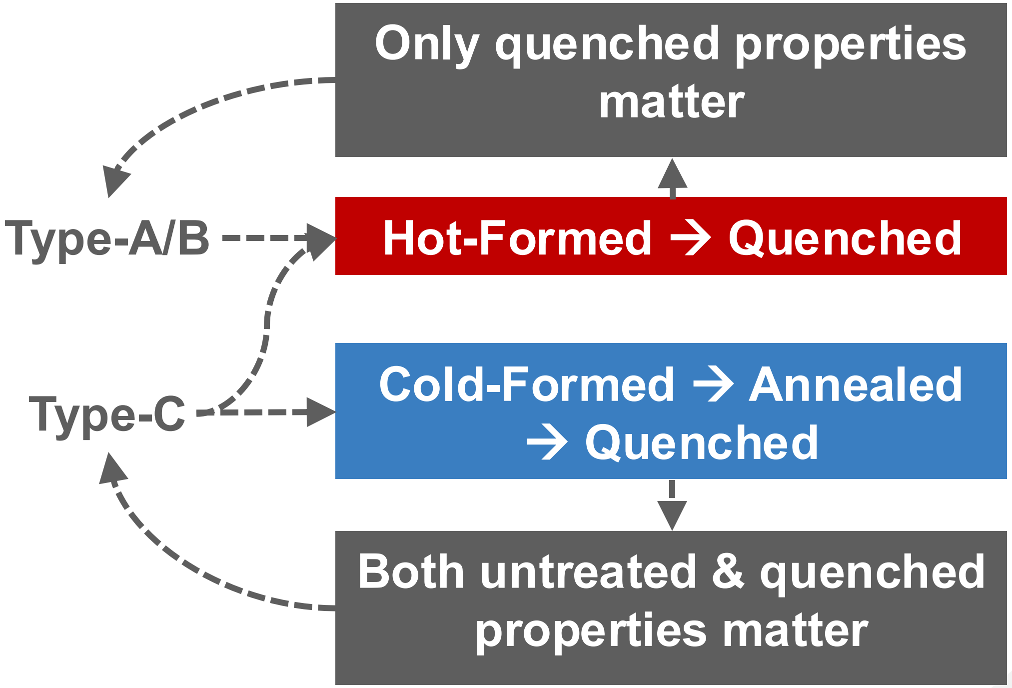


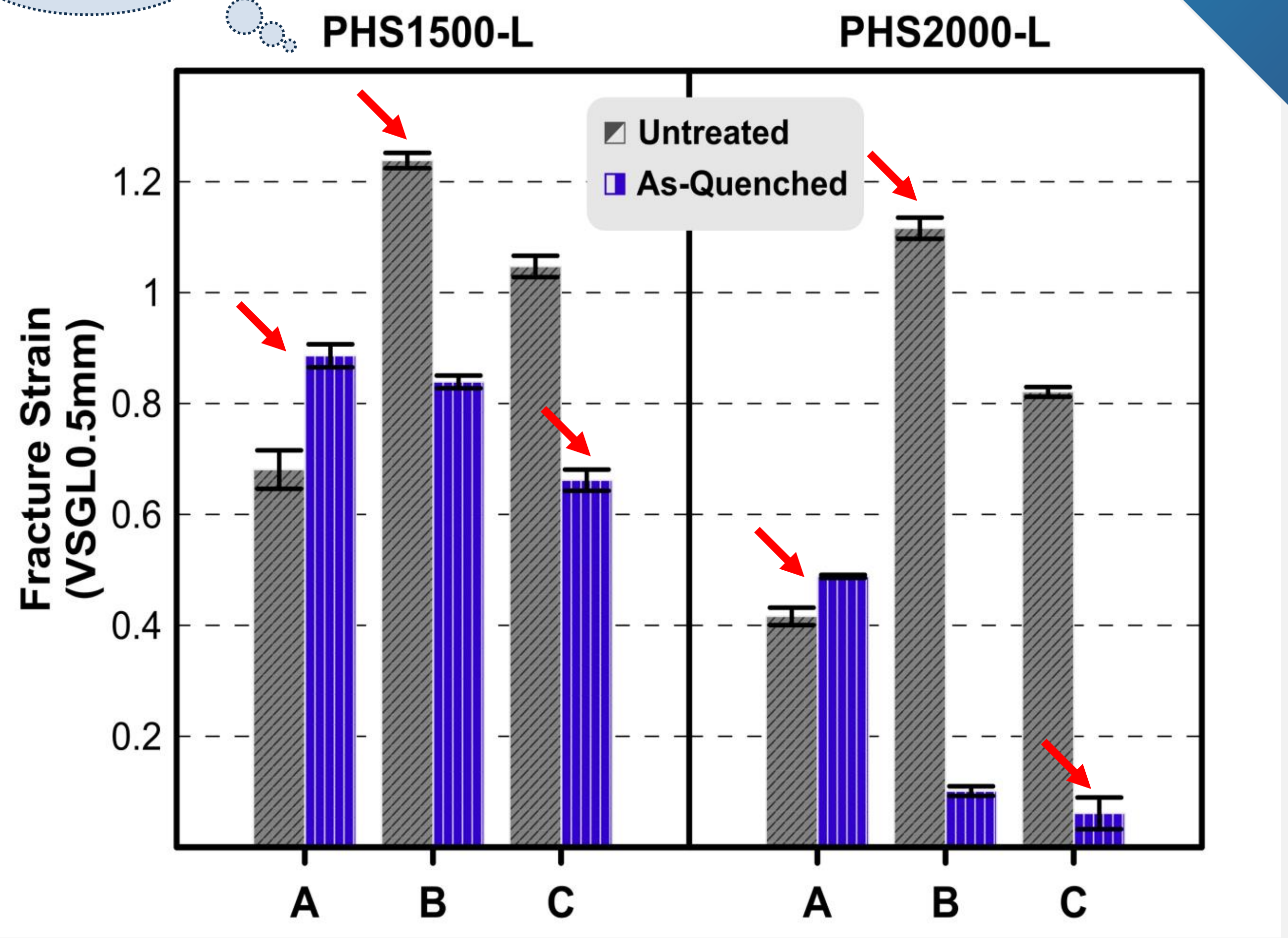
# Results: Tensile Fracture Strain

**Fracture Strain ≠ Elongation**

A. Cold-rolled, uncoated PHS
B. Annealed, uncoated PHS
C. Annealed, Al-Si coated PHS

Annealing effects?
Coating effects?

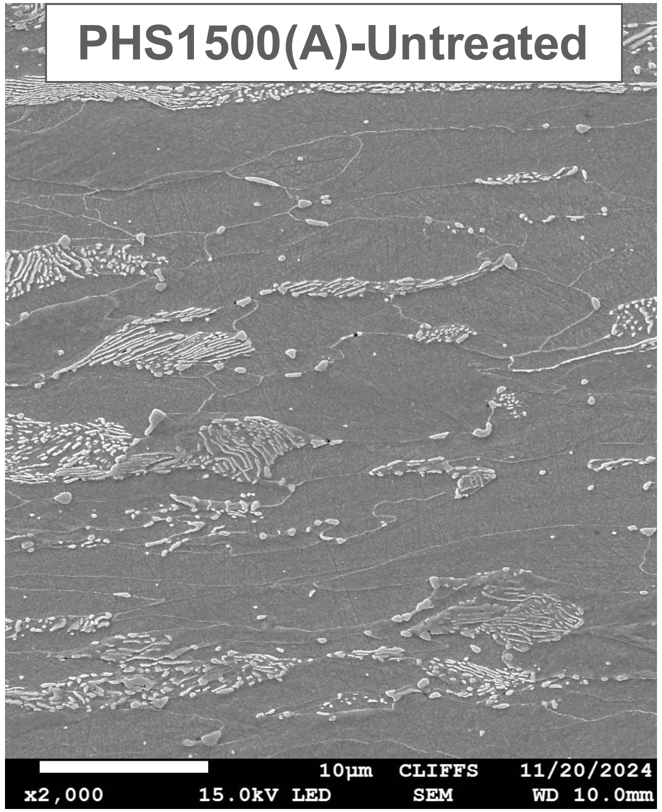


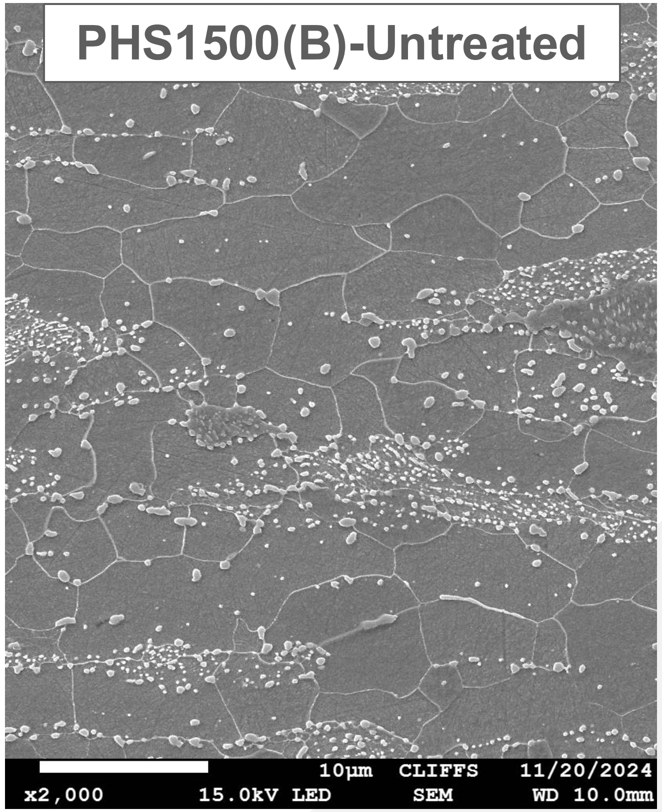



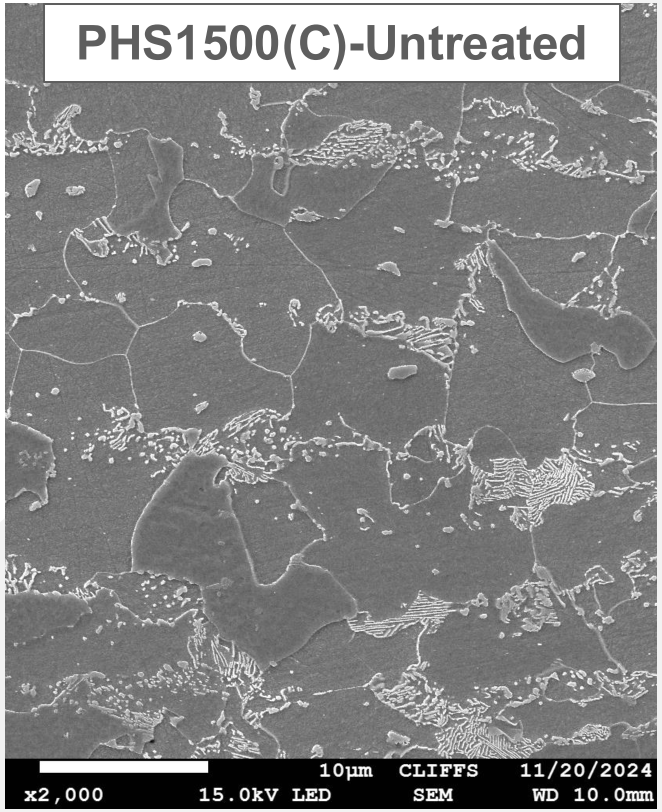
# Annealing Effects on Untreated PHS1500

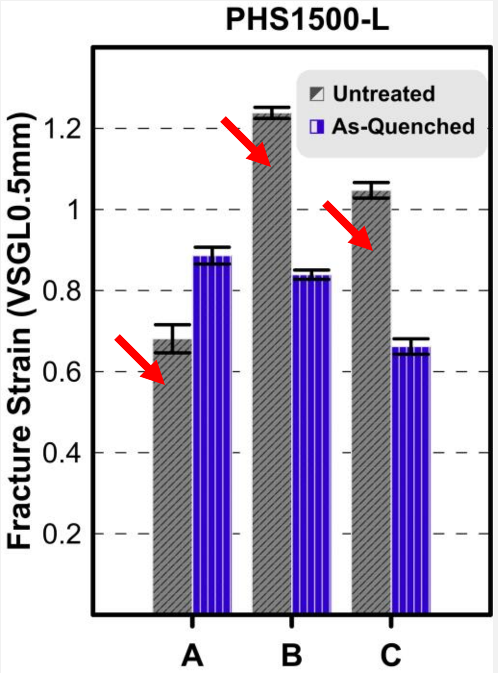


A. Cold-rolled, uncoated PHS
B. Annealed, uncoated PHS
C. Annealed, Al-Si coated PHS



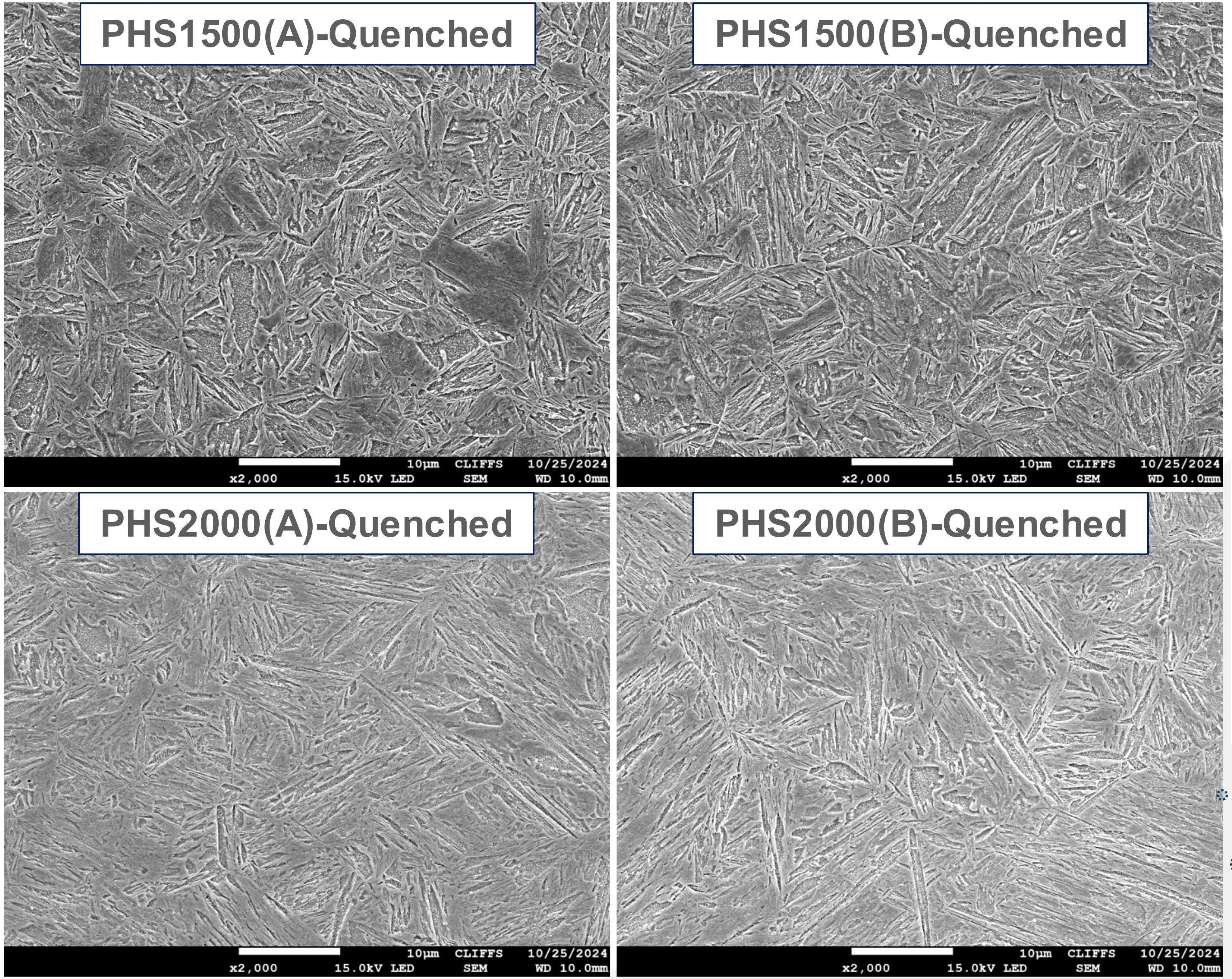



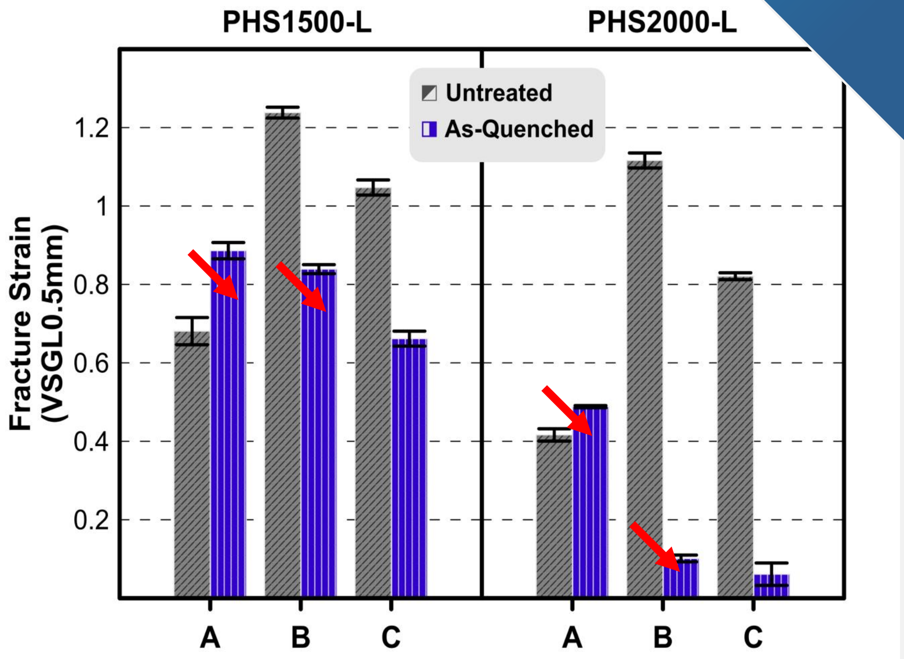



# Annealing Effects on Quenched PHSs (A vs. B)





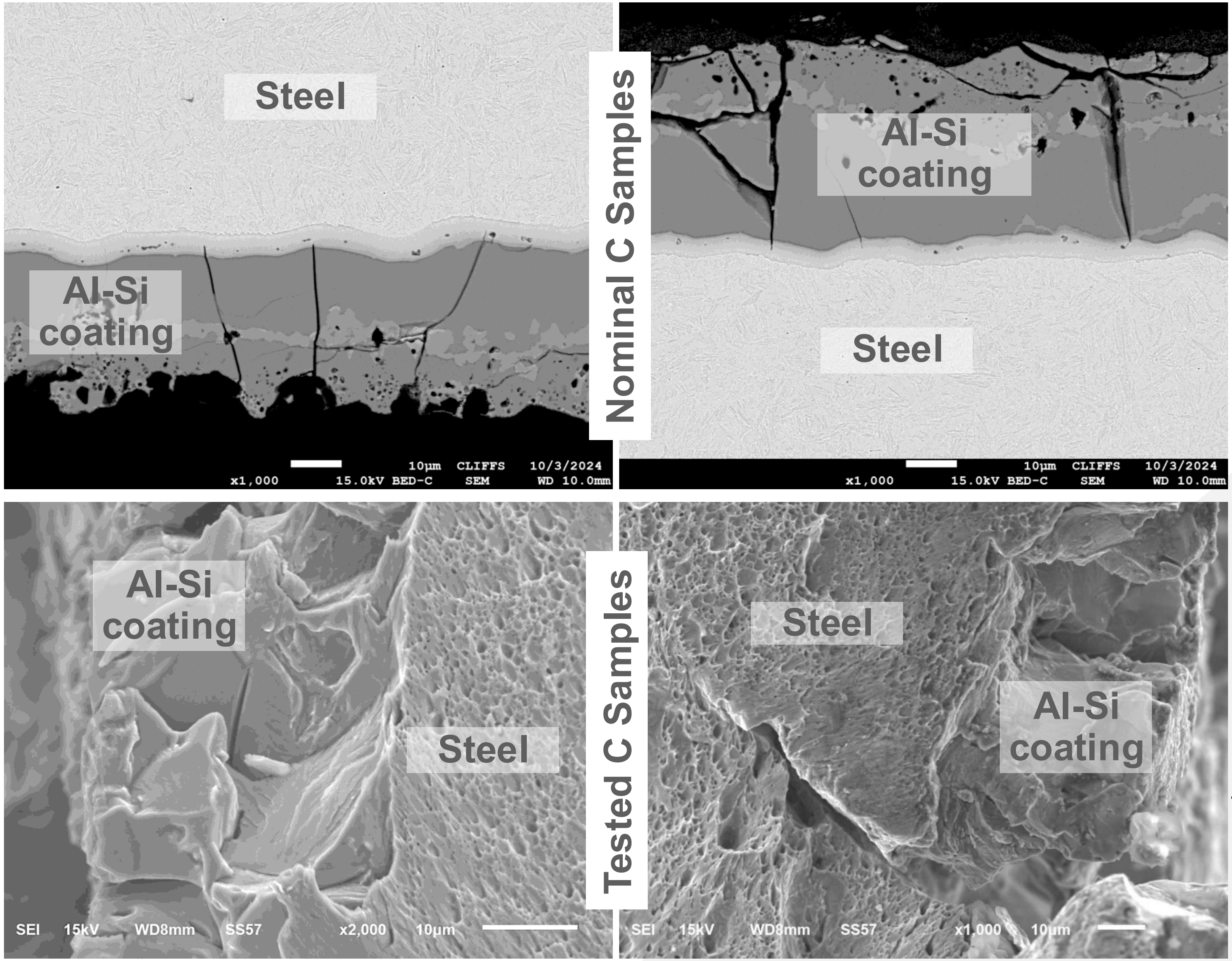

A. Cold-rolled, uncoated
B. Annealed, uncoated
C. Annealed, Al-Si coated



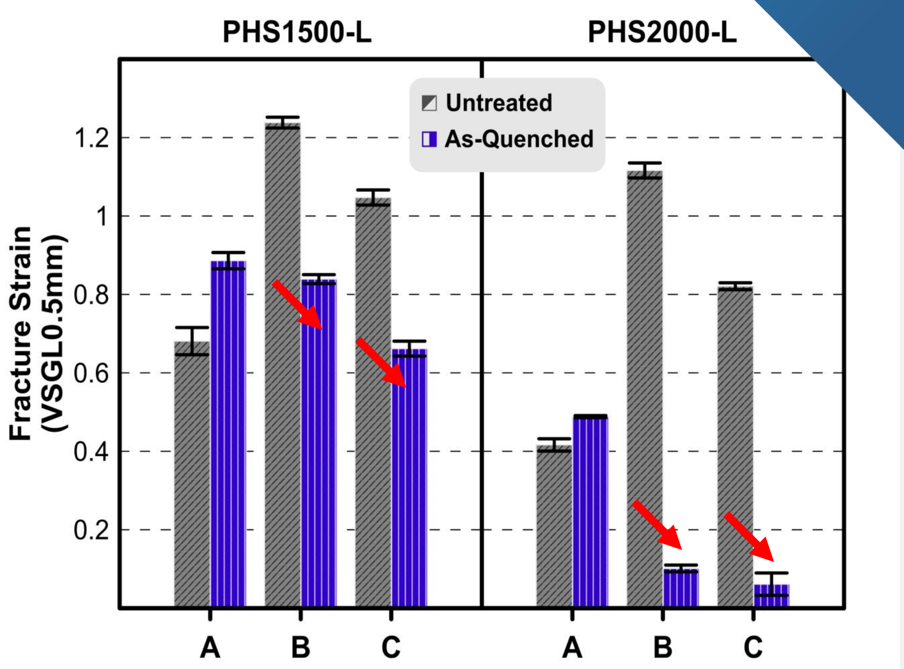

Coarsened grains?

# Coating Effects on Quenched PHSs (C vs. B)






A. Cold-rolled, uncoated
B. Annealed, uncoated
C. Annealed, Al-Si coated




Pre-cracks from Al-Si coating

# Summary of Tensile Ductility of 3 Types



**A. Cold-rolled, uncoated**

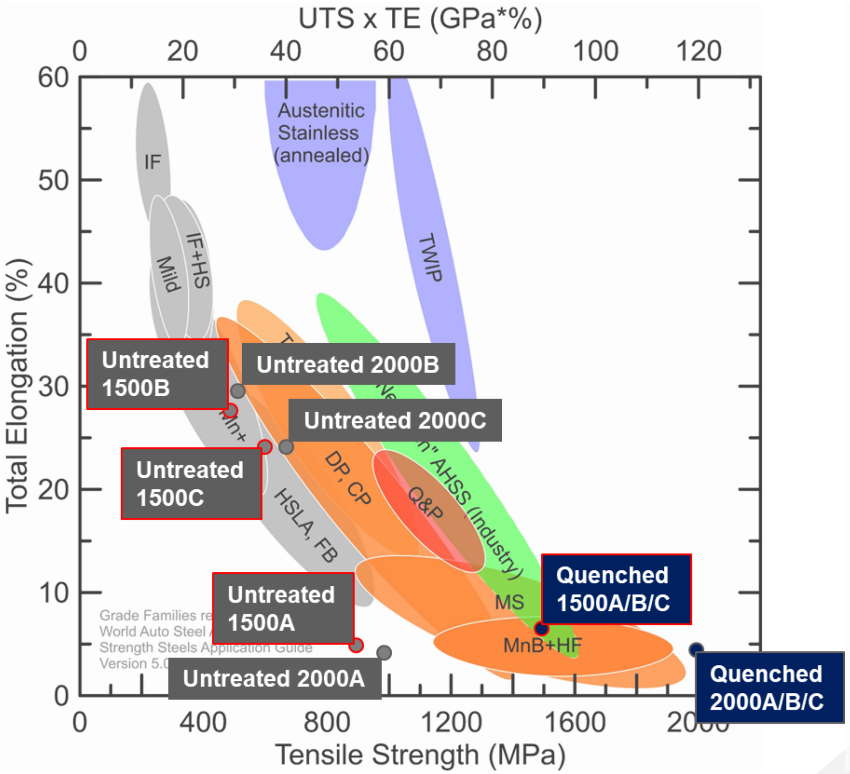
- Most brittle when untreated
- Most ductile after quenched
- Fracture strain increased after quenched

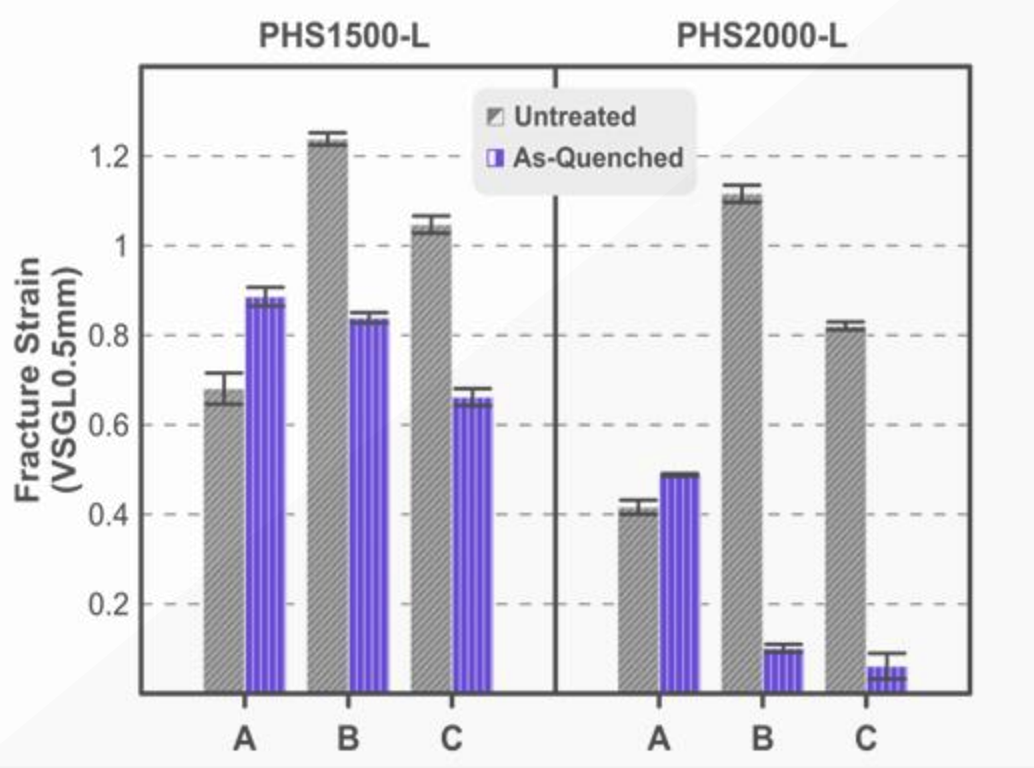
**B. Annealed, uncoated**

- Most ductile when untreated
- Fracture strain dropped after quenched

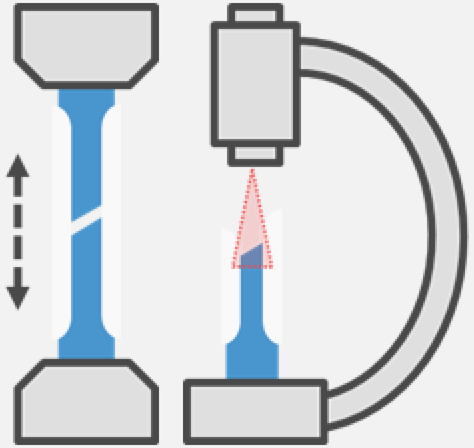
**C. Annealed, Al-Si coated**

- Most brittle after quenched
- Fracture strain dropped after quenched




**Fracture Strain ≠ Elongation**



# Evolving Fracture Resistance of PHS1500|2000

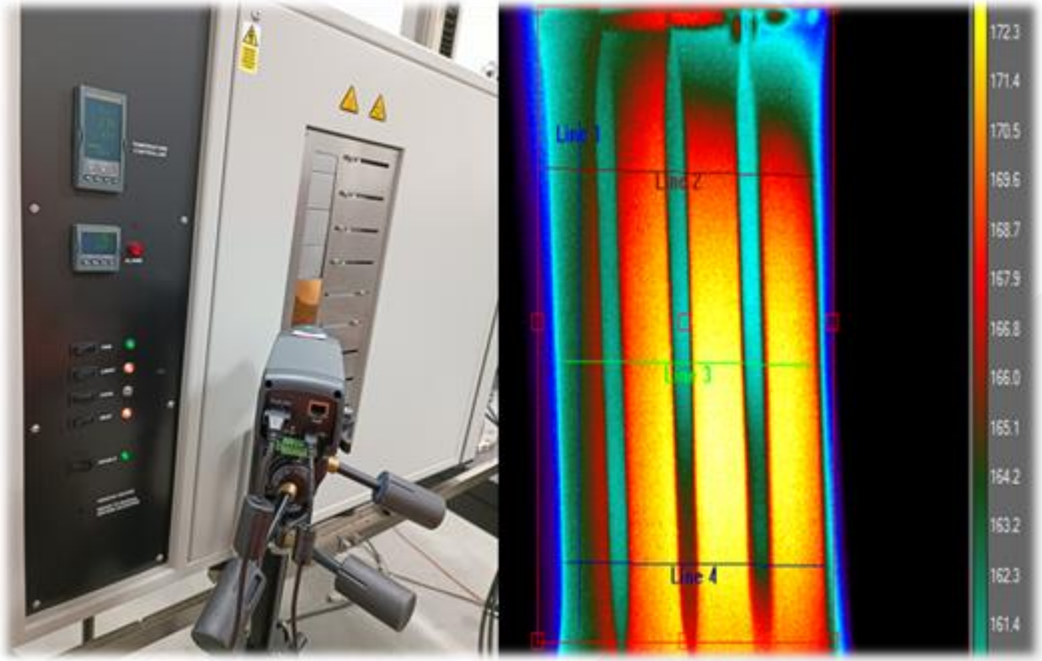
From Untreated to Quenched

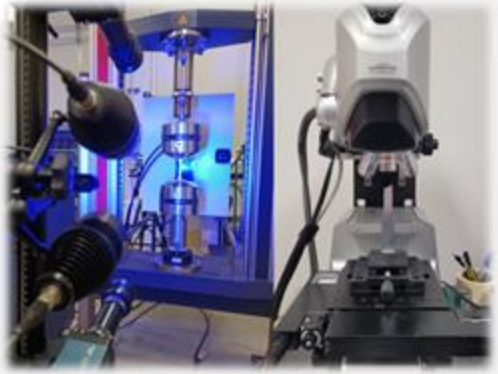
LTT (Paint-Baking) Effects

Rate / Stress-State Effects (on Type-A)

# LTT + Tensile Testing Procedure



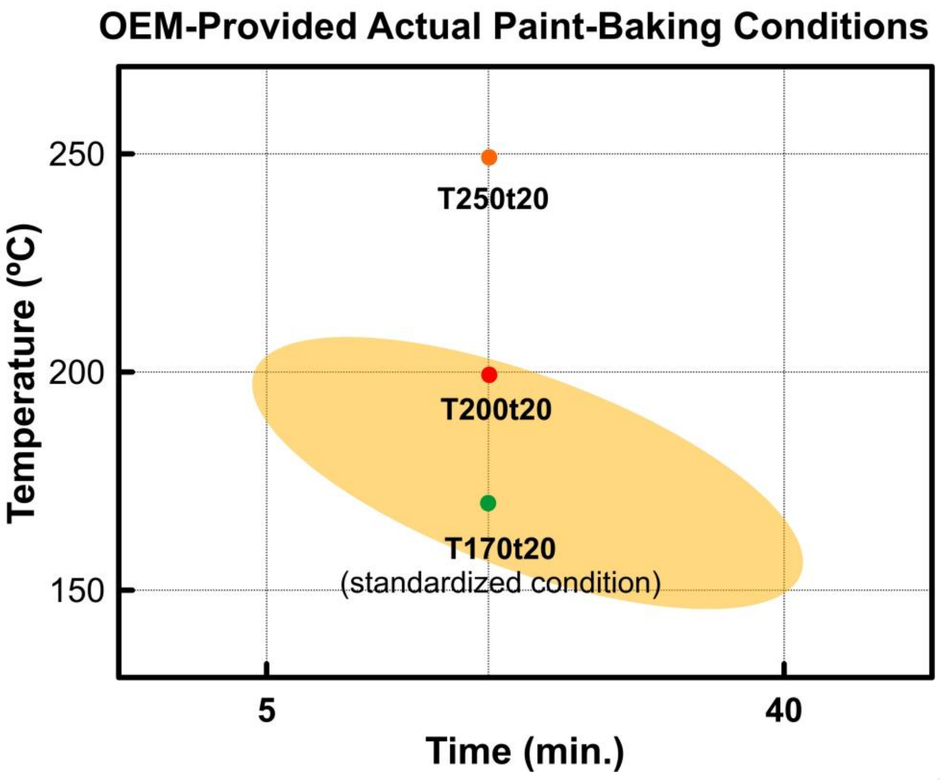
**LTT treatment**: ASTM E8 tensile test samples were heat-treated in a temperature chamber (monitored by an infrared camera) to simulate the automotive paint-baking cycles

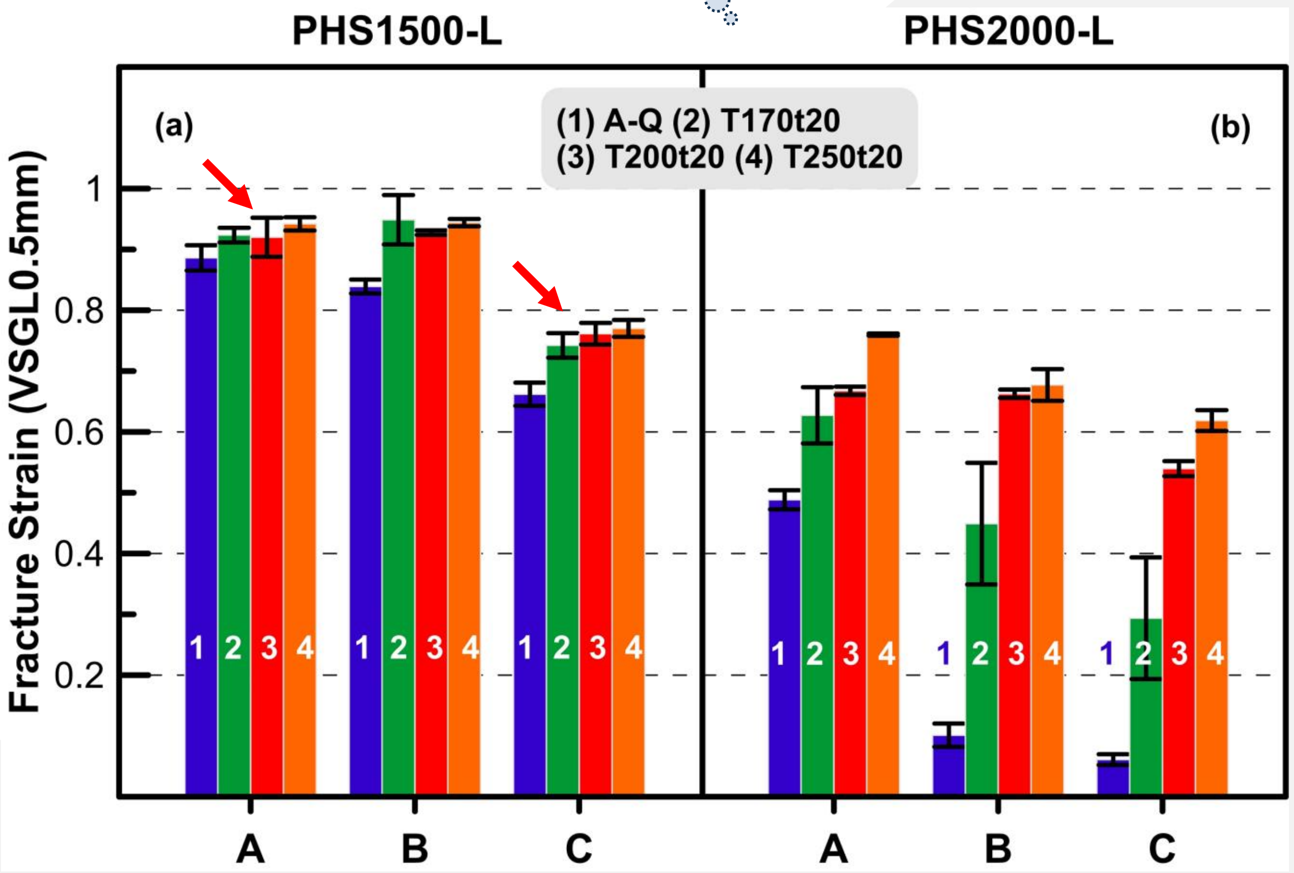
# LTT-Elevated Tensile Fracture Strain Results



A. Cold-rolled, uncoated PHS
B. Annealed, uncoated PHS
C. Annealed, Al-Si coated PHS

LTT improved PHS2000 more significantly
Higher temperature, higher elevation

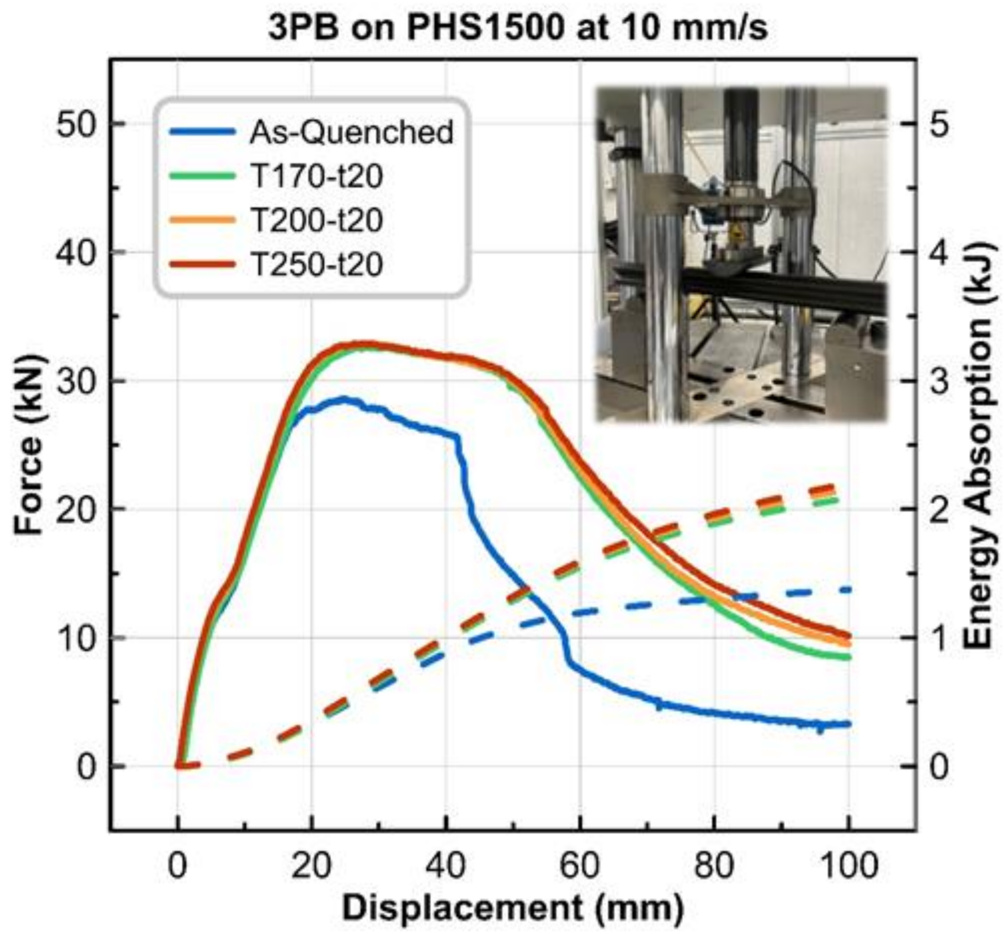


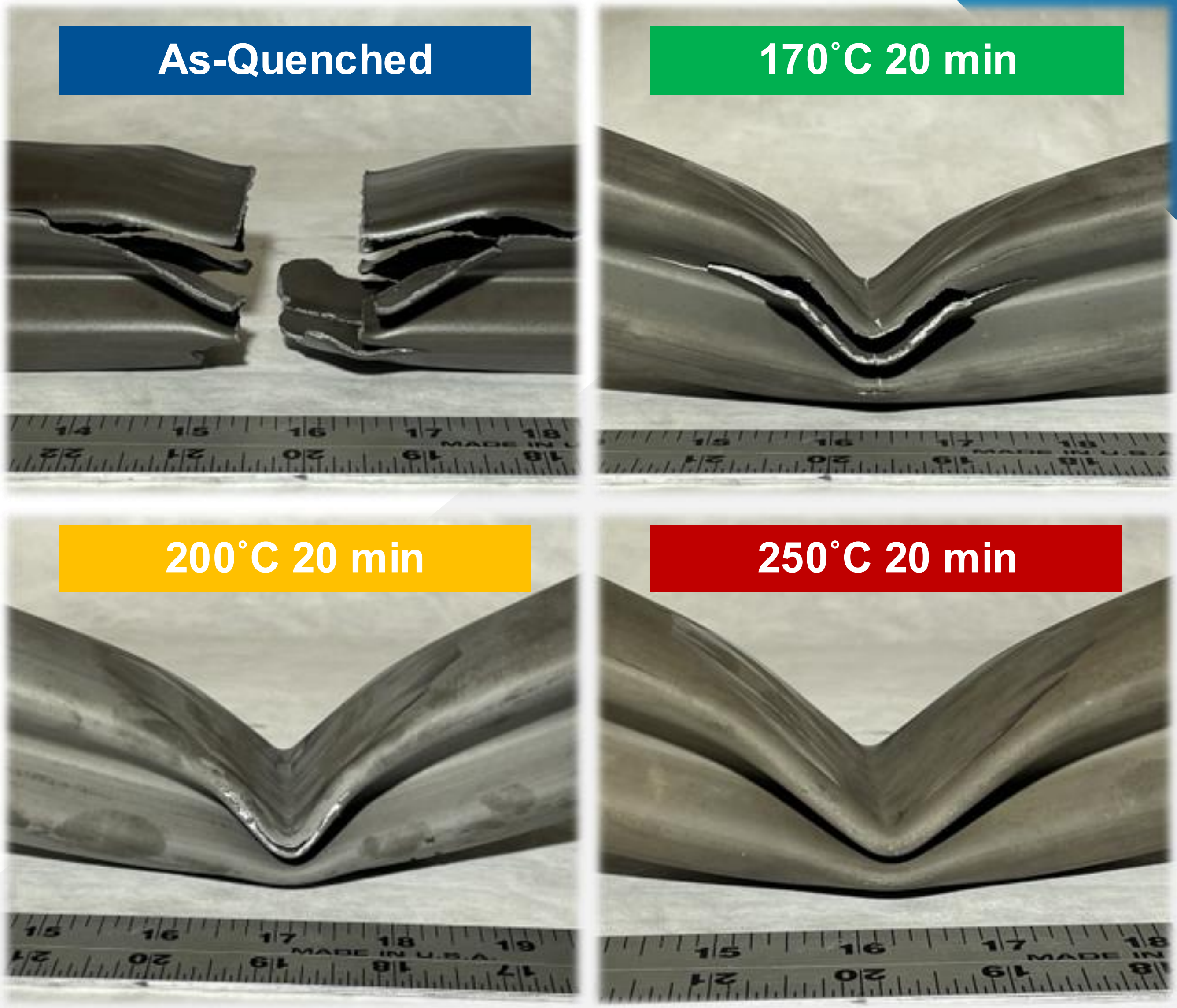



# Cross-Validation with 3PB Results in GDIS 2024





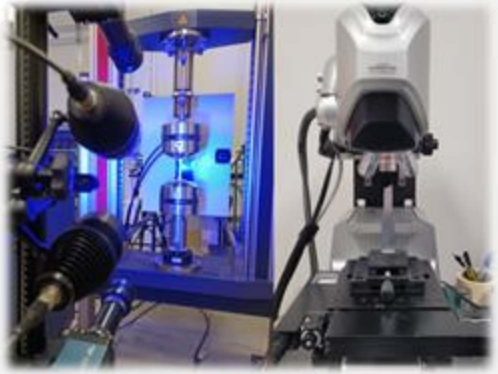



Photos captured after delayed fracture

# 2x LTT + Tensile Testing Procedure





**2x LTT treatment**: to simulate a procedure of quenched PHS components being first tempered by Cleveland-Cliffs Inc. and then paint-baked in assembly by automakers; particularly applicable for Al-Si coated PHS (Type-C) tubular components

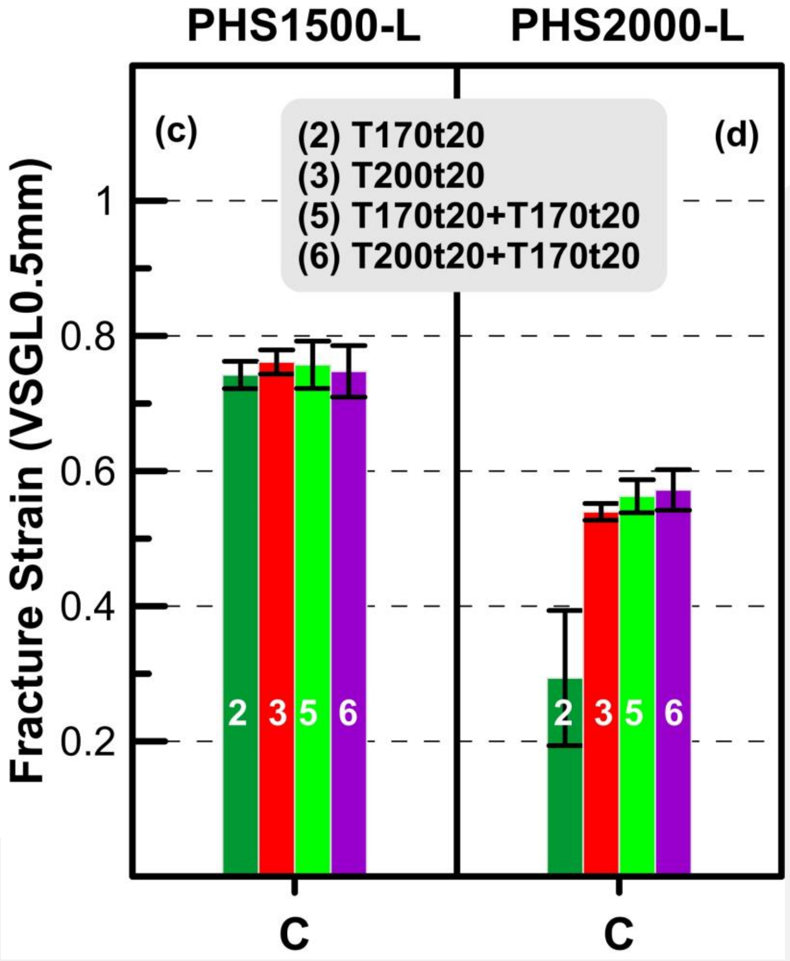
# 2x LTT-Elevated Tensile Fracture Strain Results



A. Cold-rolled, uncoated PHS
B. Annealed, uncoated PHS
C. Annealed, Al-Si coated PHS

Type-A/B → Hot-Stamped → Quenched (+Tempered by Cleveland-Cliffs Inc.) → Paint-Baked

Type-C → Cold-Rolled → Annealed → Quenched (+Tempered by Cleveland-Cliffs Inc.) → Paint-Baked




2x LTT effects on fracture strain saturated

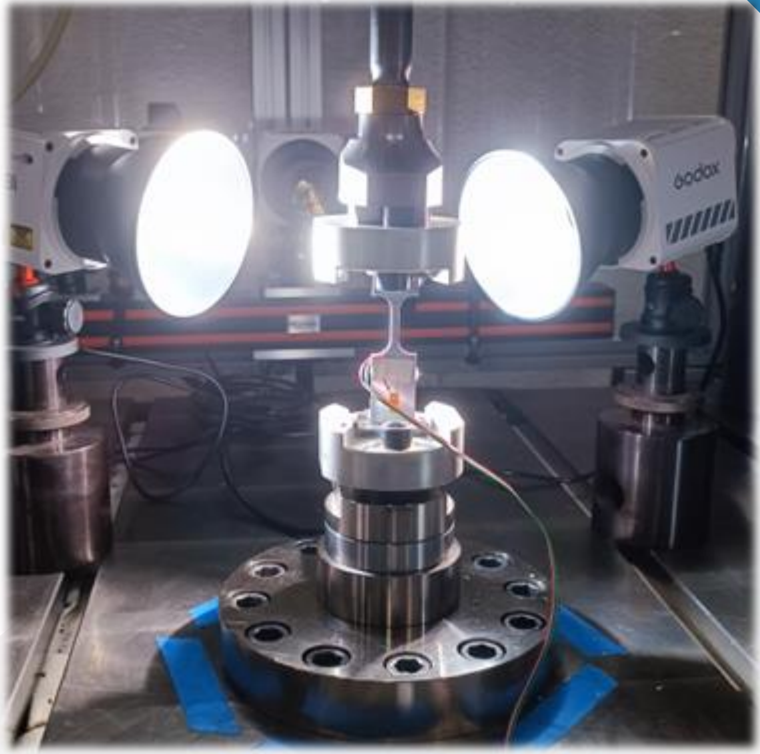
# Evolving Fracture Resistance of PHS1500|2000

From Untreated to Quenched

LTT (Paint-Baking) Effects

Rate / Stress-State Effects (on Type-A)

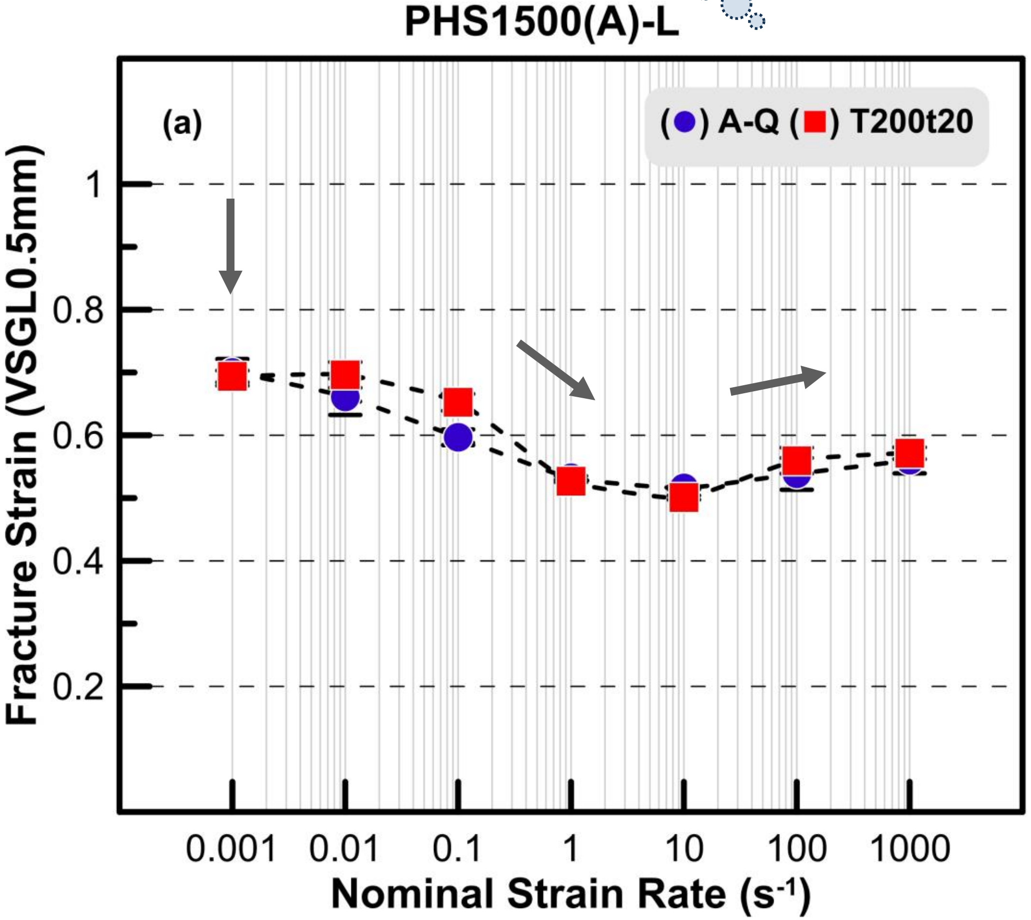
# Rate-Dependent Tensile Testing Procedure

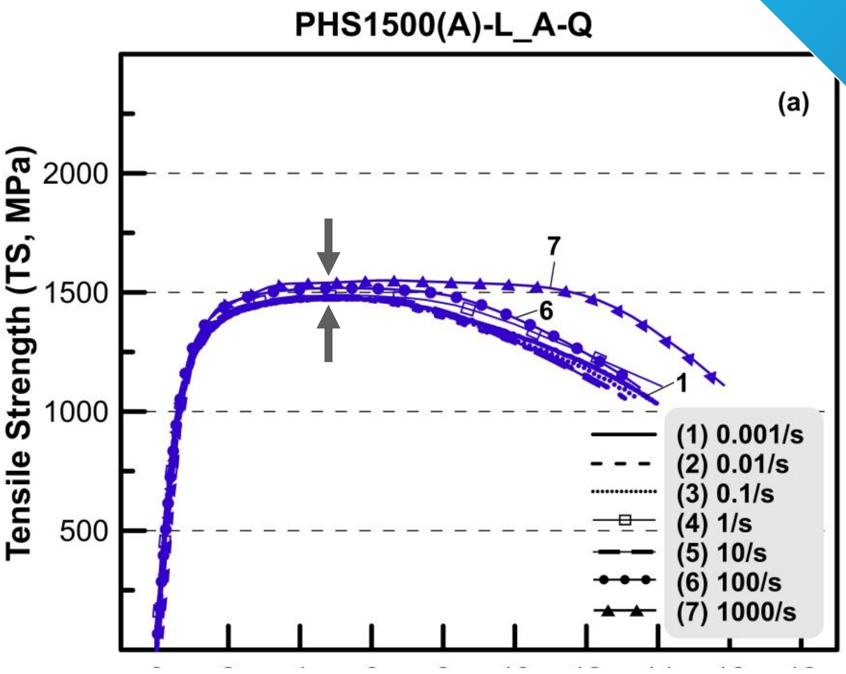



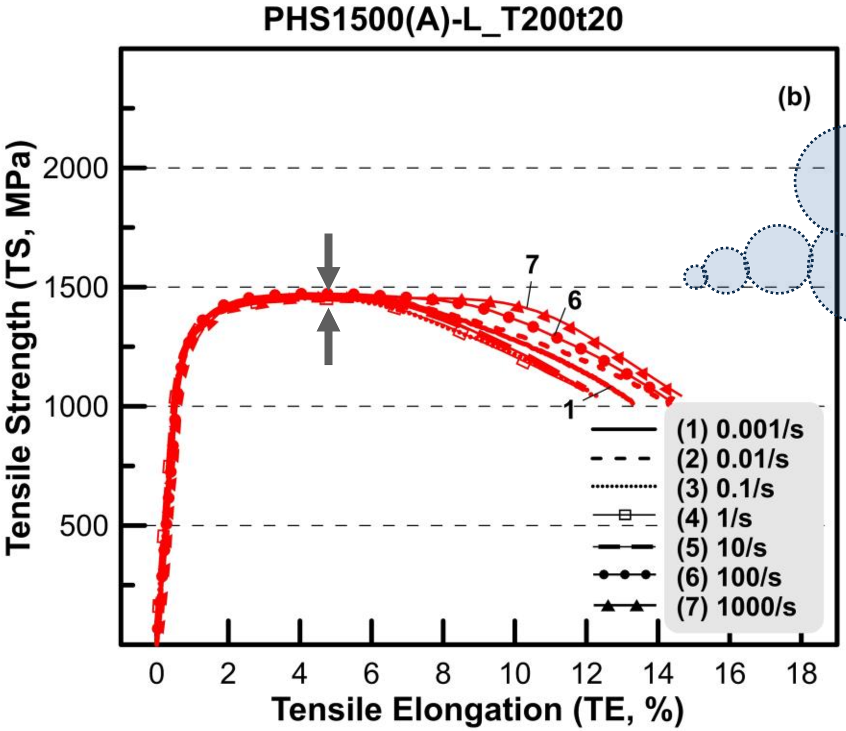
Rate-dependent tensile: as-quenched (A-Q) vs. T200t20-treated Type-A PHS1500|2000 samples were cut to modified ISO 26203-2 geometry and tested at 0.001 – 1000 $s^{-1}$ nominal strain rates and through fracture strain measurements

# Results: PHS1500(A)

Effects of sample geometry, adiabatic heating & strain hardening



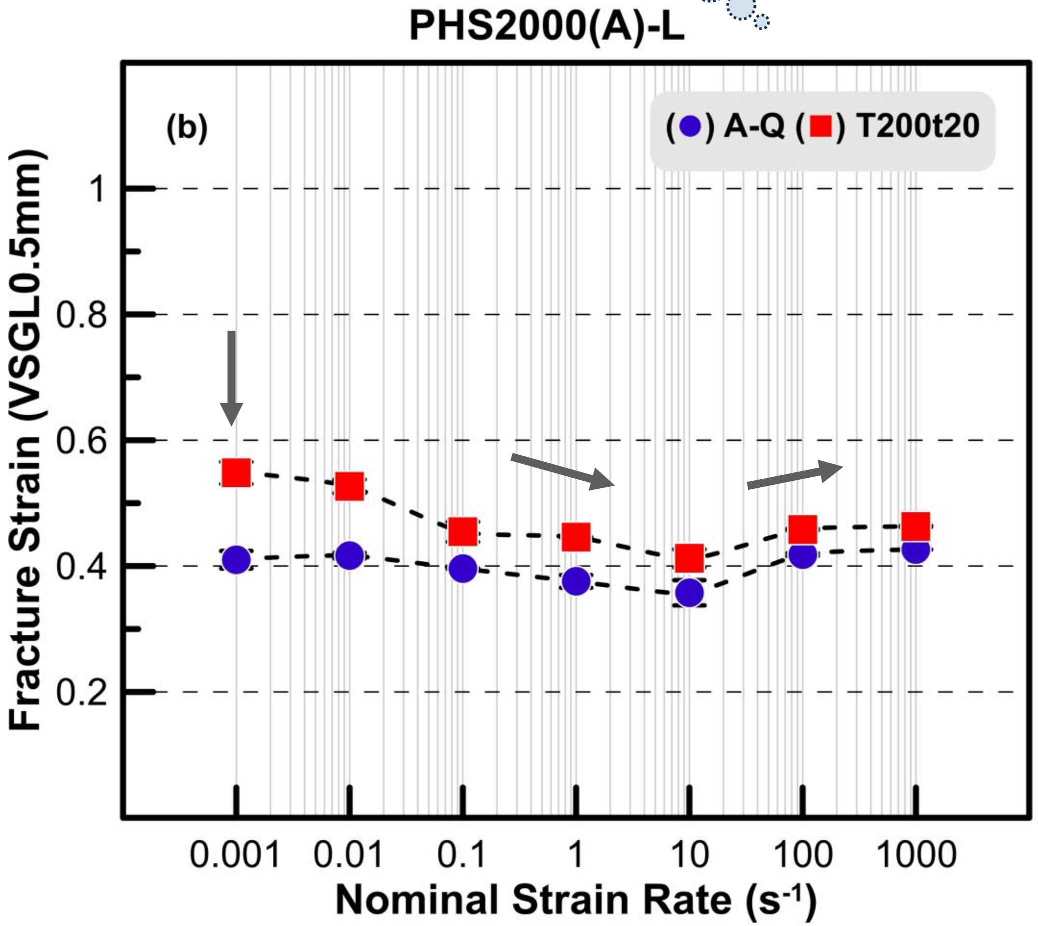



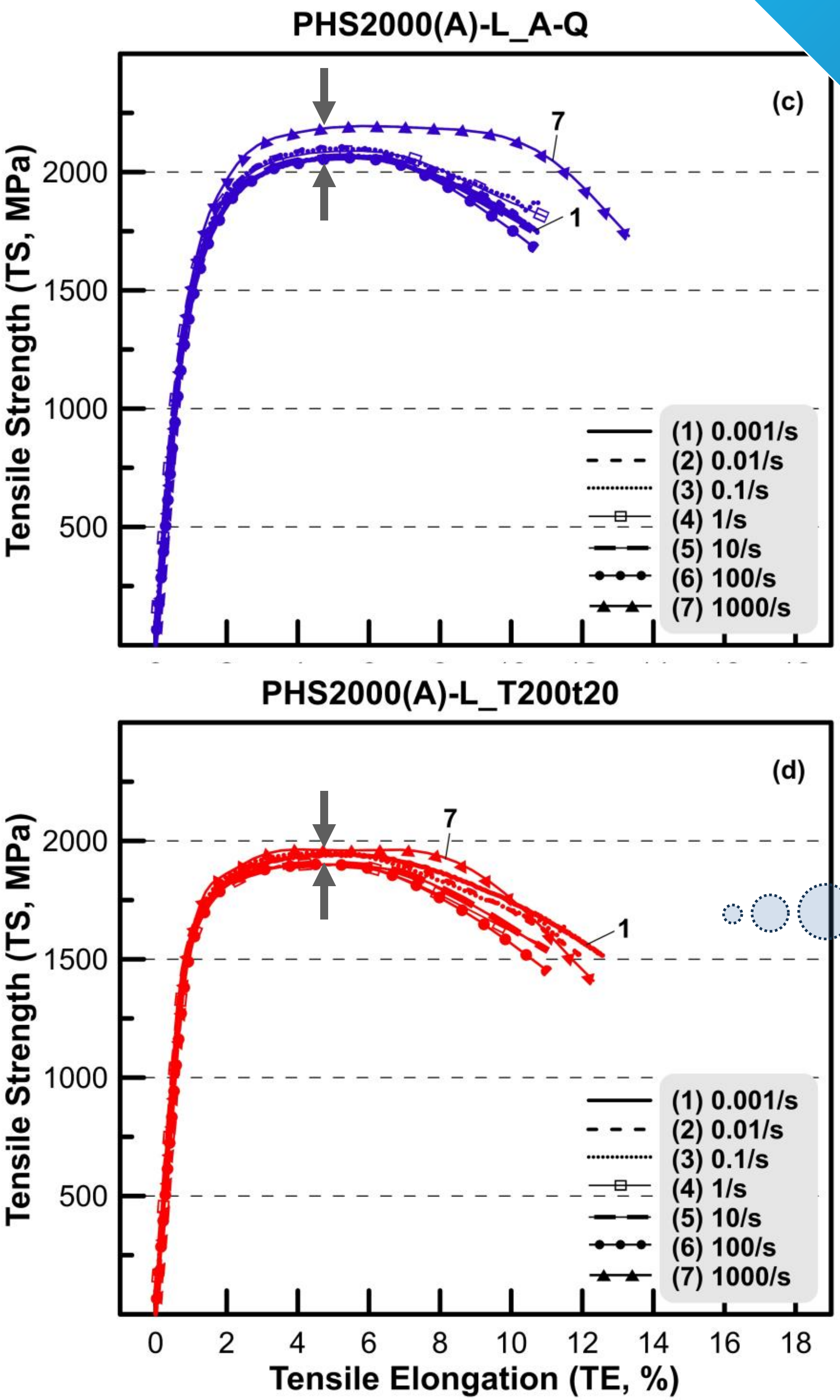

LTT decreased flow stress' rate sensitivity

# Results: PHS2000(A)



Similar trends as PHS1500(A)

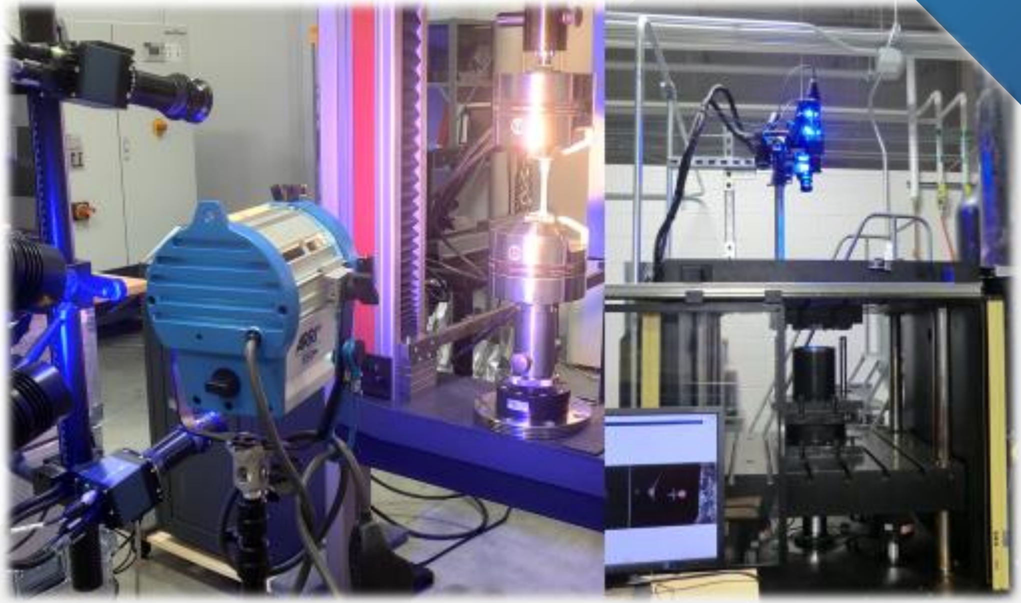



Similar trends as PHS1500(A)

# Stress-State-Dependent Testing Procedure

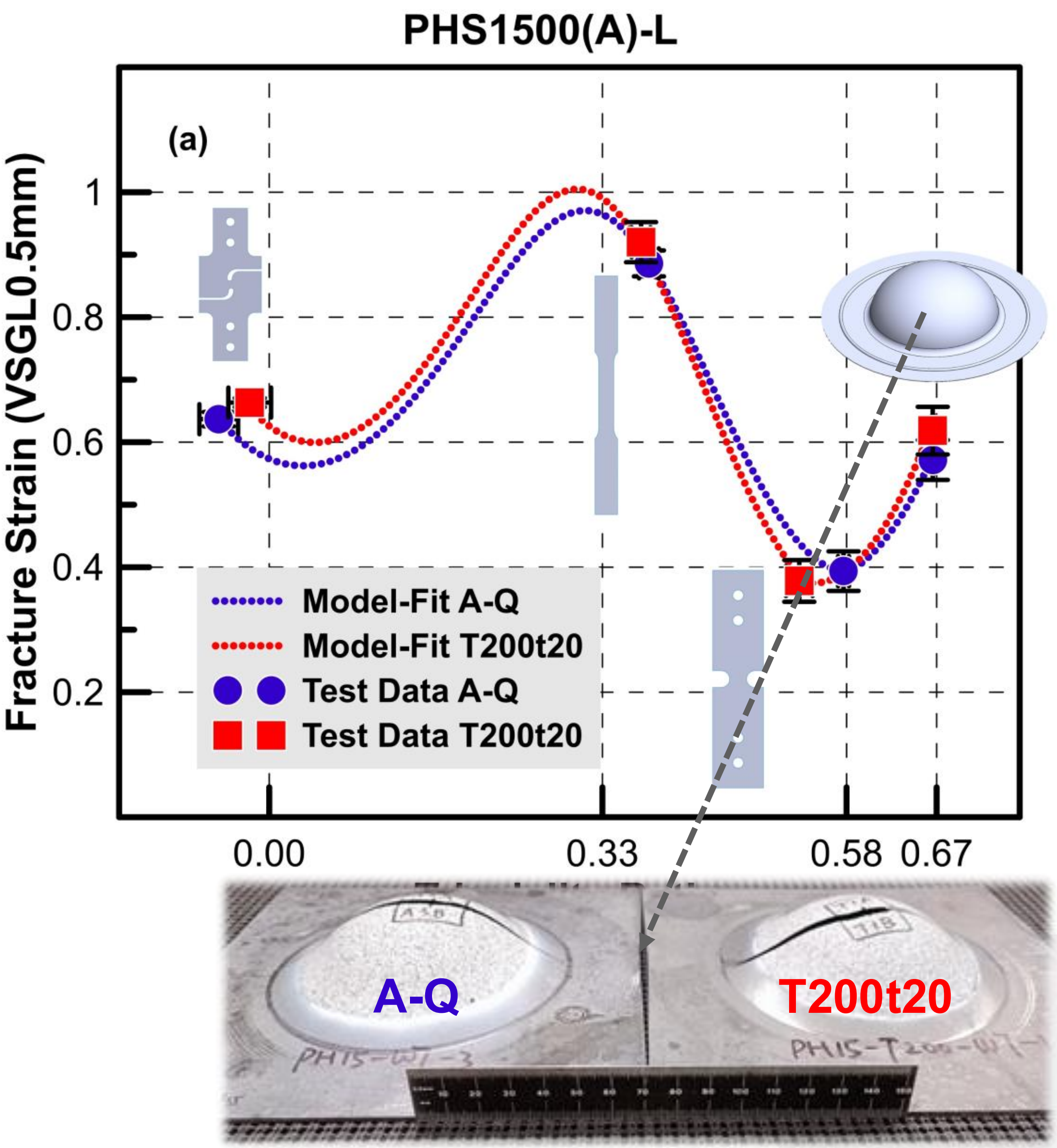


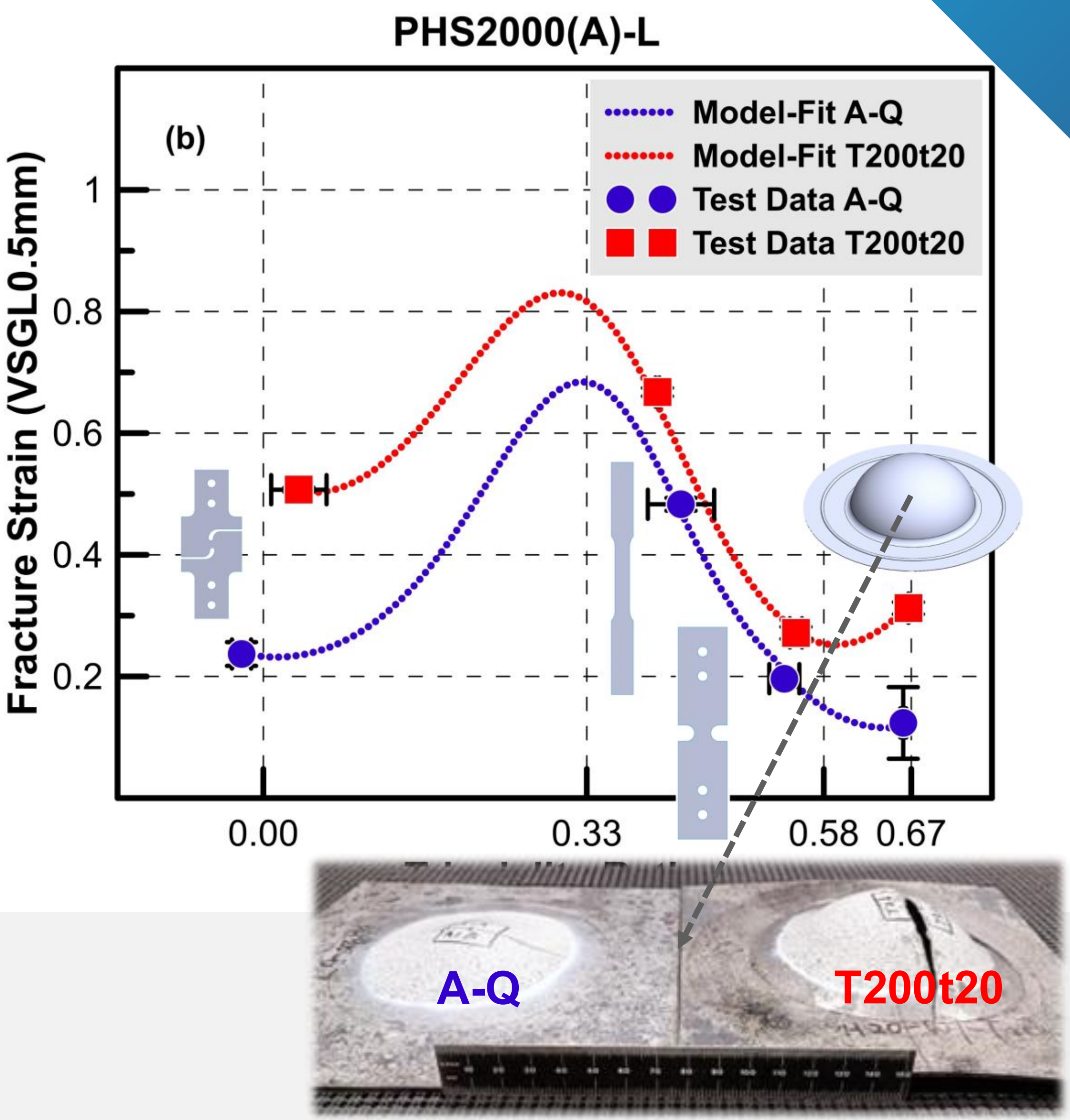



Stress states besides uniaxial tension: A-Q vs. LTT PHS1500|2000(A) samples were tested under quasi-static simple shear, plane strain, and equi-biaxial tension, and through fracture strain measurements

# Stress-State-Dependent Fracture Strain Results





# Conclusions



❖ **3 UHS-PHS types** exhibited distinct fracture resistance:

- Type-A (cold-rolled, uncoated): most brittle when untreated, yet most ductile after quenched
- Type-B (annealed, uncoated): most ductile when untreated
- Type-C (annealed, Al-Si coated): most brittle after quenched

❖ **Low-temperature tempering (LTT)** could improve fracture resistance of quenched UHS-PHS:

- LTT improved PHS2000 more significantly
- Higher LTT temperature, higher fracture strain elevation
- Longer LTT time (2x cycles), the elevation saturated

❖ **2 practical conditions** were evaluated on quenched vs. tempered PHS1500|2000(A):

- Rate-dependent tensile tests revealed a common fracture-strain minimum near 10 $s^{-1}$ due to competing strain hardening and adiabatic heating; LTT reduced rate sensitivity of flow stress and enhanced fracture strain, especially for PHS2000(A)
- Stress-state-dependent tests confirmed that LTT increased fracture strain across all stress states for PHS2000(A), with the most pronounced gains under simple shear and equi-biaxial tension

# THANK YOU!

## For More Information

→ → →

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Relevant publications:

- **On Fracture Resistance of Ultra-High-Strength Press-Hardened Steels**, *AIST 3rd Auto Steel Int. Conf. 2025*
- **Influence of Low-Temperature Tempering on Mechanical Behavior of a Press-Hardened 22MnB5 Steel Grade**, *CHS² 2024*
- **On Local Formability/Ductility of New Advanced High-Strength Steels: Temperature, Bake Hardening, and Strain Rate Effects**, *AIST Transactions 2024*
- **True Fracture Strain Measurement and Derivation for Advanced High-Strength Steel Sheets**, *SAE 2022, GDIS 2023*