GREAT DESIGNS IN STEEL

Discrepant Paint-Baking Impact on AHSSs and HSAAs Used in BEV Structures

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Acknowledgement

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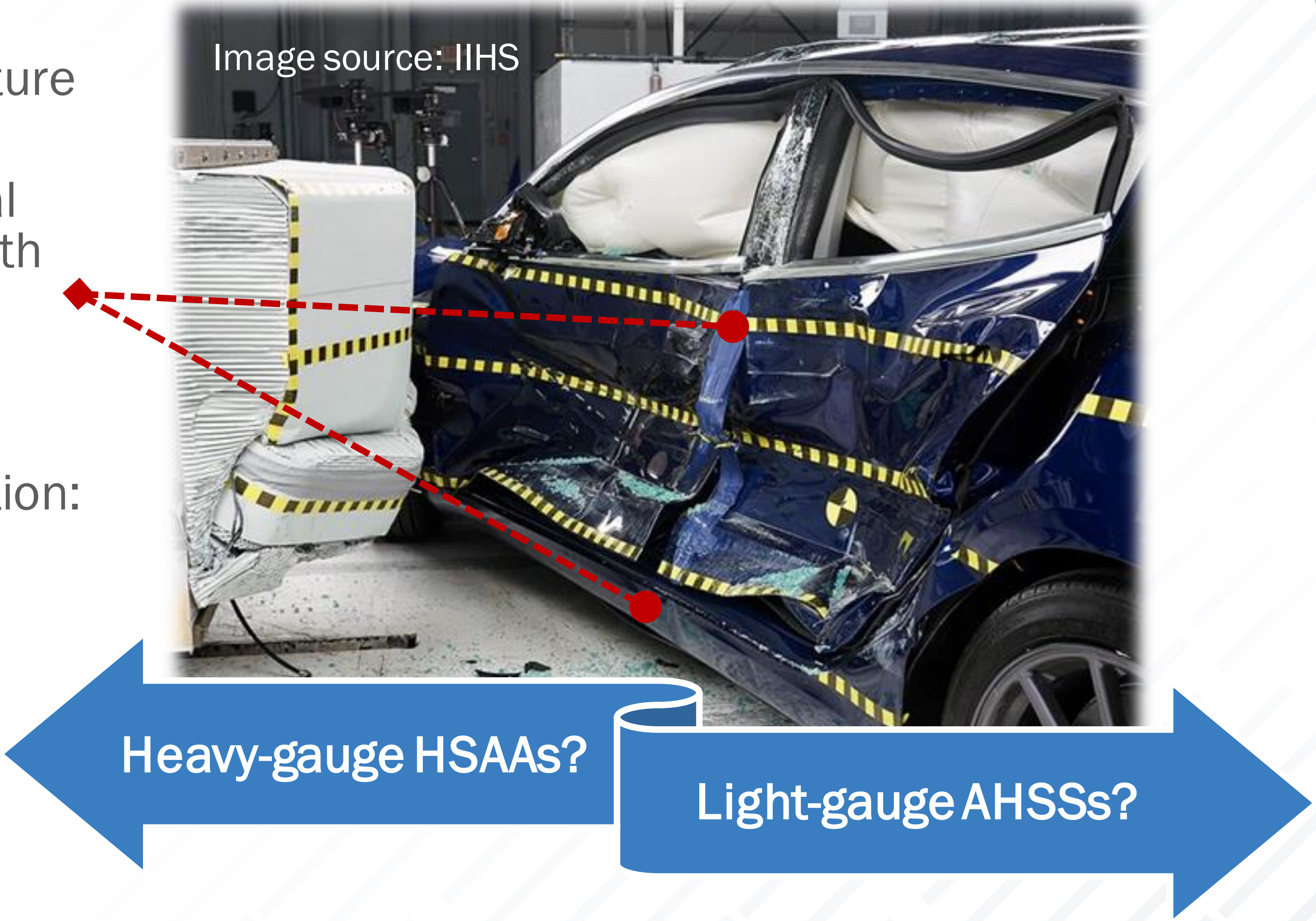
Introduction

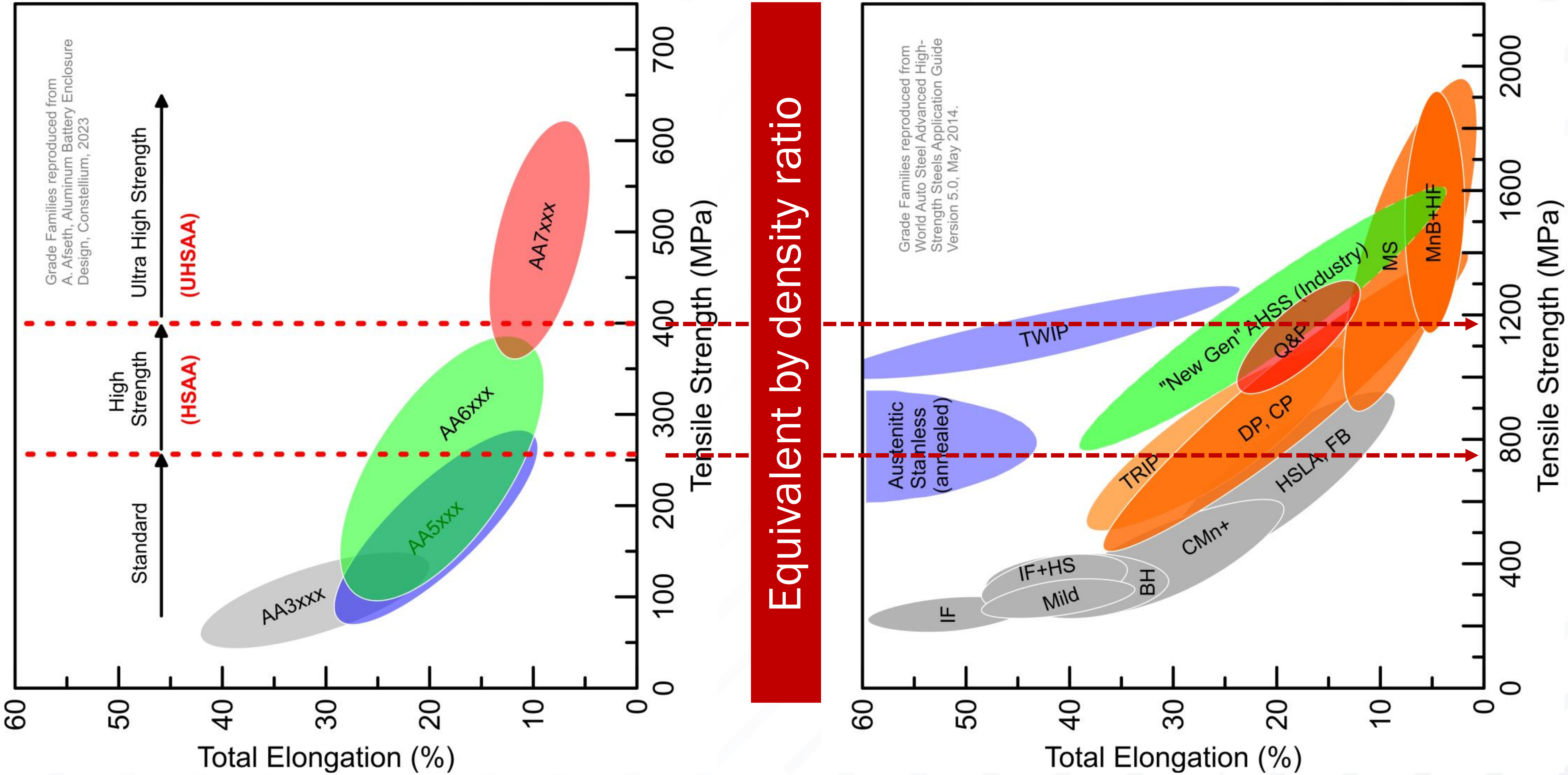
A battery electric vehicle (BEV) structure requires:

- Safety: additional protection for both occupants and battery system
- Lightweighting

On materials selection: steels or aluminum alloys (AAs)



HSAAs vs. AHSSs Overview



HSAAs vs. AHSSs in BEV Structures

AA6xxx = Al-Mg-Si-(Cu): T4 (natural aging) or T6 (artificial aging) temper

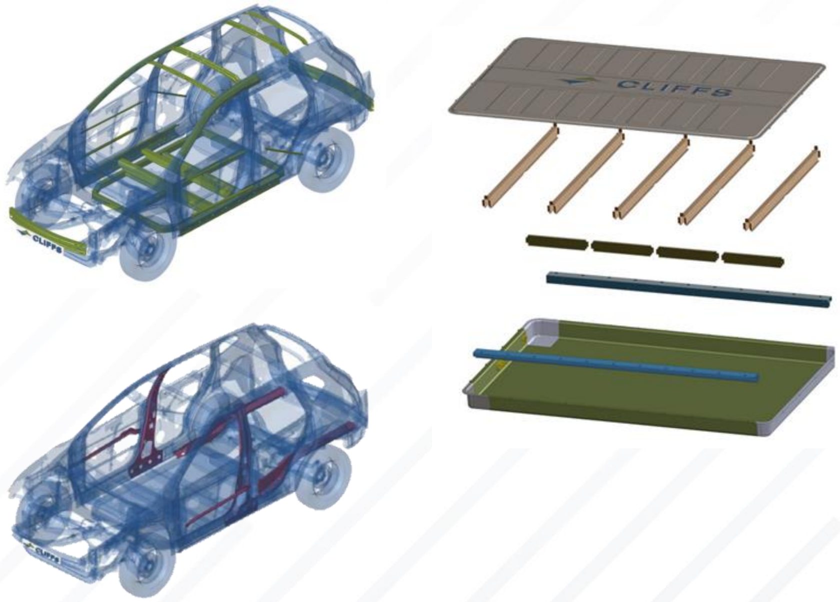
- Rolled sheets (T4/T6) for cold stamping or extruded tubes (T6)

AA7xxx = Al-Zn-Mg-(Cu): T6 temper

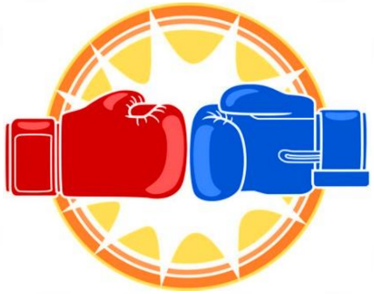
- Rolled sheets for hot/warm stamping

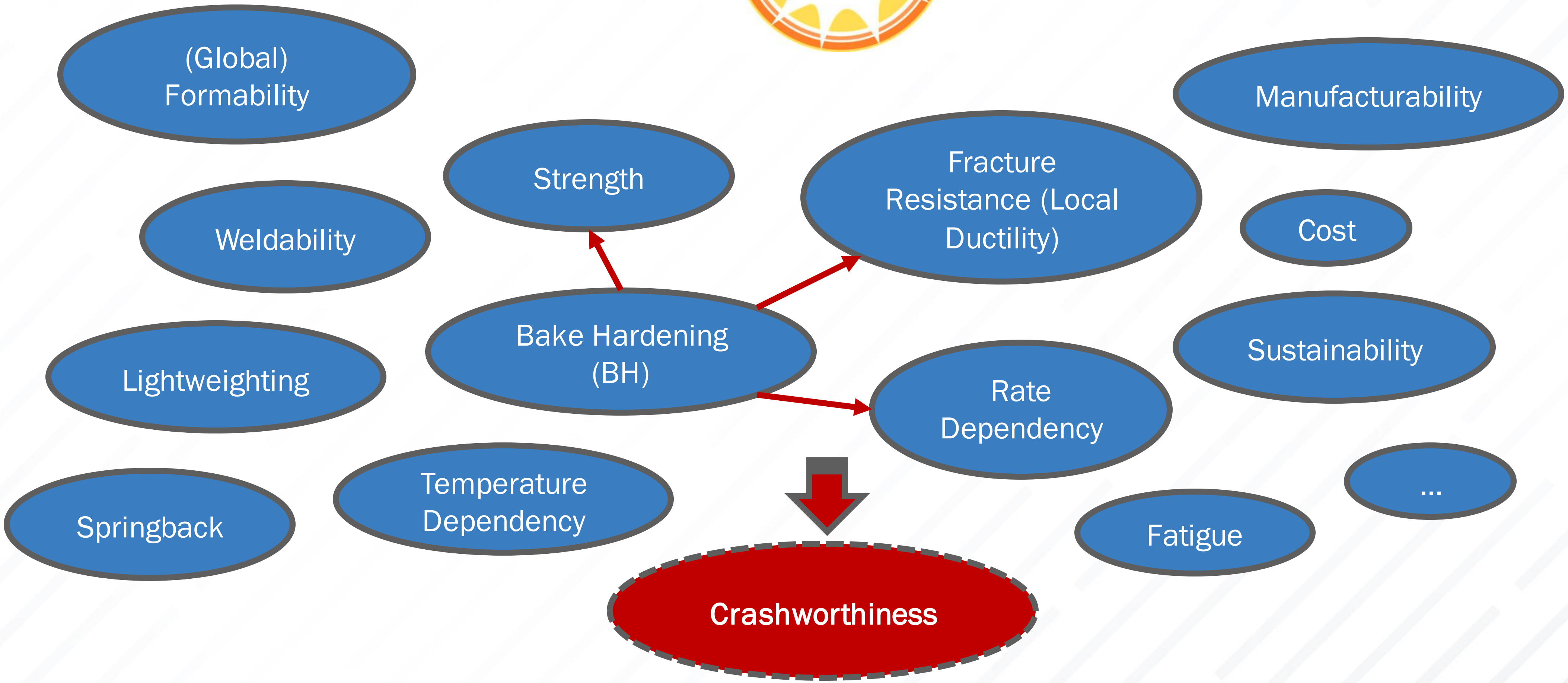
Competitive Cleveland-Cliffs U/AHSSs (UTS ≥780 MPa):

- DP/MP: 780/980/1180/1470
- CP: 780/980
- TRIP: 780
- Q&P: 980/1180
- MS: 900/1100/1300/1500/1700
- PHS: 1000/1500/(in dev.)2000
- Rolled sheets for cold/hot stamping or tubing



Scope of Work

HSAAs  AHSSs



Paint-Baking Cycle Overview

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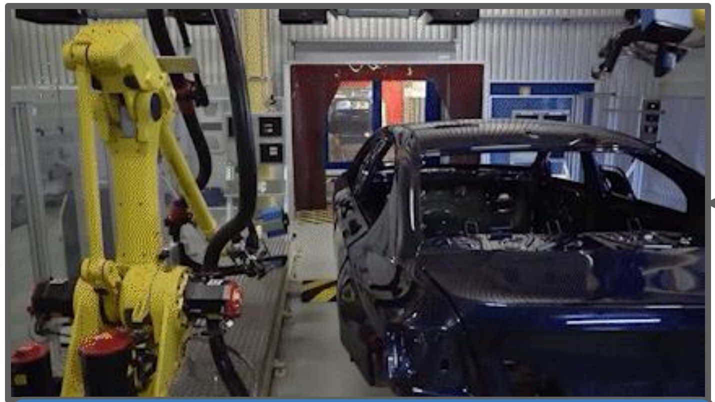
Electrodeposition

Sealing

Painting

Baking



Inspection

Assuming a battery enclosure can be treated separately in a similar cycle

Video source: https://www.youtube.com/watch?v=O0ScFQ1rbe4

BH Testing Overview

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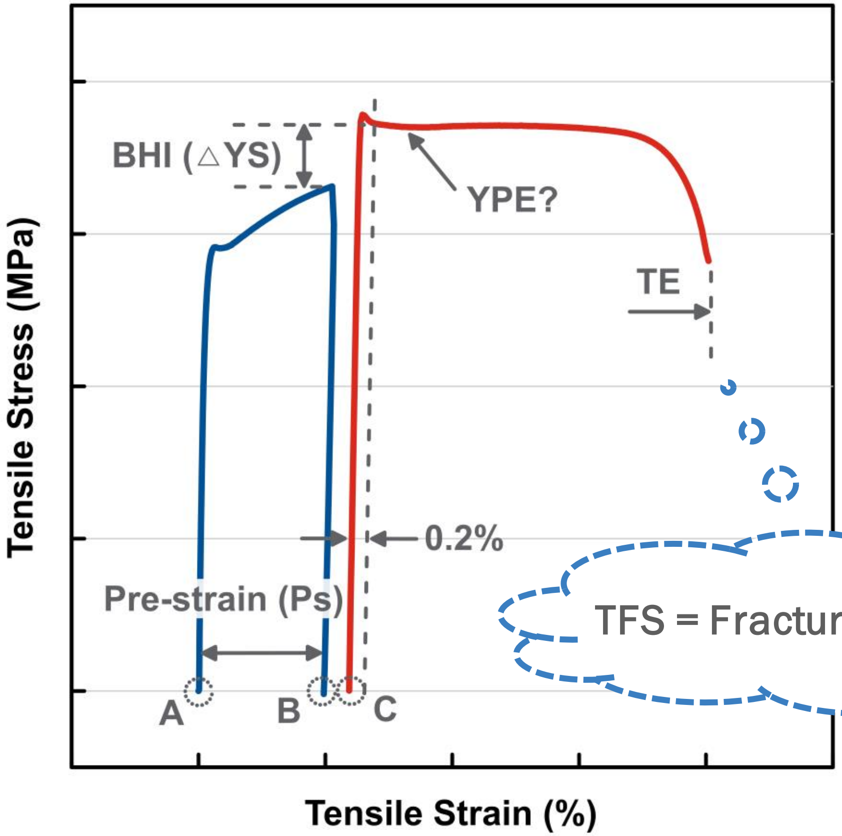
In the standards (DIN EN 10325, JIS G 3135, ISO 14590):

- For cold-forming steels only, uniaxial tension only
- Pre-strain (Ps) level: 2%
- Strain rate: quasi-static
- Baking conditions: 170±2 ˚C, 20±0.5 min.
- Target parameter: ΔYS

In 3 different case studies of this work:

- Various HSAAs and AHSSs, various stress states
- Ps levels: 0/5/10/15%
- Strain rates: 0.001/1/10/100/1000 s^{-1}
- Baking conditions: 170/200/250 ˚C, 20±0.5 min.
- Target parameters: ΔYS, true fracture strain (TFS)



TFS = Fracture Resistance ≠ TE

All the TFS results were processed via the hybrid method (SAE WCX 2022, GDIS 2023) based on 0.5 mm virtual strain gauge length (VSGL)

Case Study I: BEV Rocker Reinforcement Tubes

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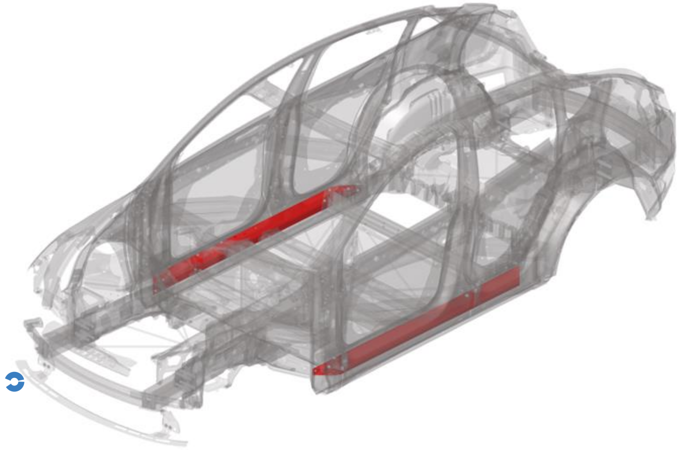
GI Q&P980 vs. AA6061-Tx:

- Cold-rolled TRIP-assisted multiphase 3G-AHSS grade vs. extruded Al-Mg-Si-(Cu) alloy
- Tubing via roll-forming-welding sheets vs. tubing via hot extrusion
- Baking after pre-strain (Ps) vs. baking without Ps
- Thickness 1.6 mm vs. 4.8 mm: similar strength-to-density ratio

3 testing conditions:

1) Quasi-static tensile
2) Rate-dependent tensile
3) Quasi-static stress-state-dependent tests

HSAA tubes → AHSS tubes: please check the C-STAR™ project presented at GDIS 2023 and SAE WCX 2024



(Images courtesy of M. Yu and Y. Wang)

Comparison of Procedures and BH Mechanisms

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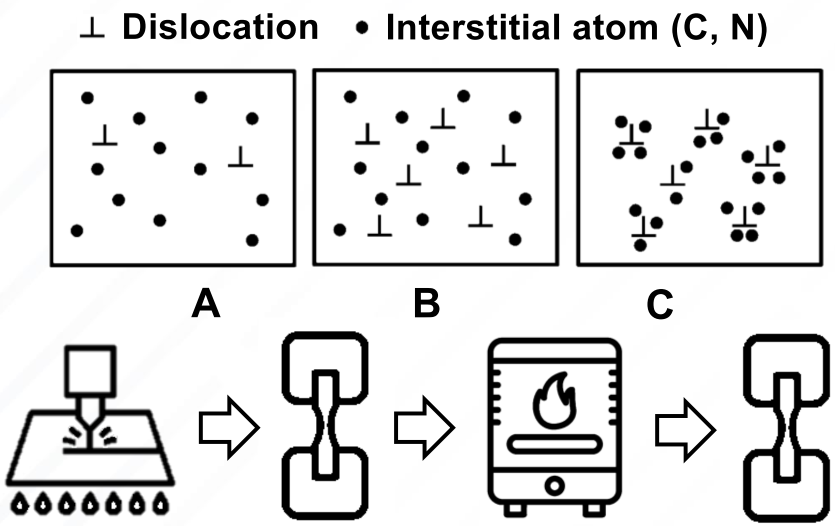
Q&P980 BH mechanism(s):

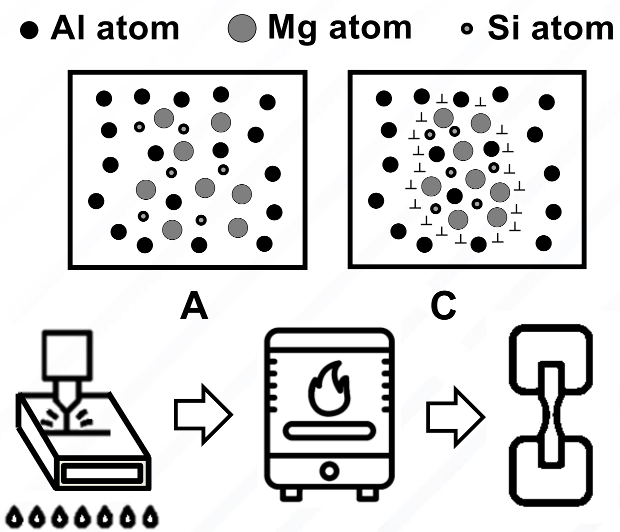
- ‘Cottrell atmospheres’
- Martensite tempering
- Carbides precipitation in ferrite
- …

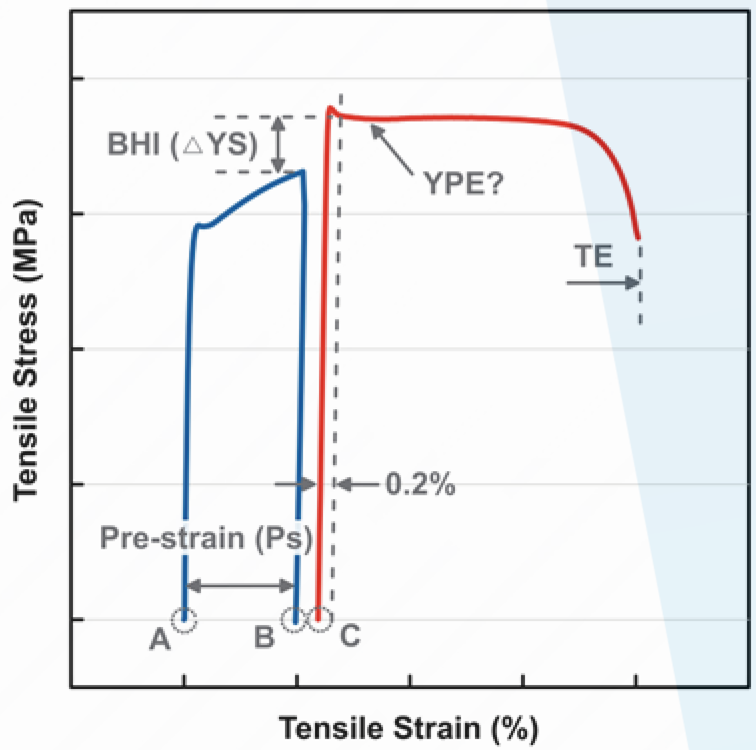
Need longer baking time and/or higher temp. to accentuate

AA6061-Tx BH mechanism(s):

- Impurities precipitation (aging)







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1) Quasi-Static Tensile: Setup & Procedure

Ps/unload ASTM E8 longitudinal samples at 0.001/s → bake at 170˚C for 20 min. → reload at 0.001/s to fracture → post-process ΔYS and TFS

DIC real-time strain control

Control signals

Strain signals

Infrared thermal camera in-situ temperature monitor

TFS measurement

$$\bar{\varepsilon}(\mathrm{vM}) \approx \sqrt{\frac{2}{3}({\varepsilon_1}^2 + {\varepsilon_2}^2 + {\varepsilon_t}^2)}$$

1) Quasi-Static Tensile: Results

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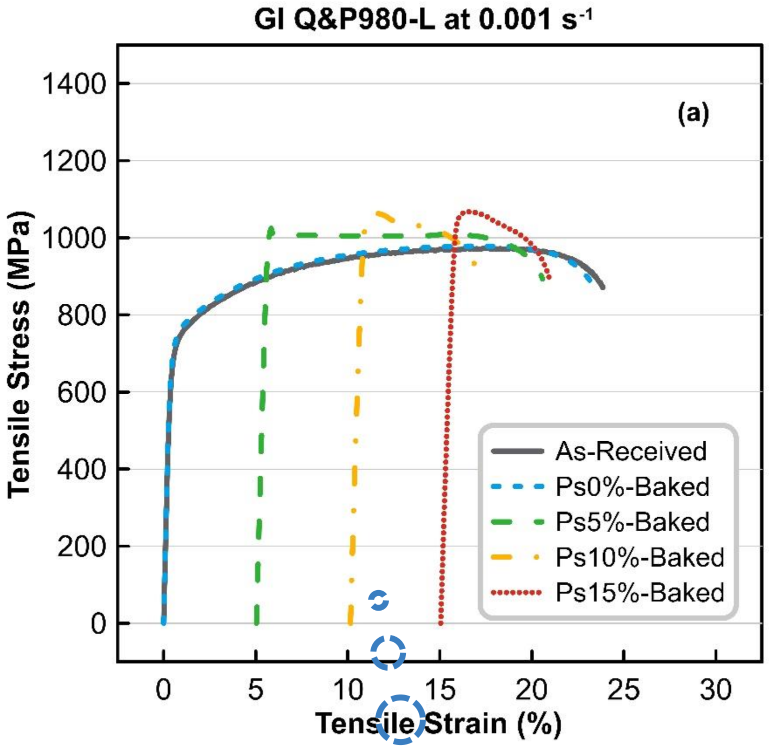
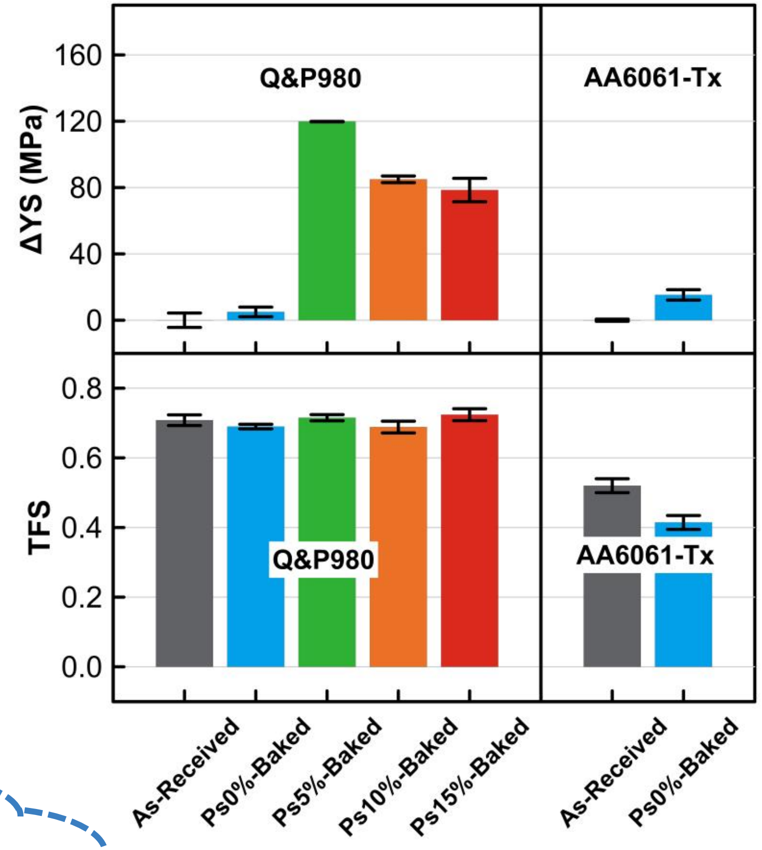
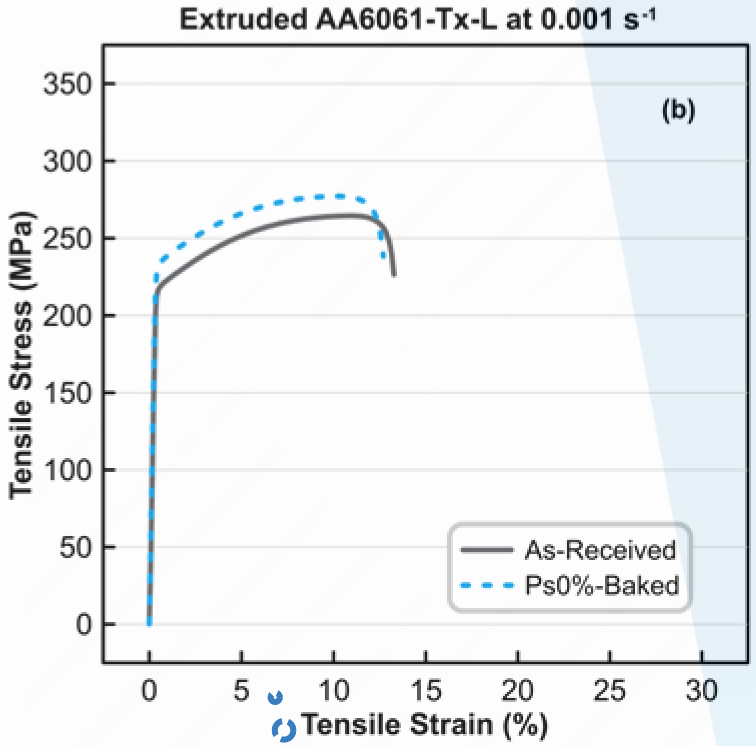
Q&P980 vs. AA6061-Tx: baking affected ΔYS and TFS







YS: strain accumulated dislocations saturate at a low Ps level

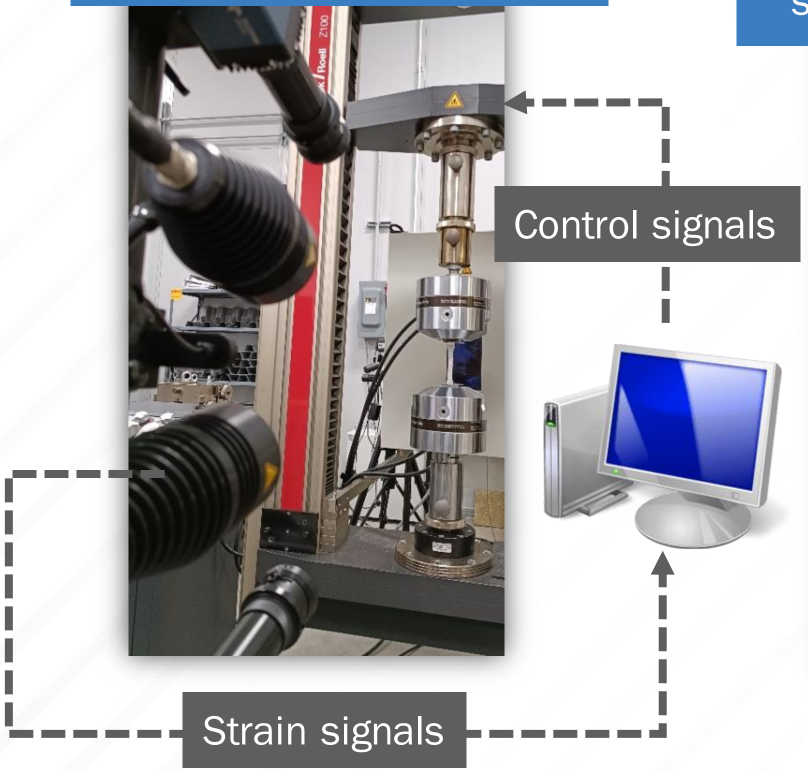
TFS: fracture mainly induced by the transformed martensite

Baking = continued artificial aging

2) Rate-Dependent Tensile: Setup & Procedure

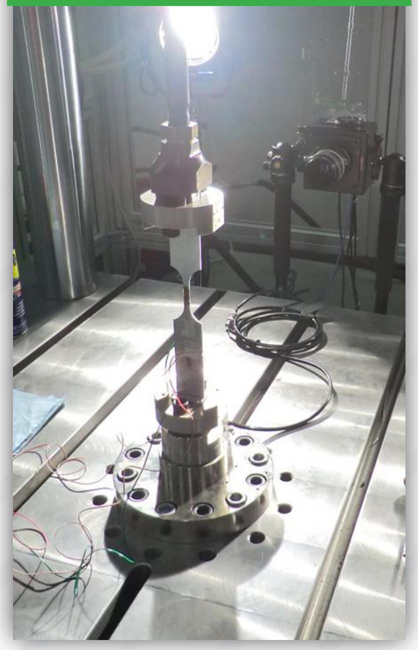
Ps/unload downsized samples at 0.001/s → bake → reload at 1/10/100/1000 s^{-1} to fracture → post-process ΔYS and TFS

DIC real-time strain control



Infrared thermal camera in-situ temperature monitor

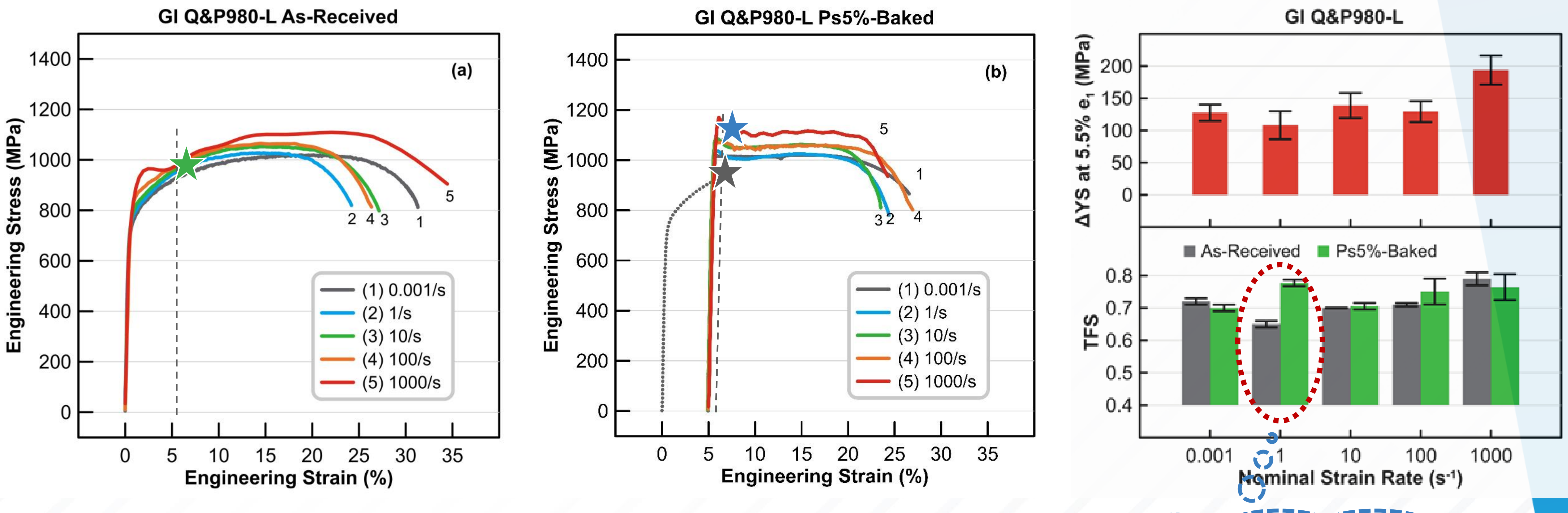
HSR testing based on ISO 26203-2



TFS measurement

2) Rate-Dependent Tensile: Q&P980 Results

When the strain rate (SR) ↑, the baking affected ΔYS + and the TFS −+



ΔYS = Ps-baked 0.2%$_{offset}$ YS – As-received 5.5% stress

The BH samples dissipated additional adiabatic heat that activated the favoring temperature range of the TFS

2) Rate-Dependent Tensile: AA6061-Tx Results

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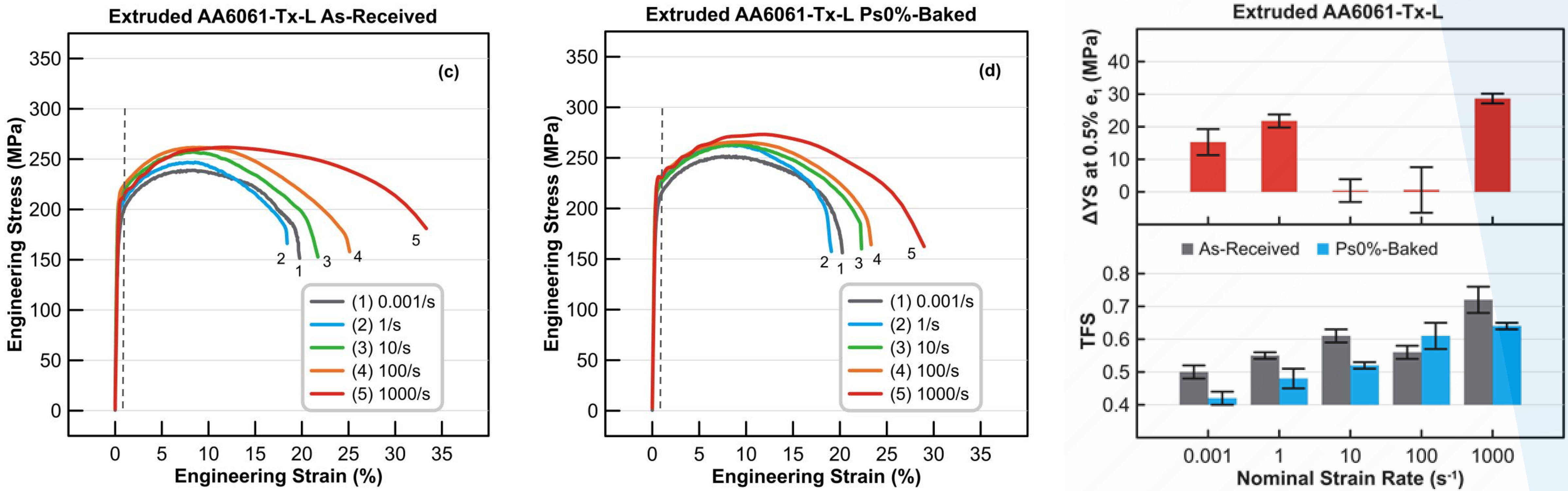
When the SR ↑, the ΔYS + yet unstable; the TFS + yet suppressed by the baking



ΔYS = Ps-baked $0.2\%_{offset}$ YS – As-received $0.2\%_{offset}$ YS

2) Rate-Dependent Tensile: Comparison

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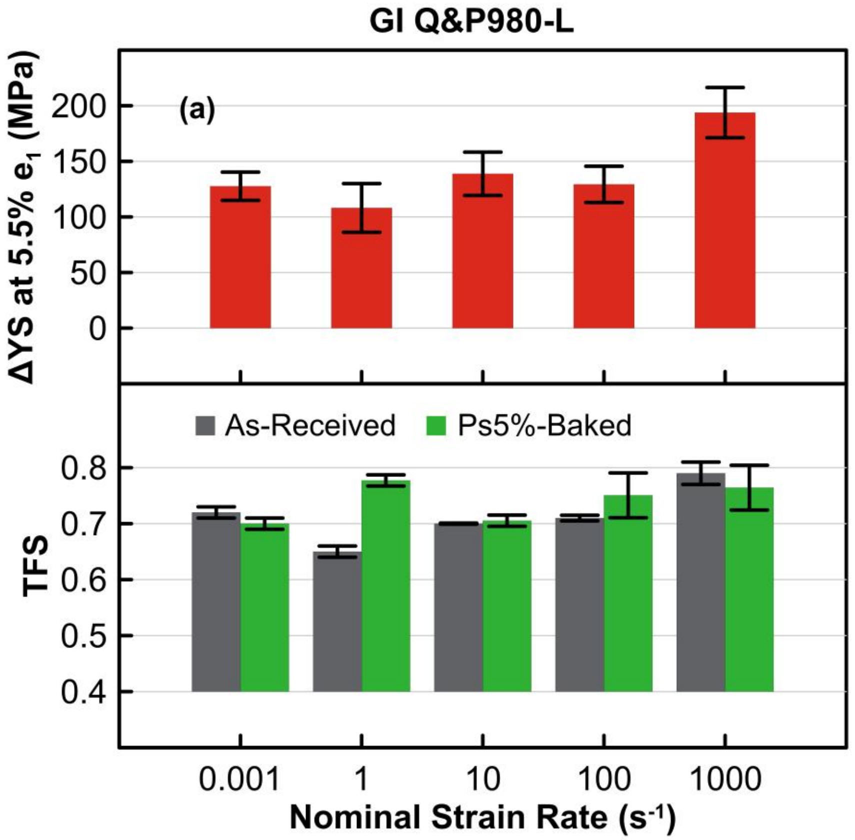
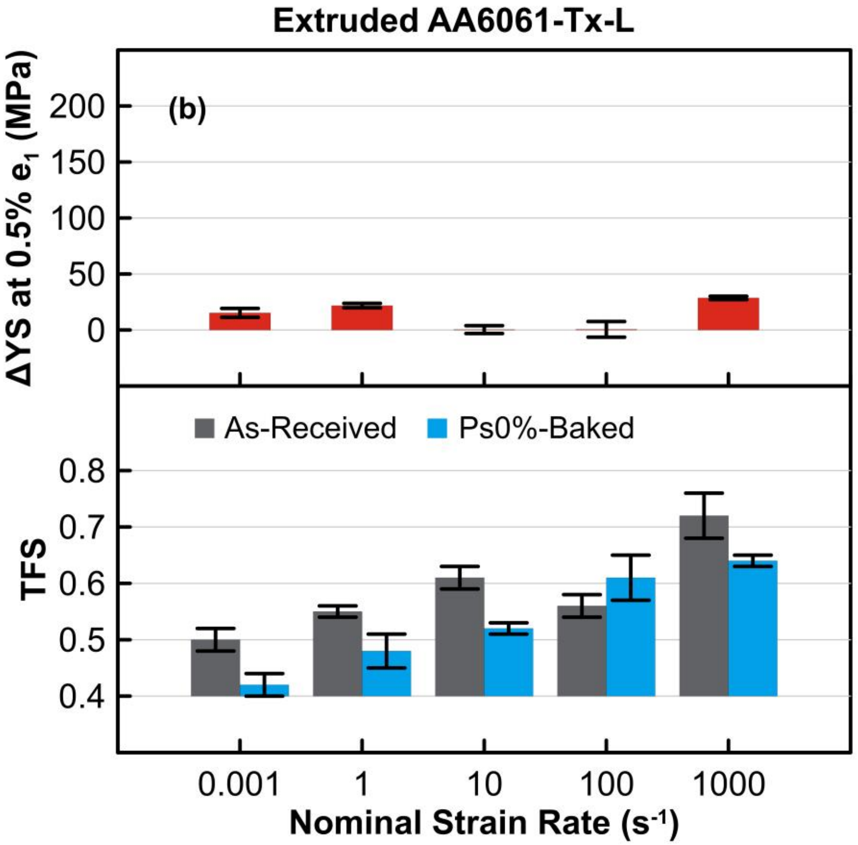
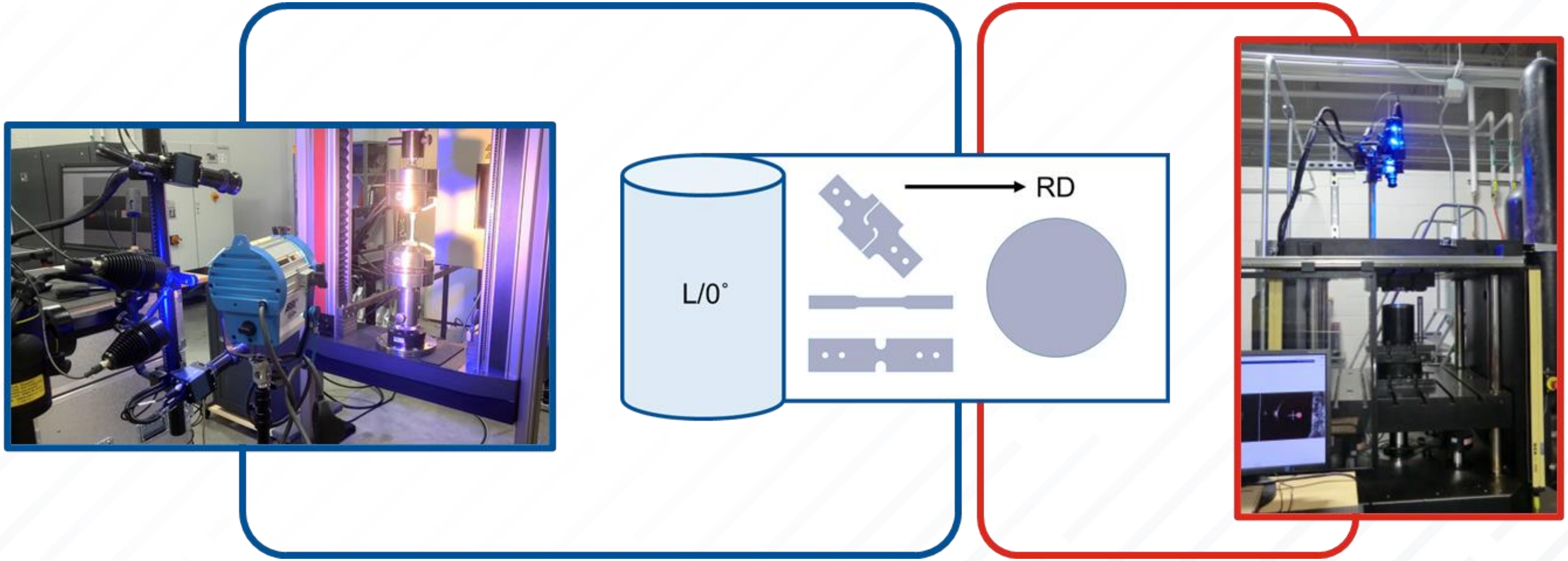
Q&P980 vs. AA6061-Tx after the Ps-baking





3) Stress-State-Dependent Tests: Setup & Procedure

Ps/unload various samples at 0.001/s → bake → reload at 0.001/s to fracture → post-process TFS



3) Stress-State-Dependent Tests: Results

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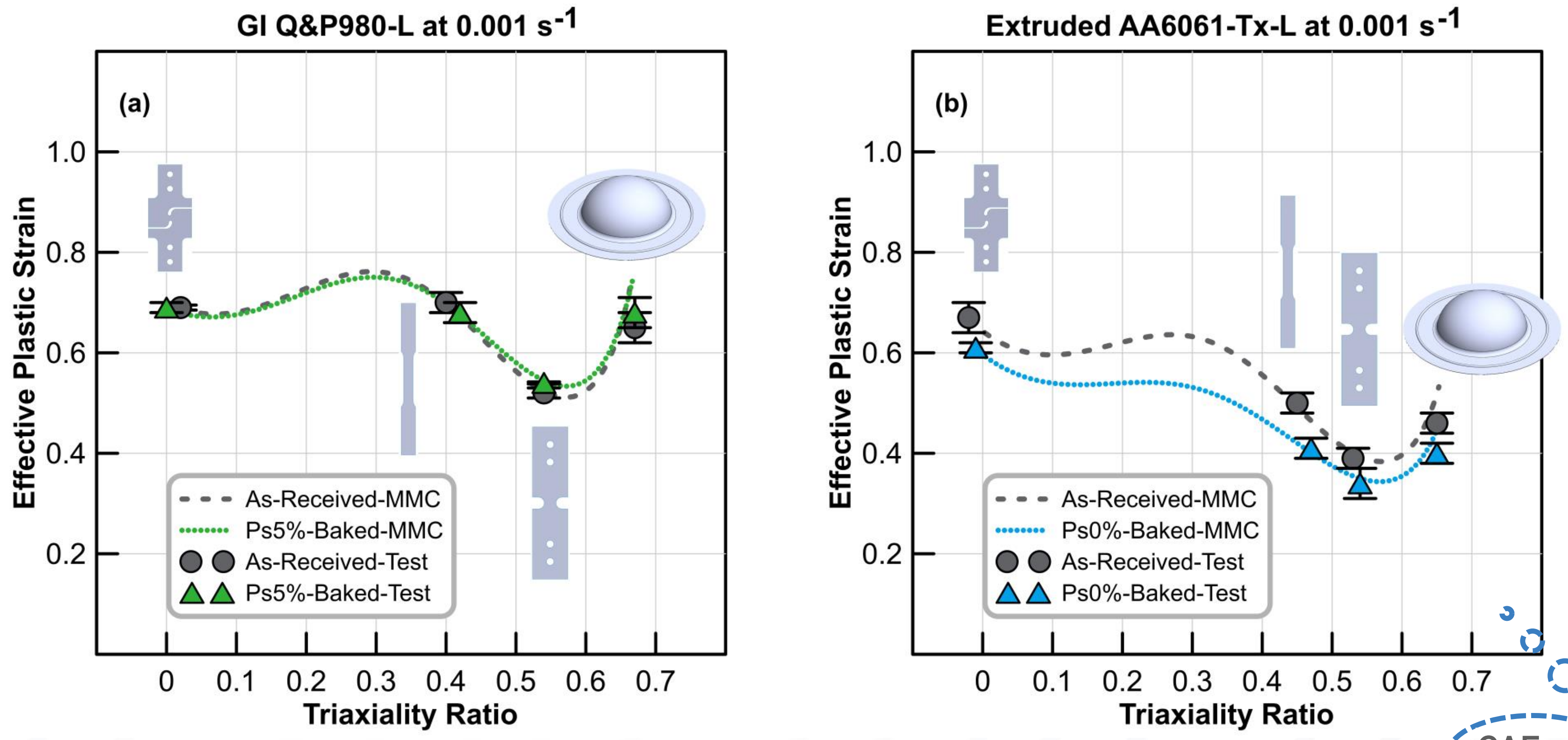
Q&P980 vs. AA6061-Tx: TFS loci (fracture resistance at different stress states)

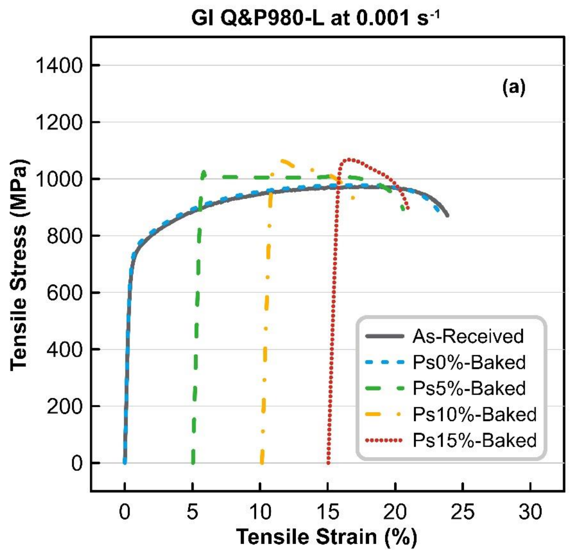


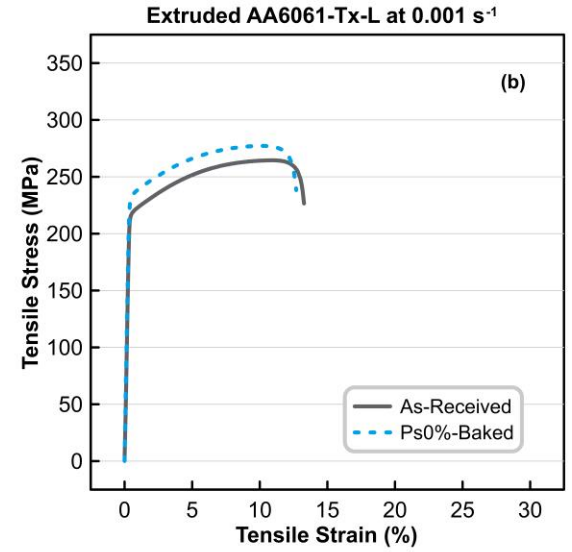
CAE engineers need to update the material cards for crash simulations

Conclusions of Case Study I

Based on the material needs in the BEV rocker reinforcement structures, Q&P980 and AA6061-Tx were investigated and compared under 1) quasi-static tensile, 2) rate-dependent tensile, and 3) quasi-static stress-state-dependent conditions.

- Q&P980: the baking elevated its YS via the 'Cottrell atmospheres' only at the re-yielding stages but hardly affected its fracture resistance.
- AA6061-Tx: its bake-hardenability was very limited and unstable especially when the strain rates changed. Since the baking was to essentially continue aging its microstructure permanently, the BH could accelerate the fracture occurrence at most of the strain rates and stress states.

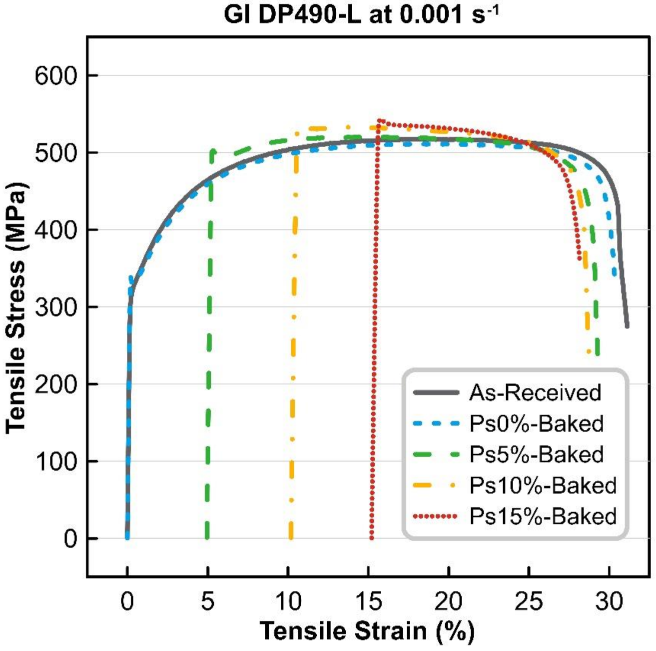


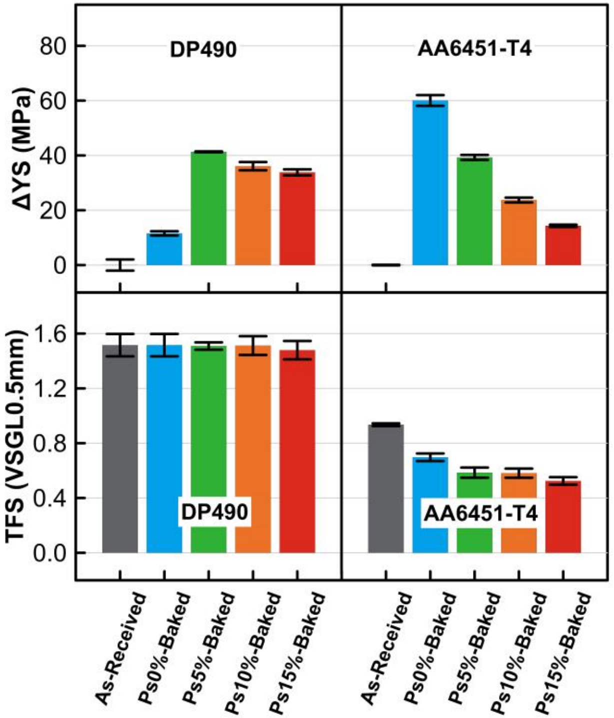


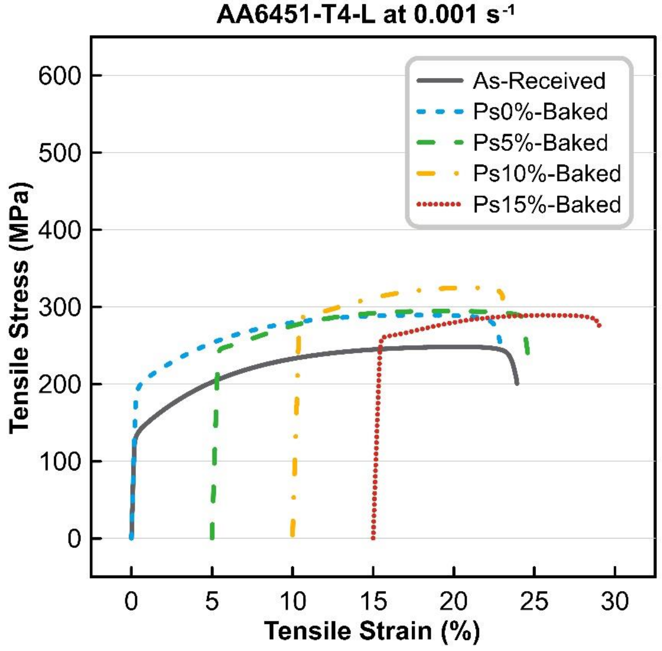
Case Study II Abstract: Exposed Panels

GI DP490 vs. AA6451-T4:

- Ps levels: 0/5/10/15%
- Strain rates: 0.001/1/10/100/1000 s^{-1}
- Baking conditions: 170˚C, 20 min.
- Target parameters: ΔYS, TFS







Case Study III Abstract: Top Critical Structures

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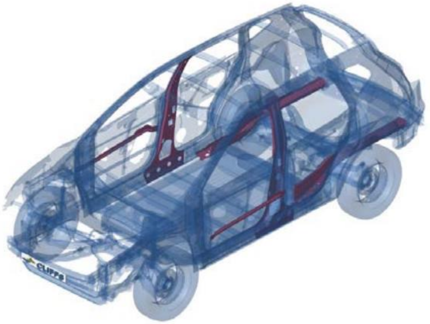
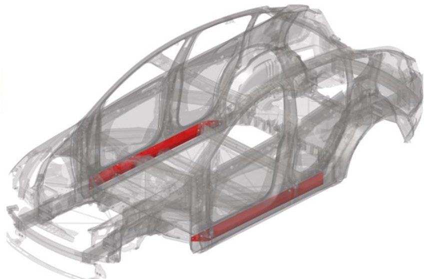
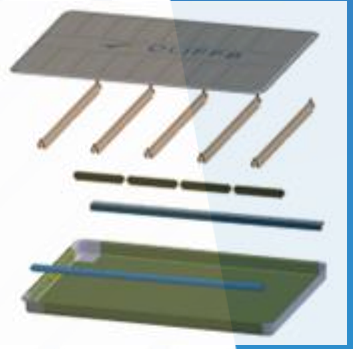
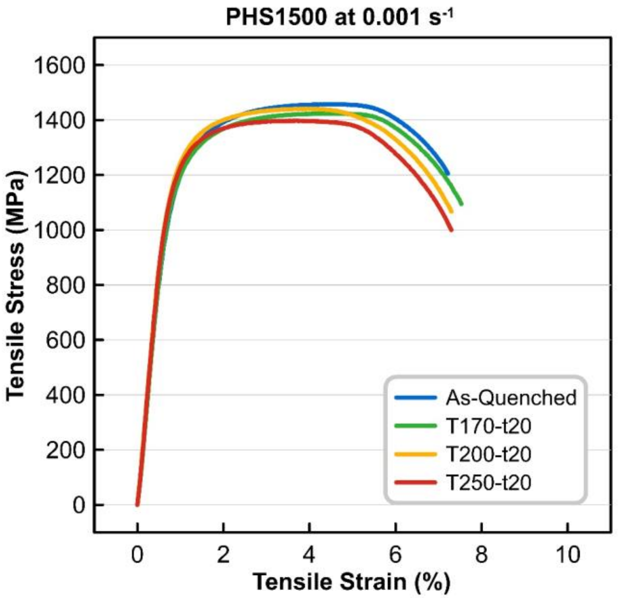
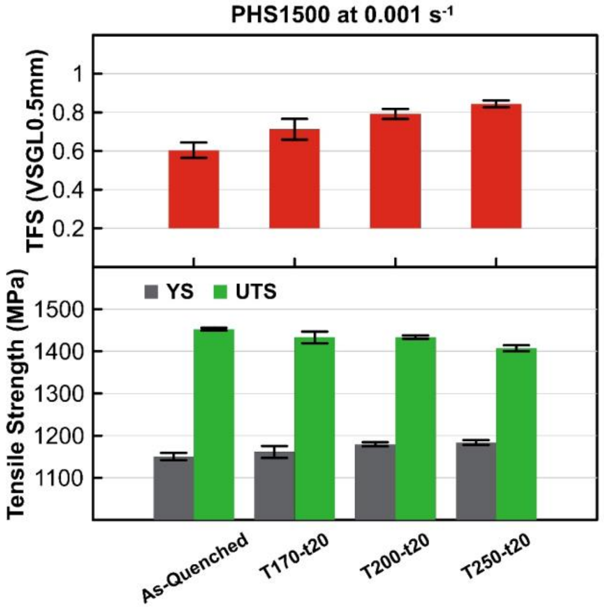
Al-Si PHS1500 vs. AA7075-T6:

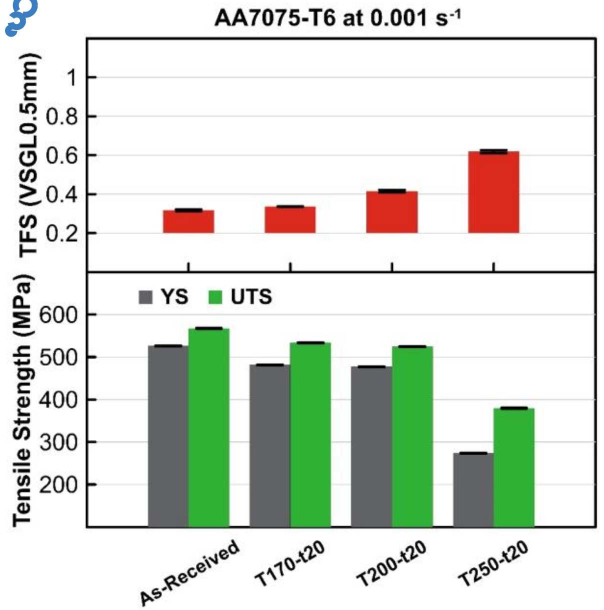
- Ps levels: 0%
- Strain rates: 0.001 s^{-1}
- Baking conditions: 170/200/250˚C, 20 min.
- Target parameters: YS, UTS, TFS

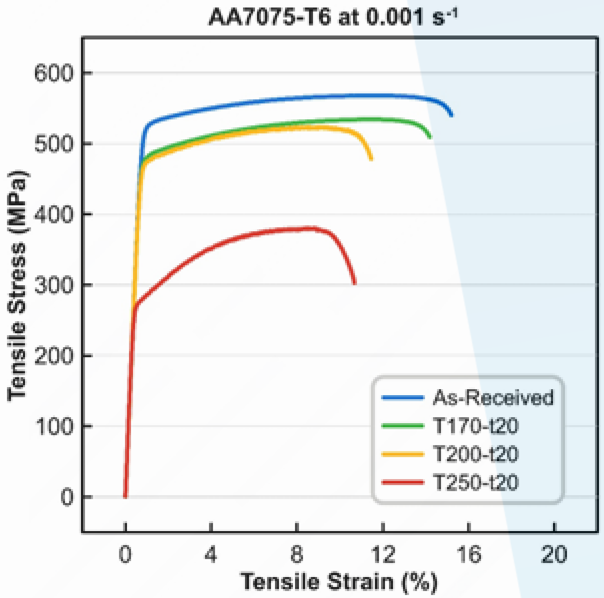




Martensite tempering vs. over-aging





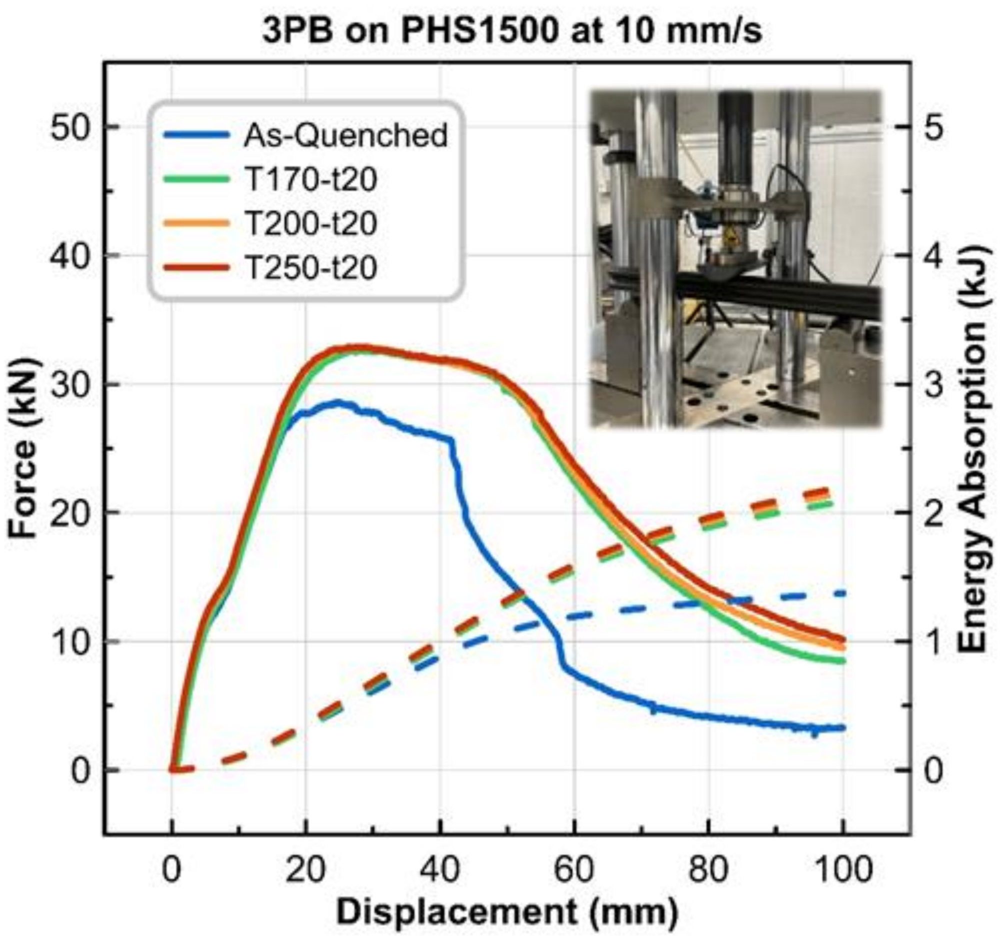


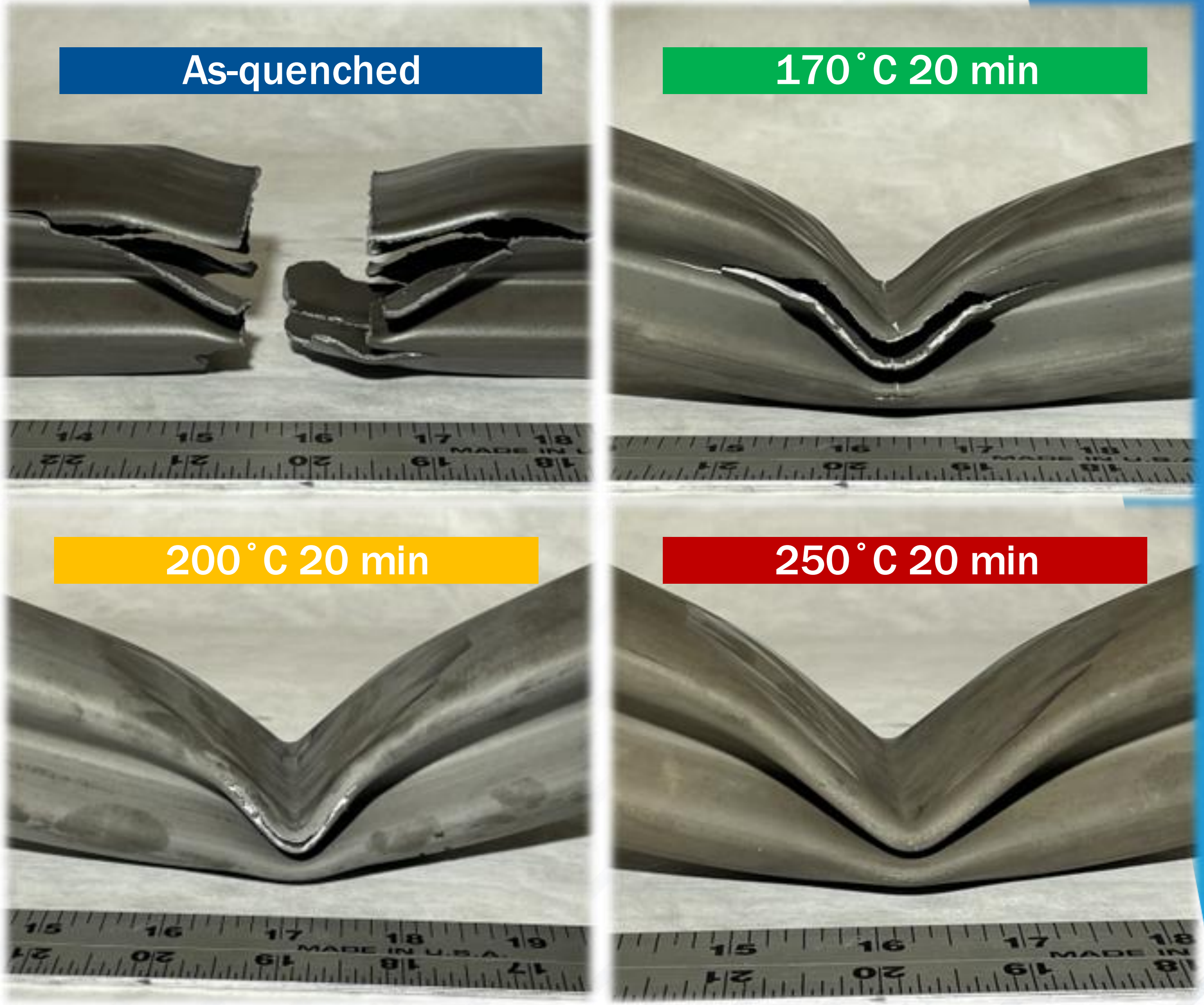


Case Study III Abstract contd.

Photos were captured after delayed fracture, courtesy of E. Hernandez-Duran

3-Point-Bending on PHS1500 Tubes





Summary

The paint-baking is favoring to AHSSs!

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Case Studies / Applications	Materials	Paint-Baking Impact on Tensile Strength	Paint-Baking Impact on Fracture Resistance
I. BEV Rocker Reinforcement	Q&P980 (Rolled)	YS ++	TFS =
	AA6061-Tx (Extruded)	YS ~+	TFS –
II. Exposed Panels	DP490 (Rolled)	YS ++	TFS =
	AA6451-T4 (Rolled)	YS ++	TFS ––
III. Top Critical Structures	PHS1500 (Rolled)	YS ~+, UTS ~–	TFS ++
	AA7075-T6 (Rolled)	YS ––, UTS ––	TFS ++

For more information

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More details of Case Study I:

- J. Hu, *et al.*: Comparison of Bake Hardening Effects on AHSSs and Extruded Aluminum Alloys Applied in BEV Reinforcement Structures, SAE WCX 2024, GDIS 2024

Paint-baking effects on press-hardening steel grades (Case Study III):

- E. Hernandez-Duran, J. Hu: Influence of Low Temperature Tempering on Mechanical Behavior of A Press Hardened 22MnB5 Steel Grade, CHS^2 2024, GDIS 2024

About the C-STAR™ Protection project:

- Y. Miao, *et al.*: C-STAR™ Protection, SAE WCX 2024, GDIS 2023

How to measure the true fracture strain (TFS) using the hybrid method:

- J. Hu, *et al.*: True Fracture Strain Measurement and Derivation for Advanced High-Strength Steel Sheets, SAE WCX 2022, GDIS 2023