THE UNIQUE FRACTURE RESISTANCE ELEVATION ON PROCESSED Q&P1180 STEEL

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CLEVELAND-CLIFFS INC.

GREAT DESIGNS IN STEEL™

Acknowledgements

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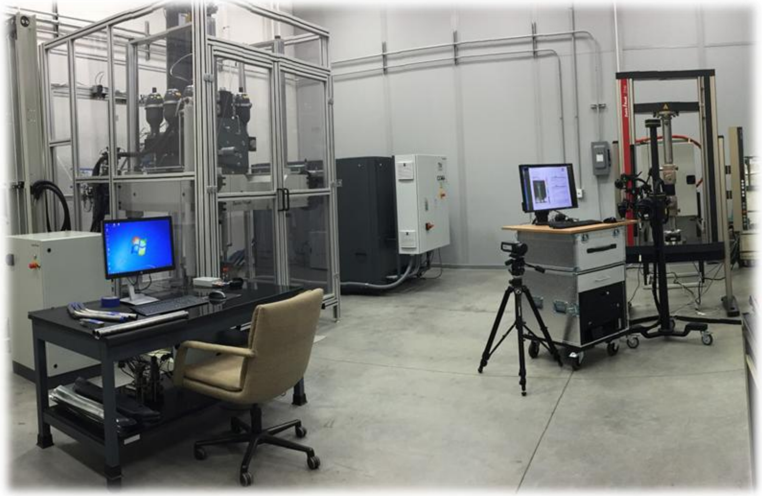
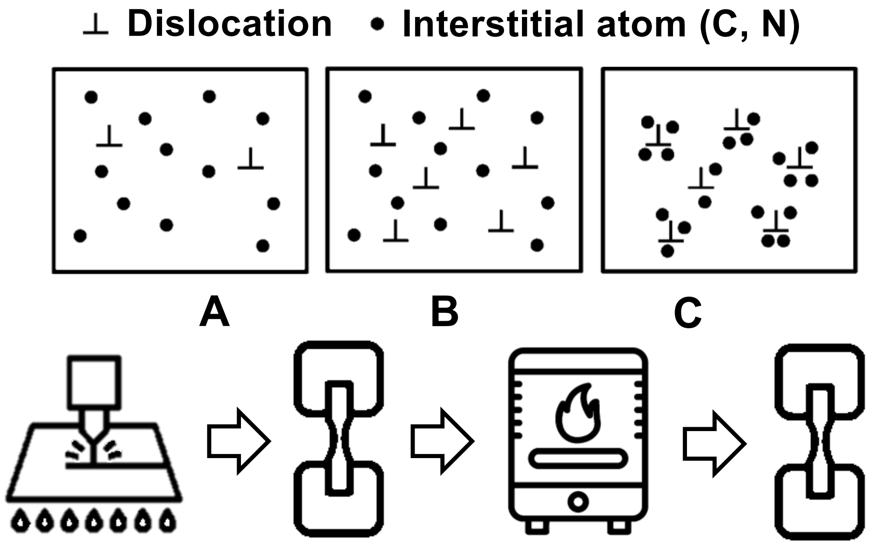
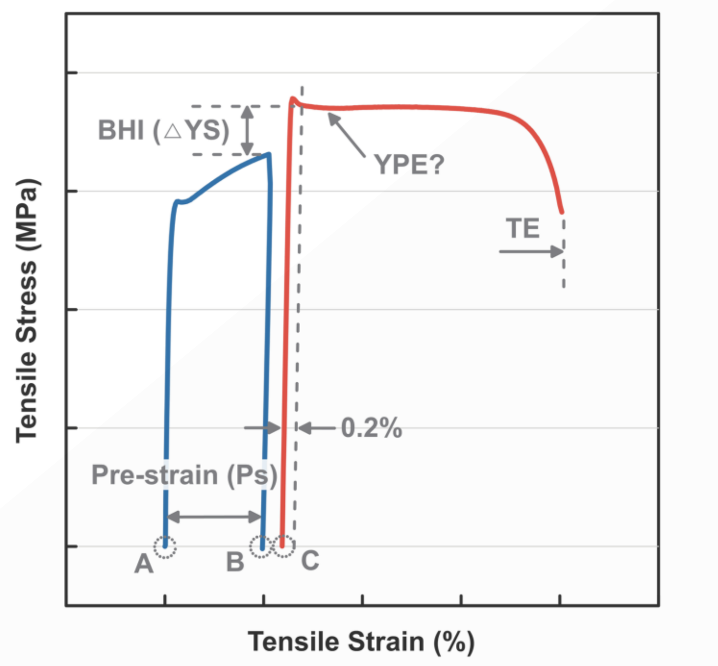


Automotive Paint-Baking Cycle and Effects





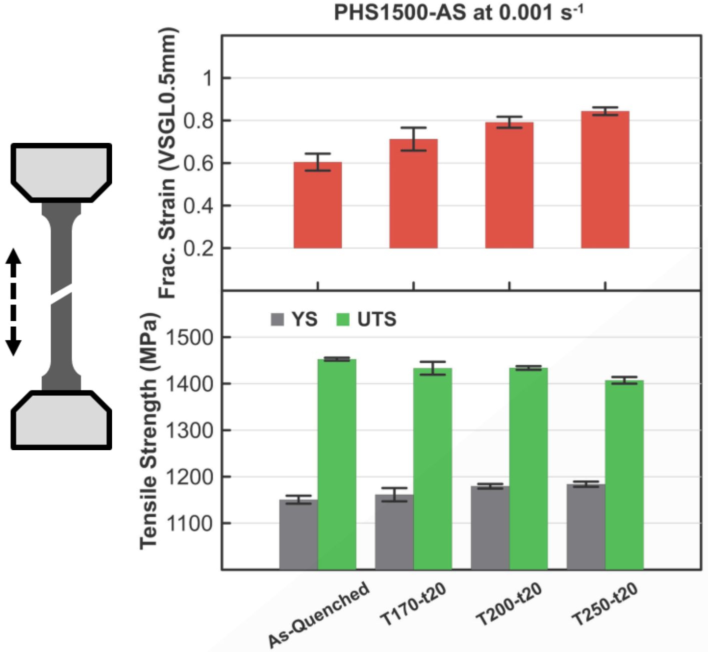
Mechanisms:

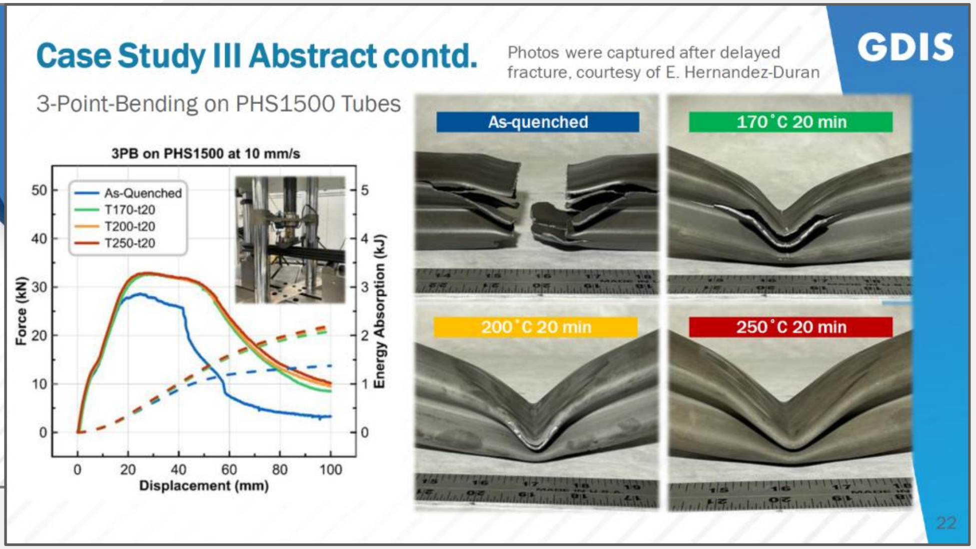
- ‘Cottrell Atmosphere’
- Martensite tempering
- Carbide precipitation
- Stress relief
- …

Bake-Hardening Effects on Fracture: PHS

Published in GDIS 2024, CHS^2 2024, AIST-Auto Steel Int. Conf. 2025:

Bake-hardening effectively elevates the fracture resistance of PHS parts, validated by coupon-assembly level tests on sheet and tubular samples



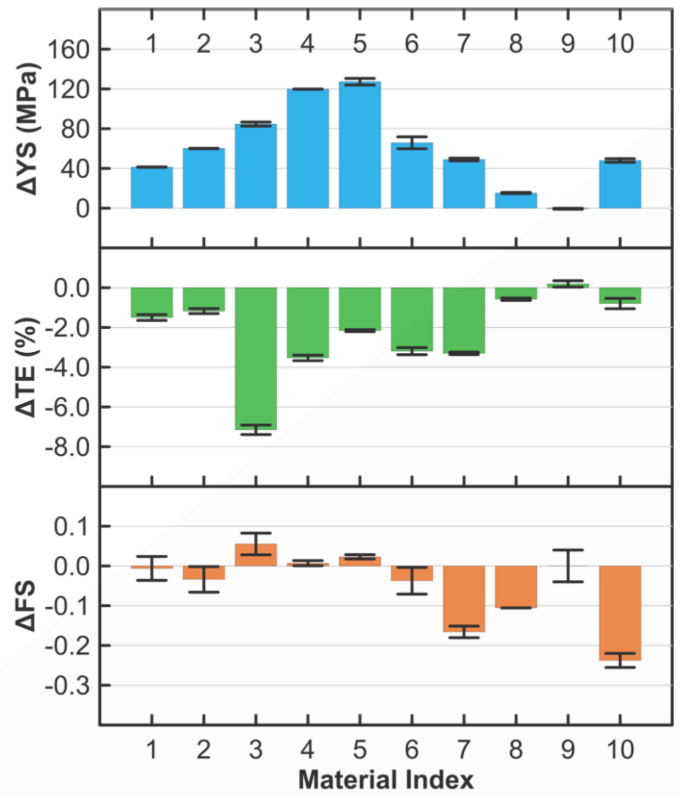


Bake-Hardening Effects on Fracture: Others

Published in SAE WCX 2024:

Bake-hardening can hardly affect the fracture resistance of many cold-forming carbon steels, yet may lead to early fracture in stainless steels and aluminium alloys

Index	Material	Ps (%)
1	DP490-GI	5
2	HSLA550-GI	5
3	CP780-GI	5
4	Q&P980-GI	5
5	DP1180-GA	5
6	DP1470-CR	2
7	201SS (1/2 Hard)	5
8	(Extruded) AA6061-T?	0
9	(Extruded) AA6???-T6	0
10	(Rolled) AA6451-T4	5

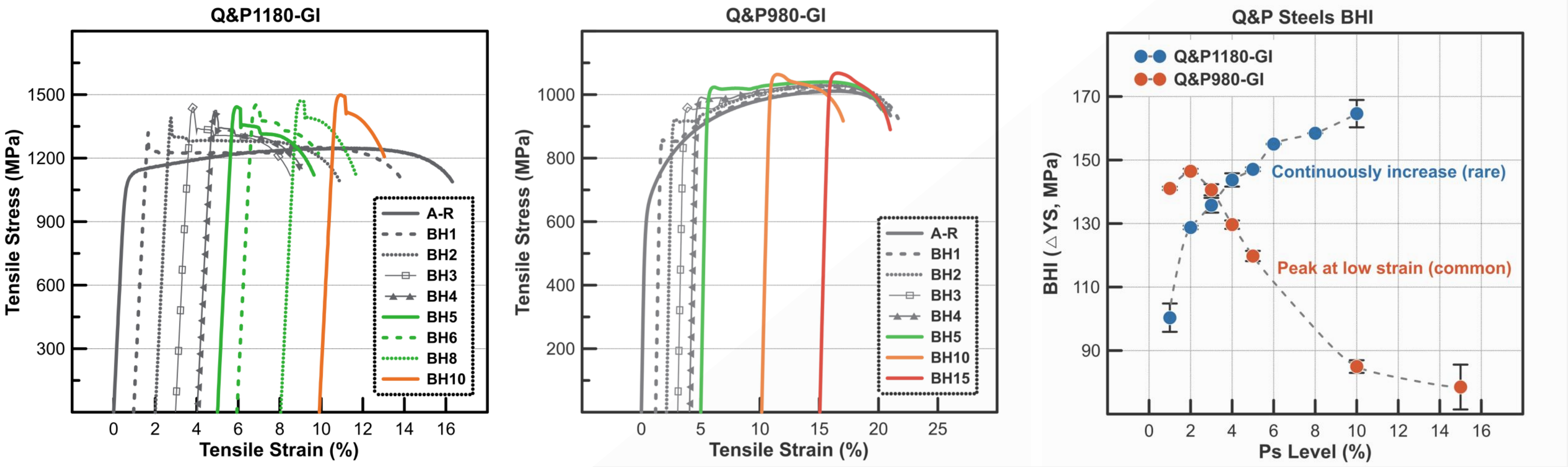


Tensile Elongation (TE) ≠ Fracture Resistance = Fracture Strain (FS)

Q&P1180: Unique BHI-Ps Trend (Abstract)

Uniqueness 1: **Continuously elevated BHI with increased pre-strain (Ps) levels**

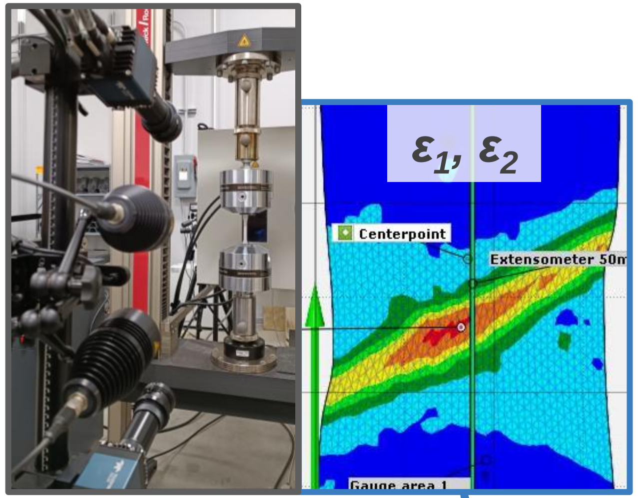
Tensile stress was calculated based on the nominal cross-sectional area **(engineering stress formula)** to avoid the 'fake bake' errors (discrepant from the DIN EN 10325 Standard)

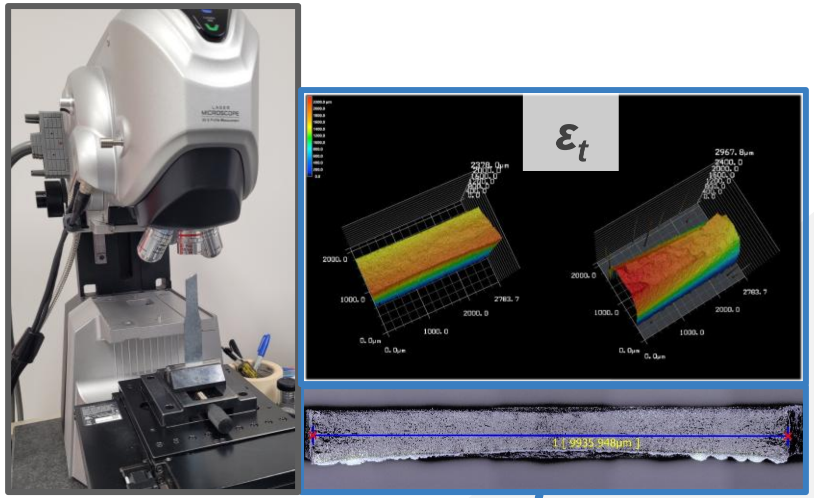


Q&P1180: Unique Fracture Strain Elevation

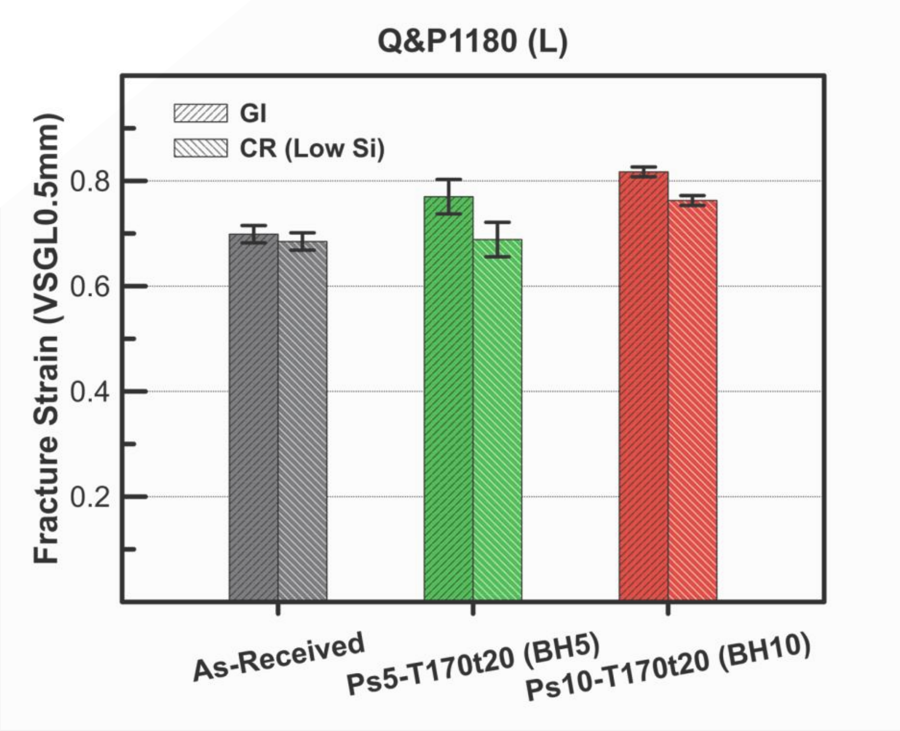
Uniqueness 2: **Elevated fracture strain after Ps-baking**

Fracture strain was derived based on the **hybrid DIC-microscopic method** (SAE WCX 2022) of virtual strain gauge length (VSGL) 0.5 mm on longitudinal (L) ASTM E8 samples





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



Discussion: Fracture Mechanisms in AHSSs

GDIS

Damage-fracture mechanisms: 1) **martensite-matrix (hard-soft phases) decohesion**, 2) martensitic grains cracking, 3) inclusions and others (Azuma *et al.*, 2012; Mohrbacher, 2013; Hudgins & Matlock, 2016; Pathak *et al.*, 2017; Heibel *et al.*, 2018)

General goodness of fracture resistance / local ductility at similar strength level:

single-phase AHSSs > multi-phase without austenite > <u>multi-phase with austenite</u>

C-enriched austenite transforms to martensite in plastic deformation → C-enriched/hardened martensite grains decohere from soft phases → Early fracture = limited local ductility (Frómeta *et al.*, 2021; Hu & Sun, 2023)

In Q&P: C stabilizes austenite during steel processing (Clarke *et al.*, 2008)

Extraordinary necking resistance / global ductility due to the transformation-induced plasticity (TRIP) effect (the essential Gen-3 AHSS microstructure design strategy)

Discussion: Mechanisms in Processed Q&P1180

GDIS

Damage-fracture mechanisms: 1) **martensite-matrix (hard-soft phases) decohesion**, 2) martensitic grains cracking, 3) inclusions and others (Azuma *et al.*, 2012; Mohrbacher, 2013; Hudgins & Matlock, 2016; Pathak *et al.*, 2017; Heibel *et al.*, 2018)

Target material – Q&P1180 (14% austenite + tempered martensite):

C-enriched austenite transforms to martensite in plastic deformation →

~~C-enriched/hardened martensite grains decohere from soft phases →~~

Paint-baking tempers/softens the transformed martensite + no soft phase →

Retarded fracture after the Ps-baking processing

Comparison – Q&P980 (14% austenite + martensite + ferrite) or DP980LCE:

With the soft ferrite, hardness difference remains → Unaffected fracture

Experimental Characterization

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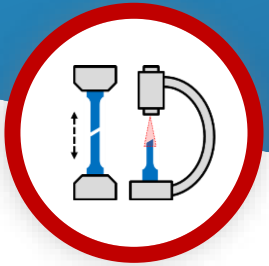
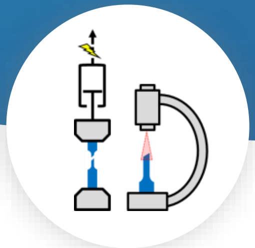
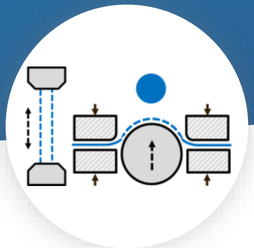
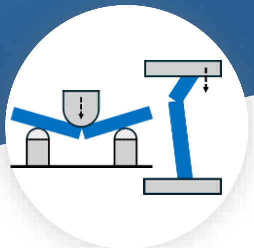
On the Fracture Strain Elevation of the Ps-Baked Q&P1180







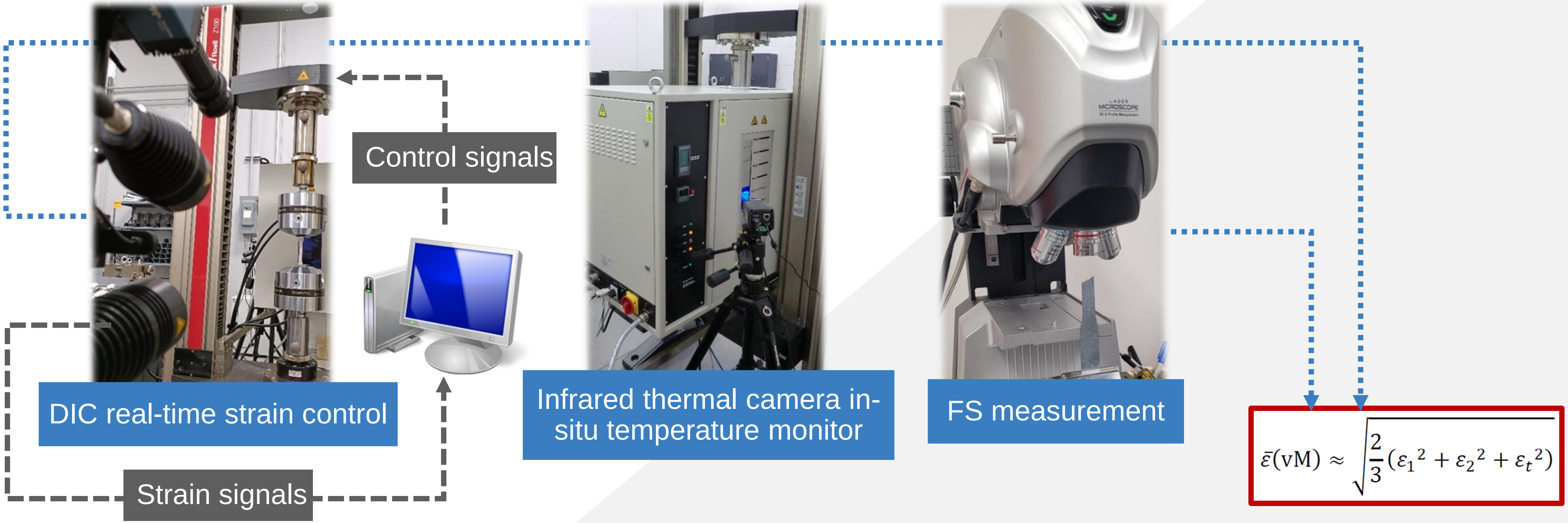


I. Quasi-Static Tensile Tests

Test Setup & Procedure I

Pre-strain (Ps) at 0.001/s → bake → reload (RL) at 0.001/s to fracture → post-process

Fracture strain formula: $\bar{\varepsilon}_f = \sqrt{2/3\,({\varepsilon_{1(\mathrm{Ps+RL})}}^2 + {\varepsilon_{2(\mathrm{Ps+RL})}}^2 + {\varepsilon_t}^2)} \neq \bar{\varepsilon}_{\mathrm{Ps}} + \bar{\varepsilon}_{\mathrm{RL}}$

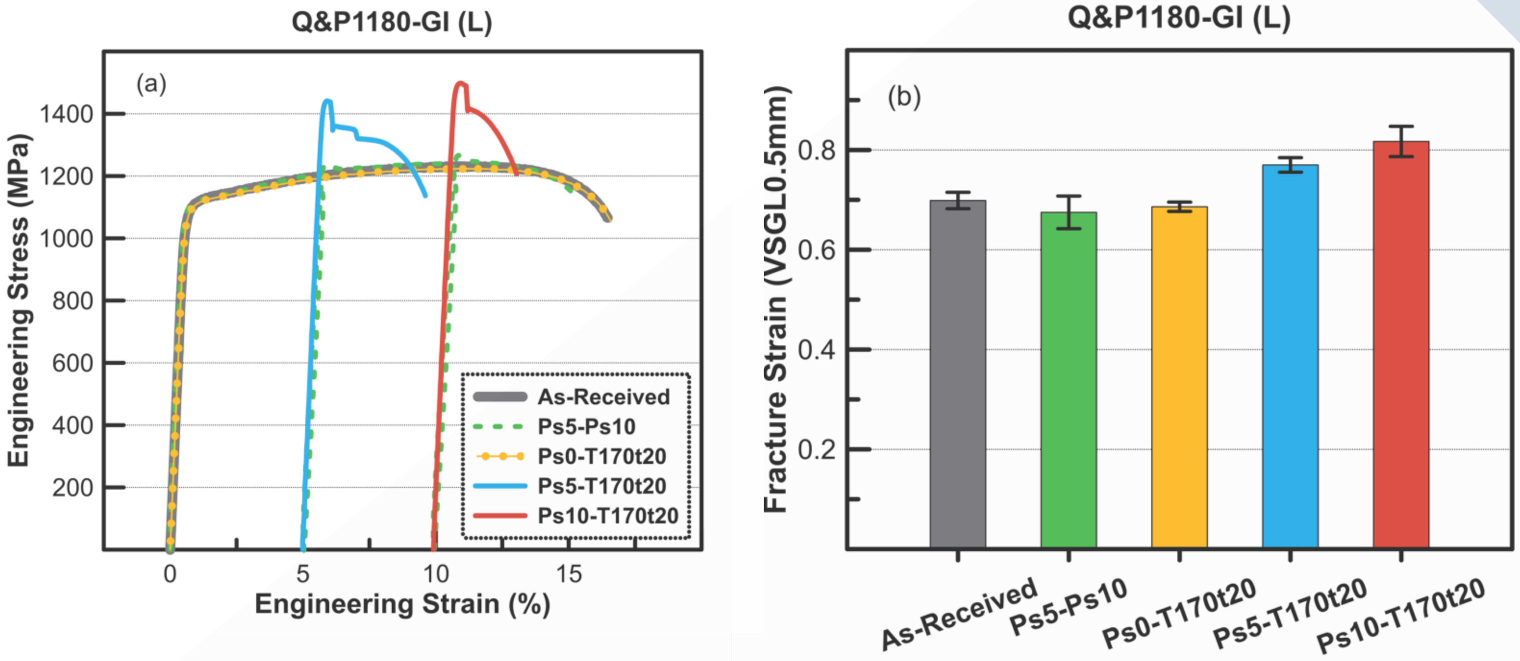


Test Group i (Consistent Baking Condition)

Standard paint-baking condition: 170˚C 20 min.

5 sample processing conditions:

1) **As-received**
2) **Ps5-Ps10** (pre-strain 2 levels, no baking)
3) **Ps0-T170t20** (no pre-strain, baking only)
4) **Ps5-T170t20** (5% pre-strain + baking)
5) **Ps10-T170t20** (10% pre-strain + baking)



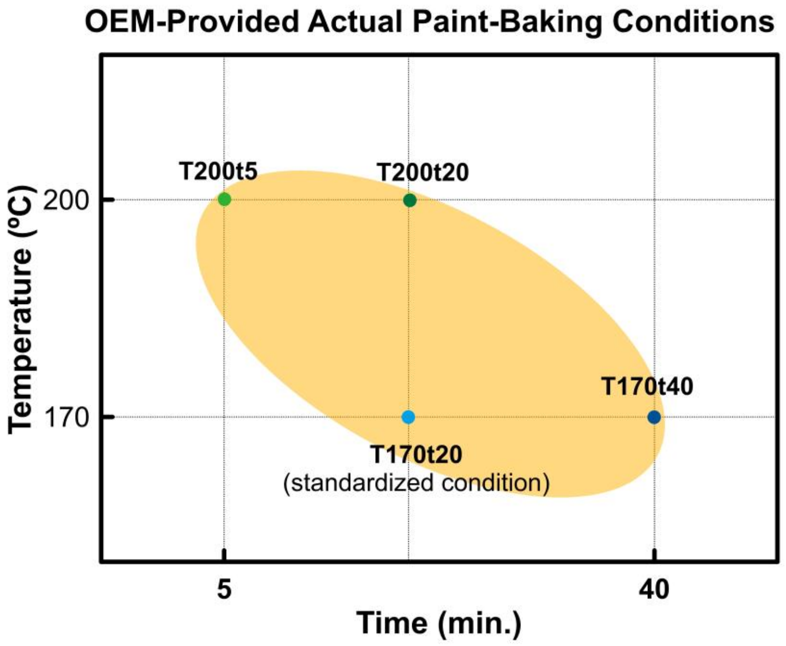
Test Group ii (Consistent Ps Level)

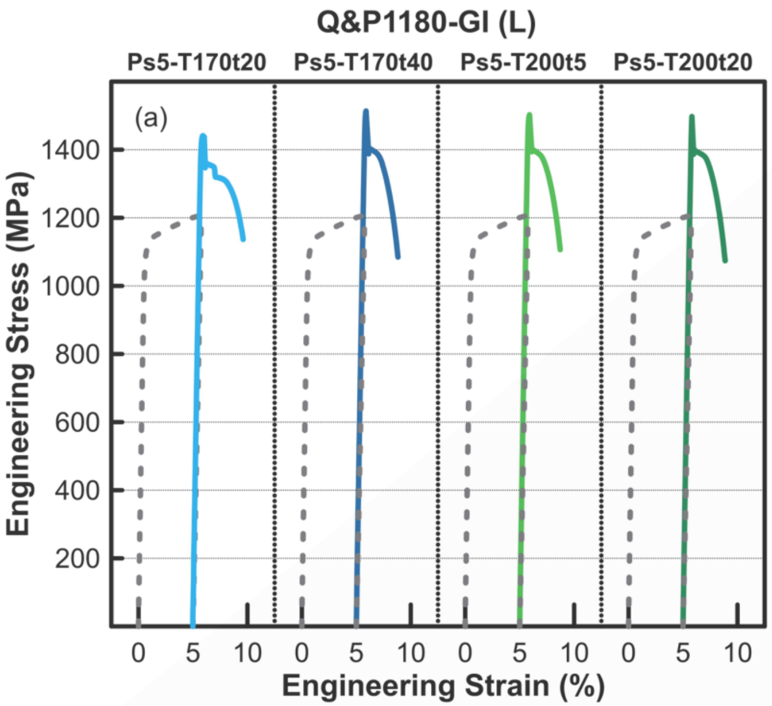
3 other practical baking conditions:

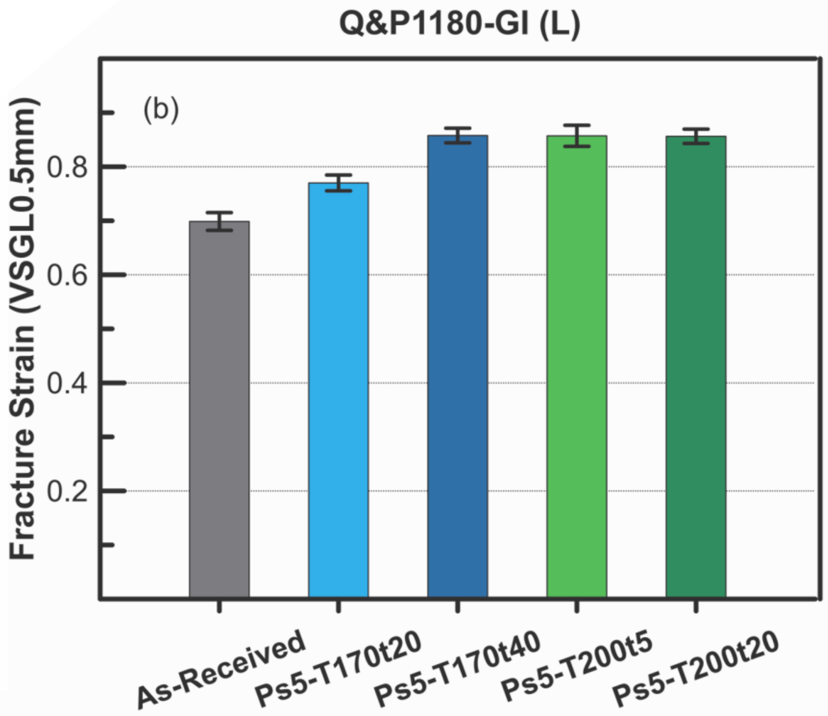
6) **Ps5-T170t40** (longer baking time)

7) **Ps5-T200t5** (higher temperature, shorter time)

8) **Ps5-T200t20** (higher temperature)







Summary & Remarks

Group i: Only baking or pre-strain cannot elevate the fracture strain of Q&P1180.

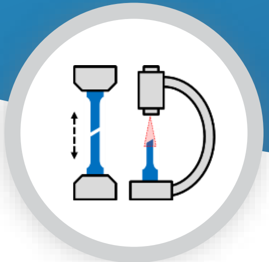
Group i: Higher Ps level, higher fracture strain elevation.

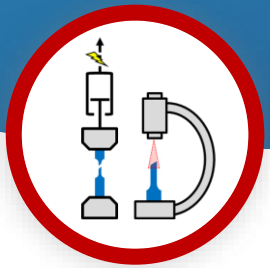
Group ii: At a certain Ps level, either elevated temperature or extended time can elevate higher fracture strain, yet such an elevation saturates at a certain limit.

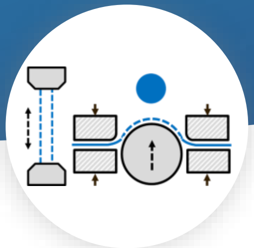
Group	Ps Level (%)	Baking Temp. (˚C)	Baking Time (min.)	Fracture Strain Compared to As-Received
i	5-10	No baking		-0.02 (≈)
	0	170	20	-0.01 (≈)
	5			+0.07 (↑)
	10			+0.12 (↑↑)
ii	5	170	20	+0.07 (↑)
			40	+0.16 (↑↑↑)
		200	5	+0.16 (↑↑↑)
			20	+0.16 (↑↑↑)

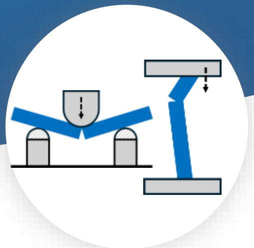
Experimental Characterization

On the Fracture Strain Elevation of the Ps-Baked Q&P1180







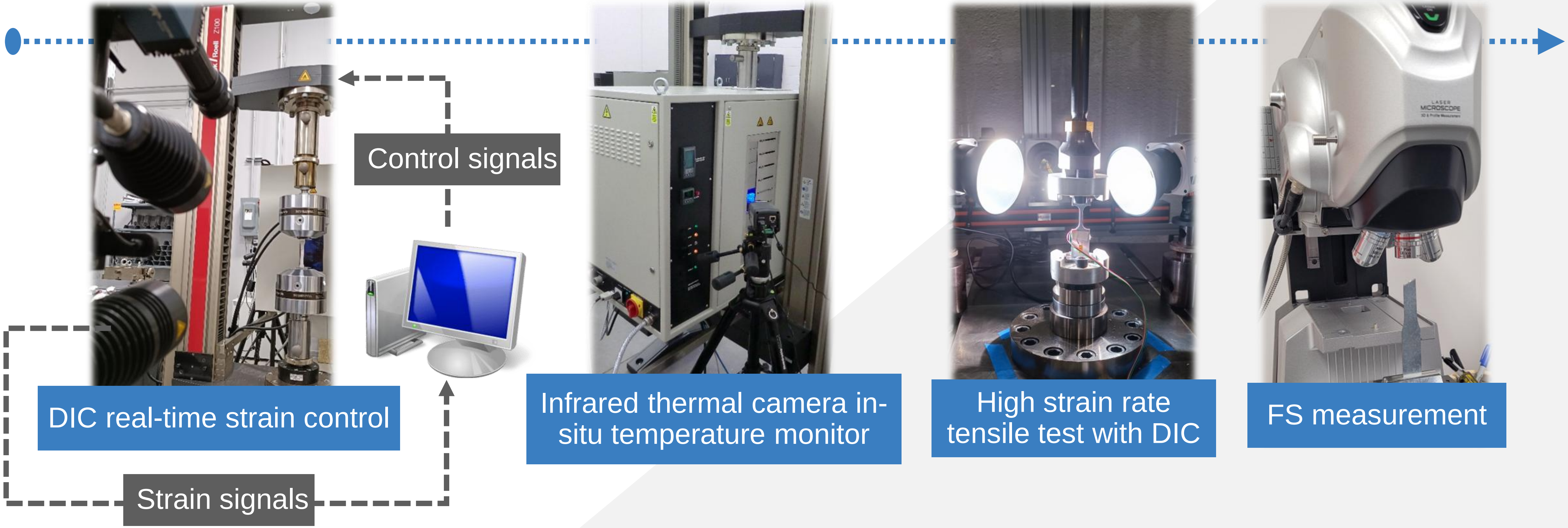


II. Rate-Dependent Tensile Tests

Test Setup & Procedure II

Pre-strain (Ps) at 0.001/s → bake → reload (RL) at 1-1000/s to fracture → post-process

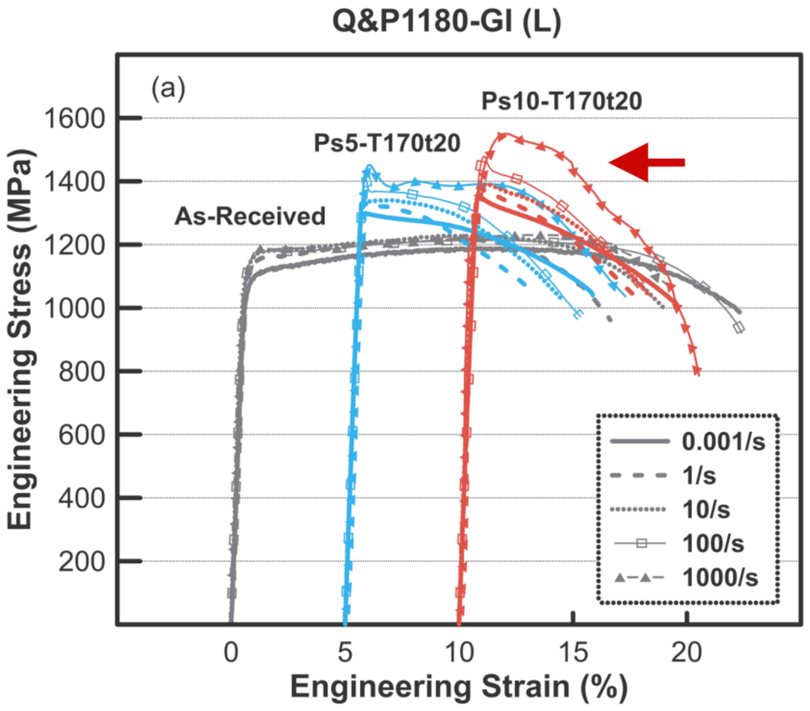
Fracture strain formula: $\bar{\varepsilon}_f = \sqrt{2/3\,(\varepsilon_{1(\mathrm{Ps+RL})}{}^2 + \varepsilon_{2(\mathrm{Ps+RL})}{}^2 + \varepsilon_t{}^2)} \neq \bar{\varepsilon}_{\mathrm{Ps}} + \bar{\varepsilon}_{\mathrm{RL}}$

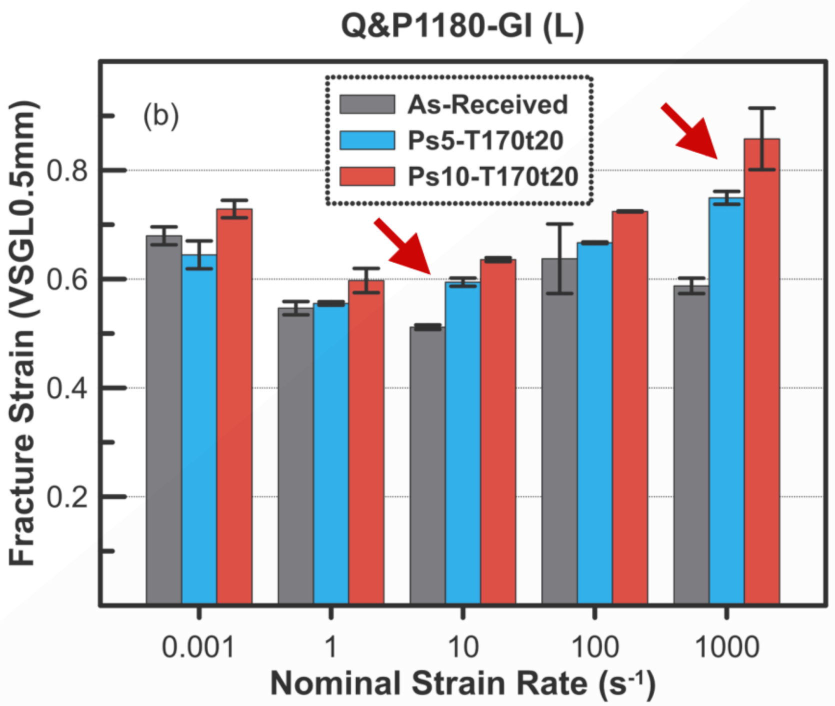


At Elevated Strain Rate Conditions

2 Ps levels (5% & 10%) vs. as-received samples:

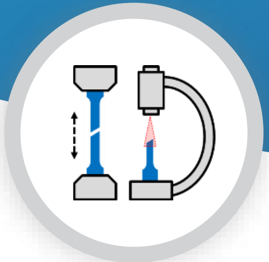
- Higher Ps leads to higher tensile strength
- Similar fracture strain value valley at 10/s
- Higher Ps level contributes to better fracture resistance at all strain rates

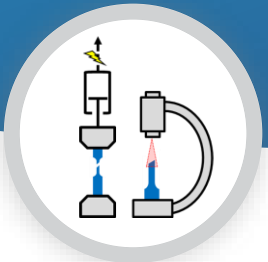


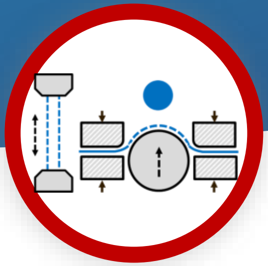


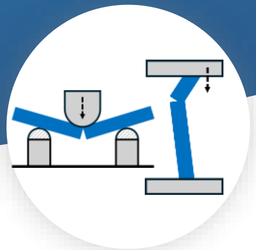
Experimental Characterization

On the Fracture Strain Elevation of the Ps-Baked Q&P1180









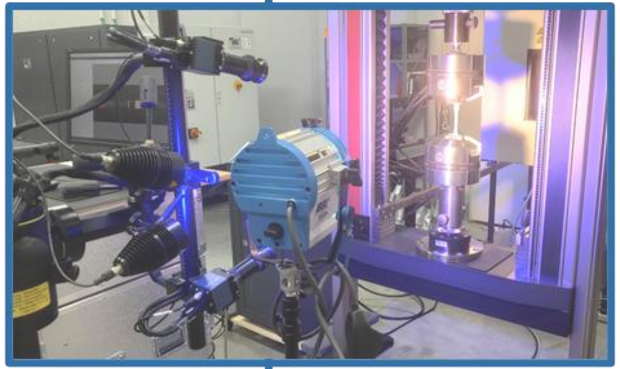
III. Stress-State-Dependent Tests

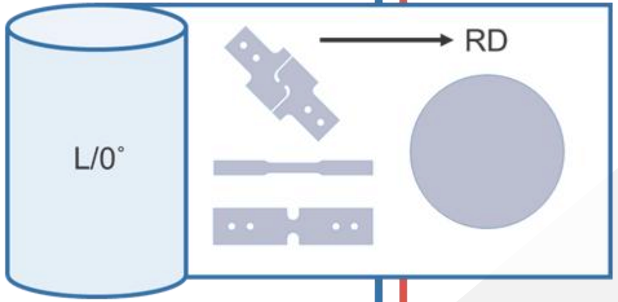
Test Setup & Procedure III

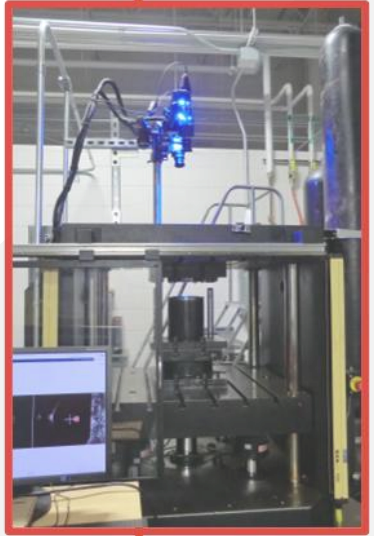
Pre-strain (Ps) at 0.001/s → bake → reload (RL) at 0.001/s to fracture → post-process

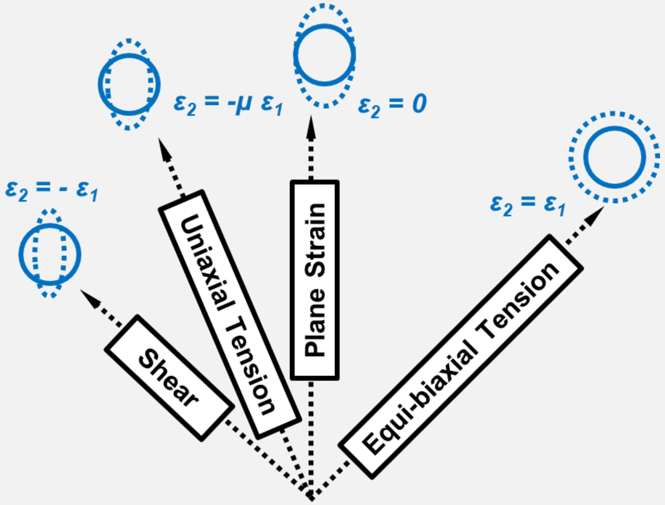
Ps control based on effective strain – displacement relationships from repeated pre-tests

Fracture strain formula: $\bar{\varepsilon}_f = \sqrt{2/3\,(\varepsilon_{1(\mathrm{Ps+RL})}{}^2 + \varepsilon_{2(\mathrm{Ps+RL})}{}^2 + \varepsilon_t{}^2)} \neq \bar{\varepsilon}_{\mathrm{Ps}} + \bar{\varepsilon}_{\mathrm{RL}}$







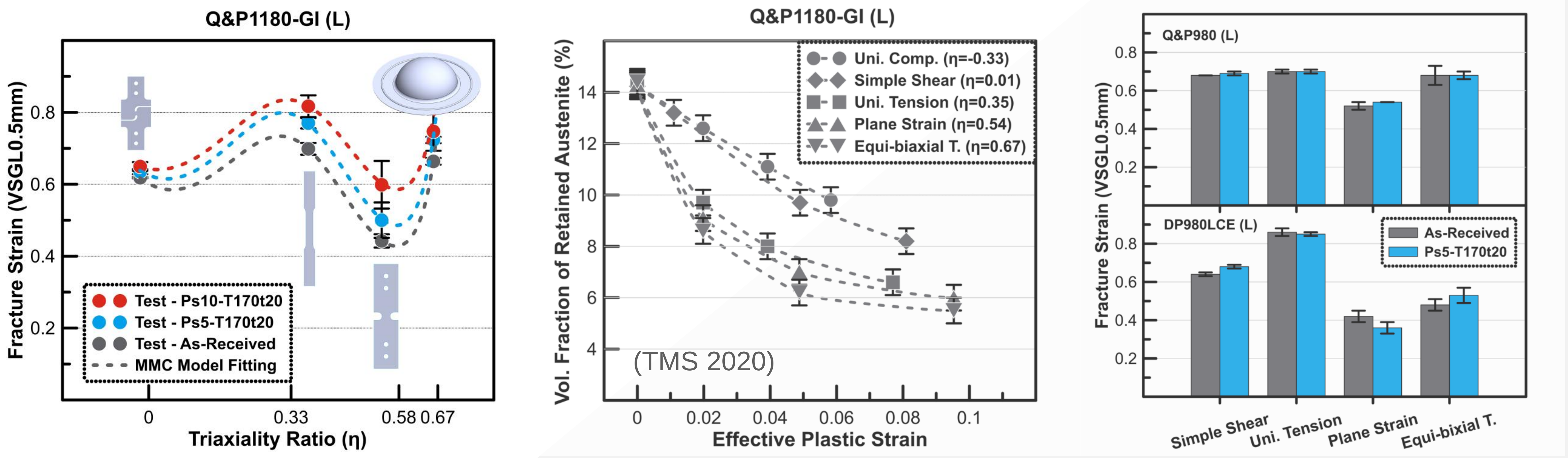


At Stress-State-Dependent Conditions

2 Ps levels (5% & 10%) vs. as-received samples:

- Higher triaxiality ratio, more martensite was transformed at a certain Ps, and thus more tempered during baking
- Higher triaxiality ratio, higher fracture strain elevation (equi-biaxial may need to be reworked in the future)

Comparison: neither Q&P980 nor DP980LCE exhibited similar FS elevation after Ps-baking



Experimental Characterization

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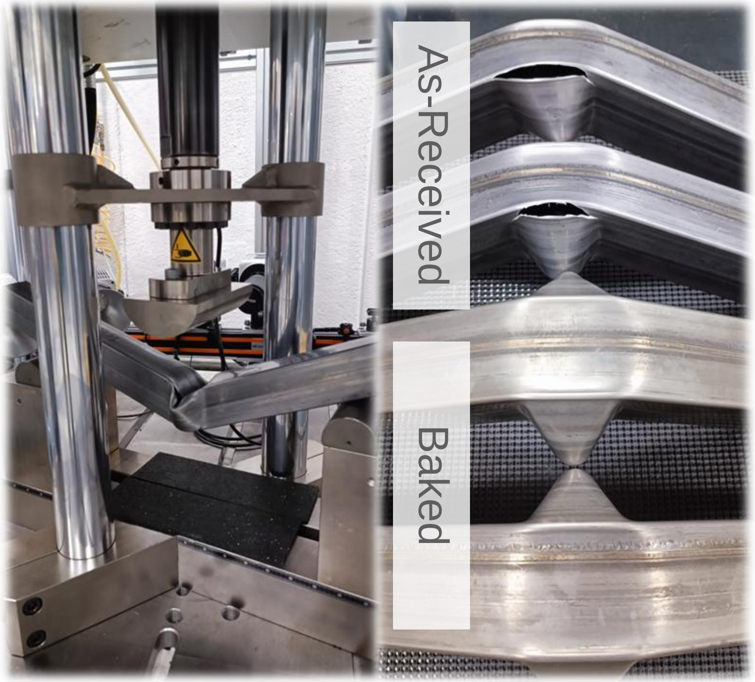
On the Fracture Strain Elevation of the Ps-Baked Q&P1180

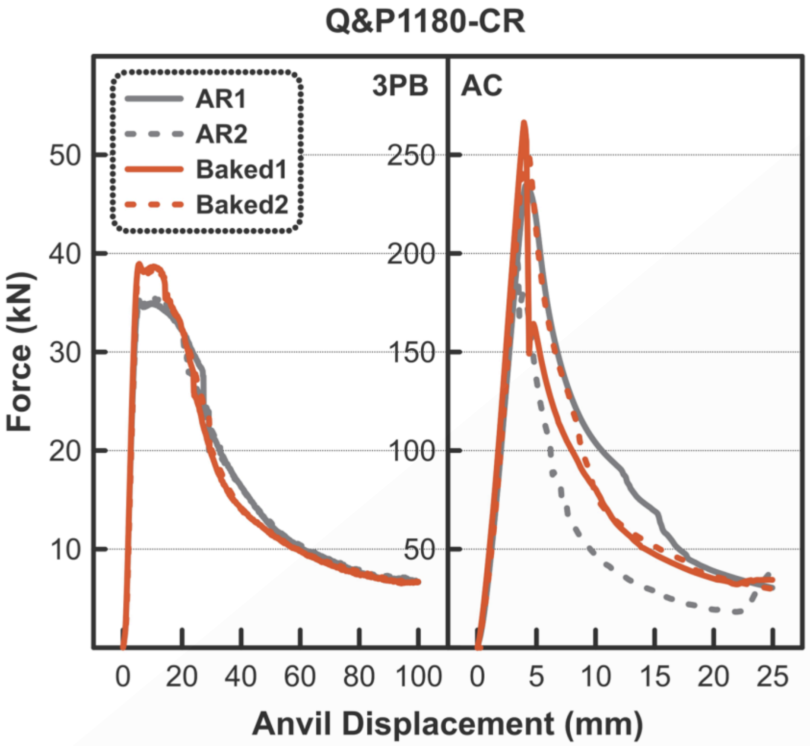
IV. Ongoing & Future Work

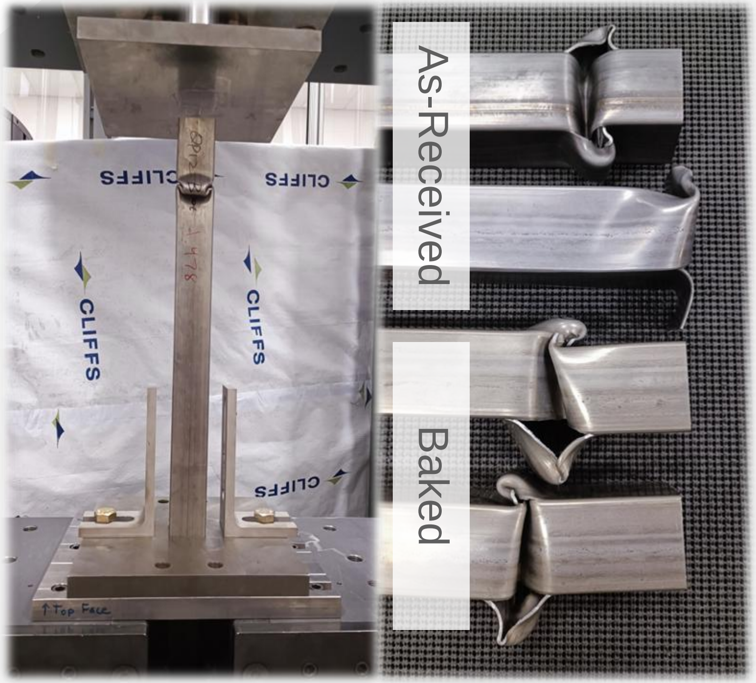
Tests on Tubular Samples

3-point-bending (3PB) and axial crush (AC) testing on Q&P1180-CR square tubes:

- 3PB: 400 mm span between the 2 supporters, ø100 mm anvil head, 10 mm/s anvil speed
- AC: 2 mm/s anvil speed
- As-received vs. baked (T200t20) tubes







Ongoing & Future Tests

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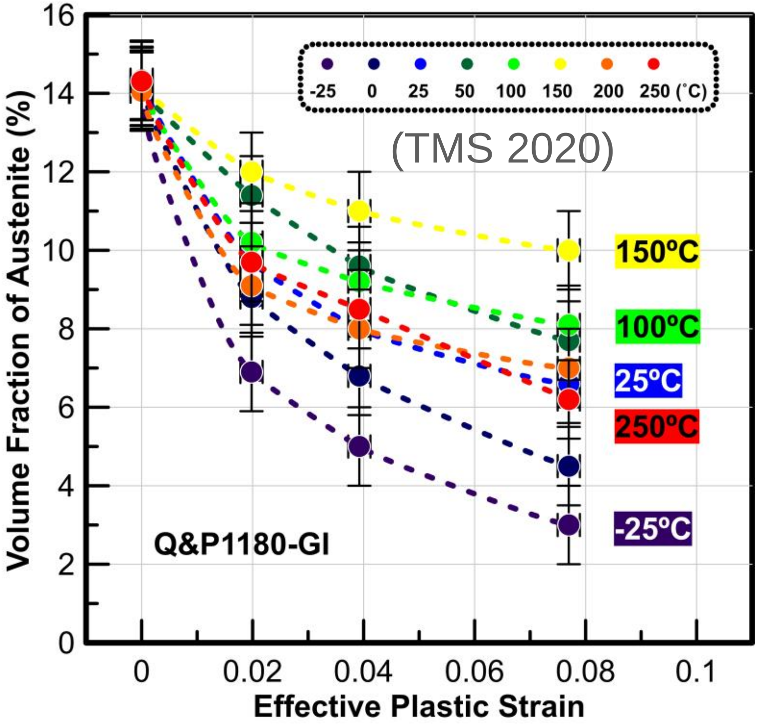
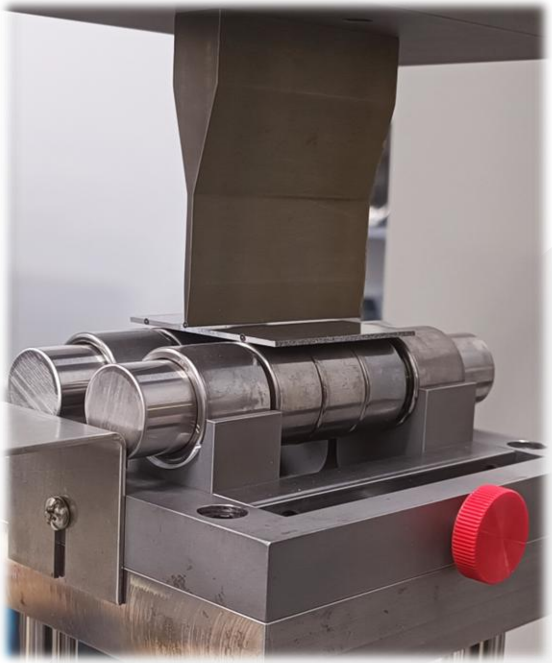
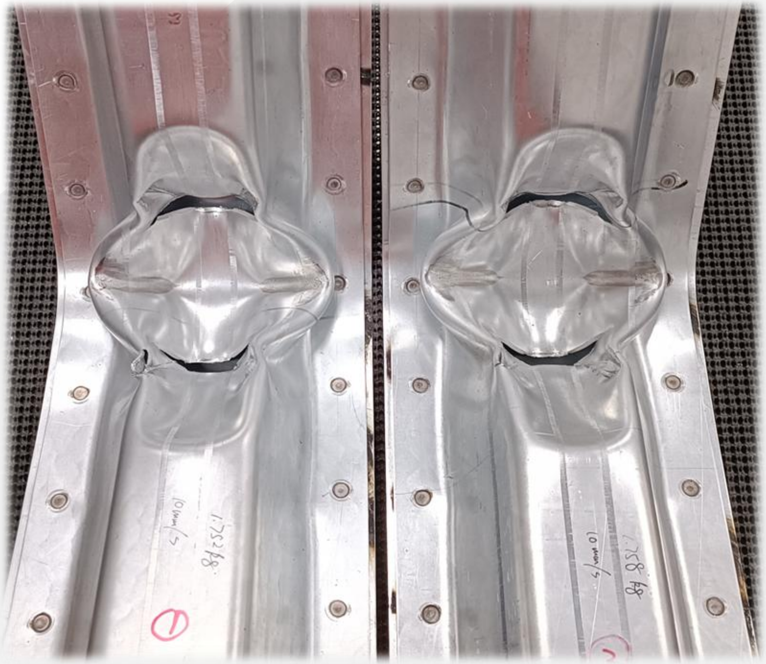
More advanced tests are ongoing or in preparation:

- Pre-strain at a subzero or warm temperature → bake → reload to fracture
- Pre-strain → bake → reload along a different strain path to fracture
- 3PB on as-received vs. baked Q&P1180-GI hat-section samples at various speeds







Conclusions

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- Q&P1180 was found to exhibit elevated fracture resistance (as well as BHI) after Ps-baking, which is unique in the investigated cold-forming AHSSs.
- 2 mechanisms determine such an elevation in the processed Q&P1180:
    1. No soft ferrite grains (not as in Q&P980)
    2. Mitigated micro-hardness differences between the transformed martensite and matrix after Ps-baking
- The microstructure of Q&P1180 keeps evolving in the automotive processing:
    1. As-received: dual phase (austenite + tempered martensite)
    2. After forming, a different dual phase (low austenite + transformed & tempered martensite)
    3. After paint-baking, approximately monotonic phase (low austenite + tempered martensite)
- Various mechanical tests characterized such a fracture strain elevation.
- The ultimate goal is to inspire the future AHSS development and applications.

THANK YOU!

For More Information

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Relative publications:

- **Elevated Fracture Resistance of Q&P1180 Steel after Forming and Paint-Baking Treatment**, SAE WCX 2025
- **Comparison of Bake Hardening Effects on AHSSs and Extruded Aluminum Alloys Applied in BEV Reinforcement Structures**, SAE WCX 2024, GDIS 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 WCX 2022, GDIS 2023