A Methodology to Characterize the Influence of Pre-Straining on the Paint Bake Sensitivity of 3G-AHSS

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GREAT DESIGNS IN STEEL™

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Outline

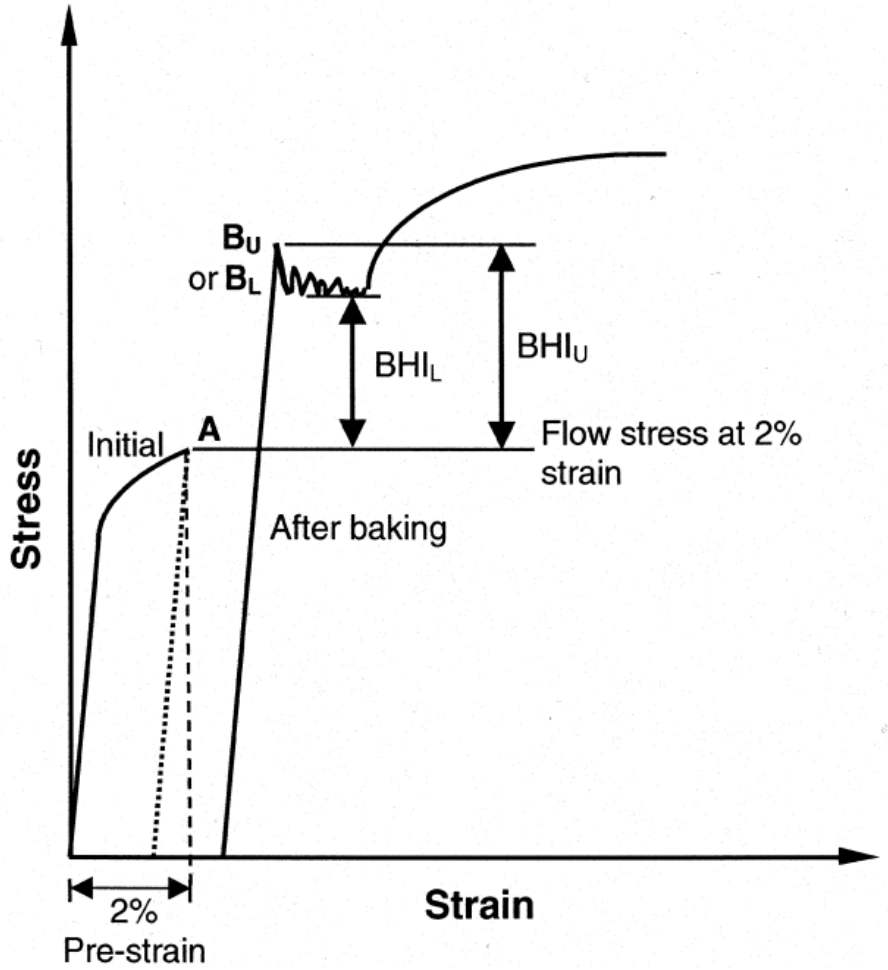
- Introduction: Bake Hardening Index, Motivation, and ASTM A653
- Developed KS-1B Methodology
- Paint Bake Cycle, Test Matrix, and Materials
- Effect of Pre-Strain on the Bake Hardening Index using the KS-1B Methodology
- Comparison between KS-1B and ASTM A653
- Effect of Paint Bake Cycle on Sheared Edge Stretchability

Bake Hardening

Sheet metal components making up the vehicle BIW are subjected a baking cycle to cure applied paint coats

- The baking cycle is often referred to as paint baking
- Paint baking can increase yield strength due to static strain ageing known as bake hardening
- The level of bake hardening can be quantified by the Bake Hardening Index (BHI),

$$\text{BHI} = (\text{Post-Bake Yield Stress}) - (\text{Pre-Bake Flow Stress})$$

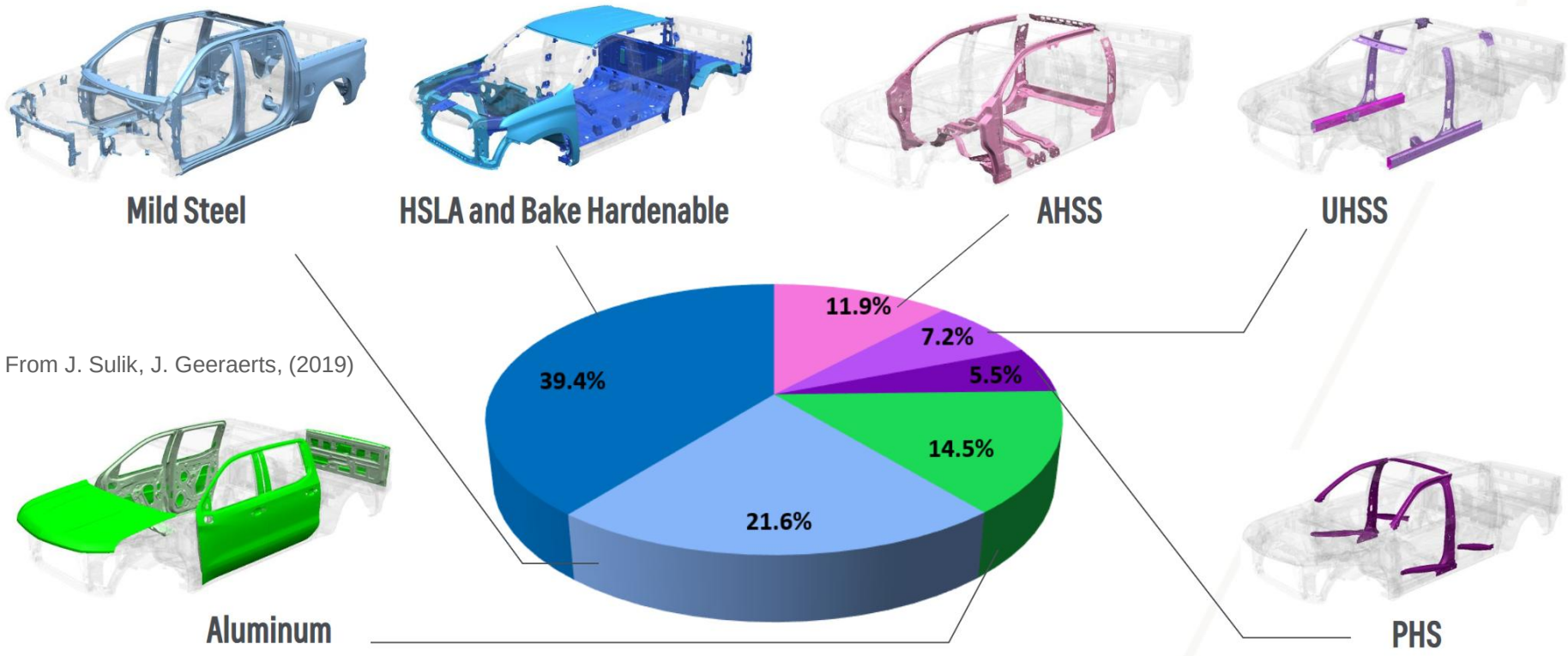


ASTM International. *Standard Specification for Steel Sheet, Zinc-Coated (galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process.* ASTM A653/A653M-23. ASTM International, June 2023. https://www.astm.org/a0653_a0653m-23.html

Motivation

- Bake hardenable steels typically exhibit BHI between 30-70 MPa depending on the bake cycle and pre-strain[1]
- The BHI of 3G-AHSS has potential to be even more sensitive to pre-strain as the microstructure evolves throughout plastic straining with retained austenite transforming to martensite

2019 Chevrolet Silverado – Cab with Closures and Box



[1] Jain, V., Misal, S., Paliwal, L., and Sathaye, A., "Effect of Pre-Strain and Baking Temperature on Bake-Hardening Behaviour of BH220 Steel," SAE Technical Paper 2023- 01-0078 (2023). https://doi.org/10.4271/2023-01-0078.

[2] J. Sulik, J. Geeraerts, "2019 Chevrolet Silverado Structure Review", Presented at 2019 Great Designs in Steel, Sponsored by American Iron and Steel Institute

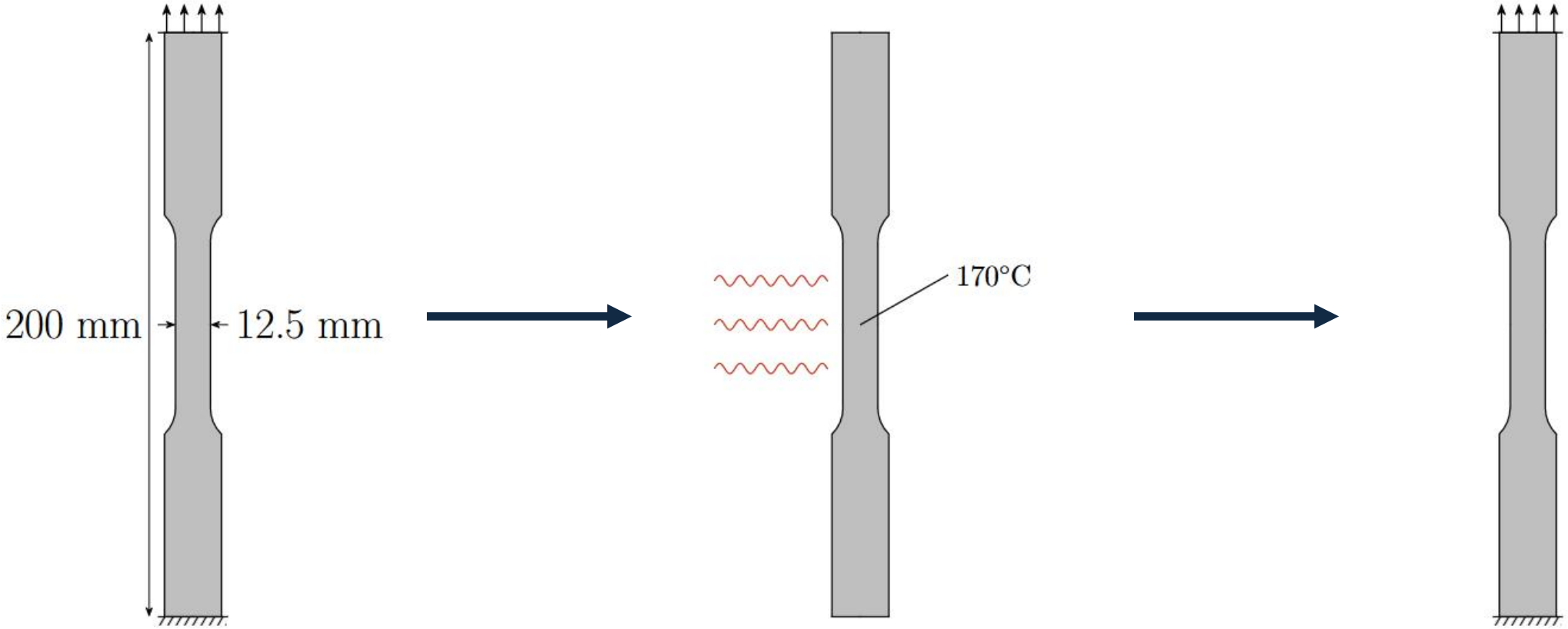
ASTM A653 Methodology

- The ASTM A653 standard is specified for 2% pre-strain however, forming strains typically exceed 2% requiring higher pre-strains to be tested

1. Pre-strain ASTM E8 coupon (2% per standard)

2. Paint bake pre-strained coupon (170°C, 20 minutes)

3. Retest bake hardened coupon

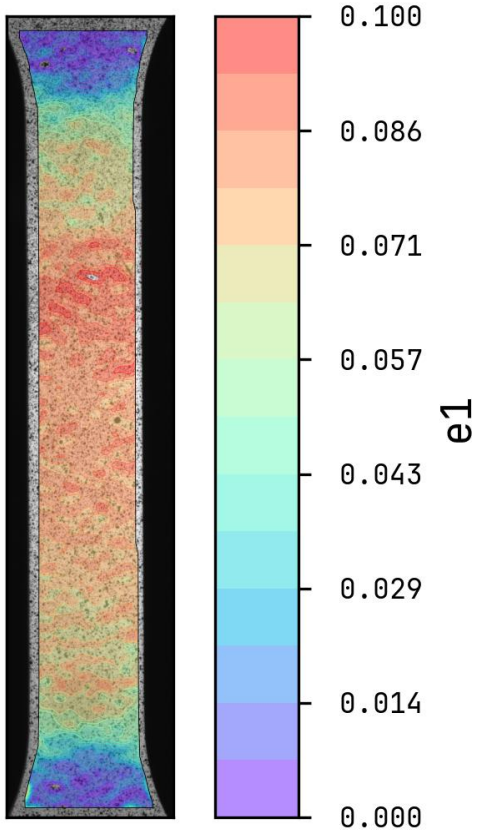


Application of ASTM A653 to 3G-AHSS

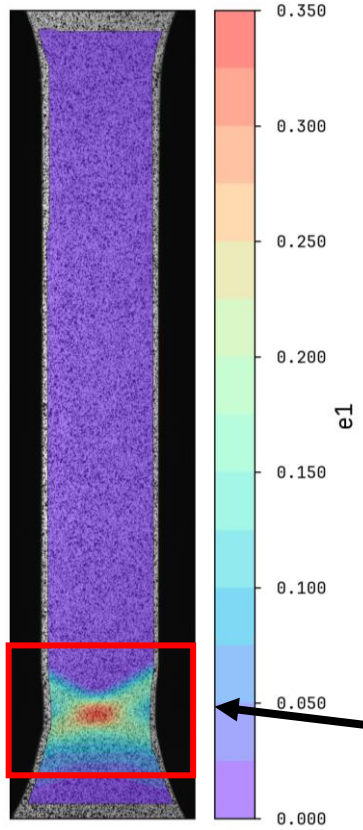
- For certain 3G-AHSS grades with pre-strains exceeding 2%, ASTM A653 is unable to determine the BHI
- Non-uniform pre-strain assumed to promote premature strain localization during retesting of baked coupons

Example: 1180GEN3 8% pre-strain

Pre-Strain Contour

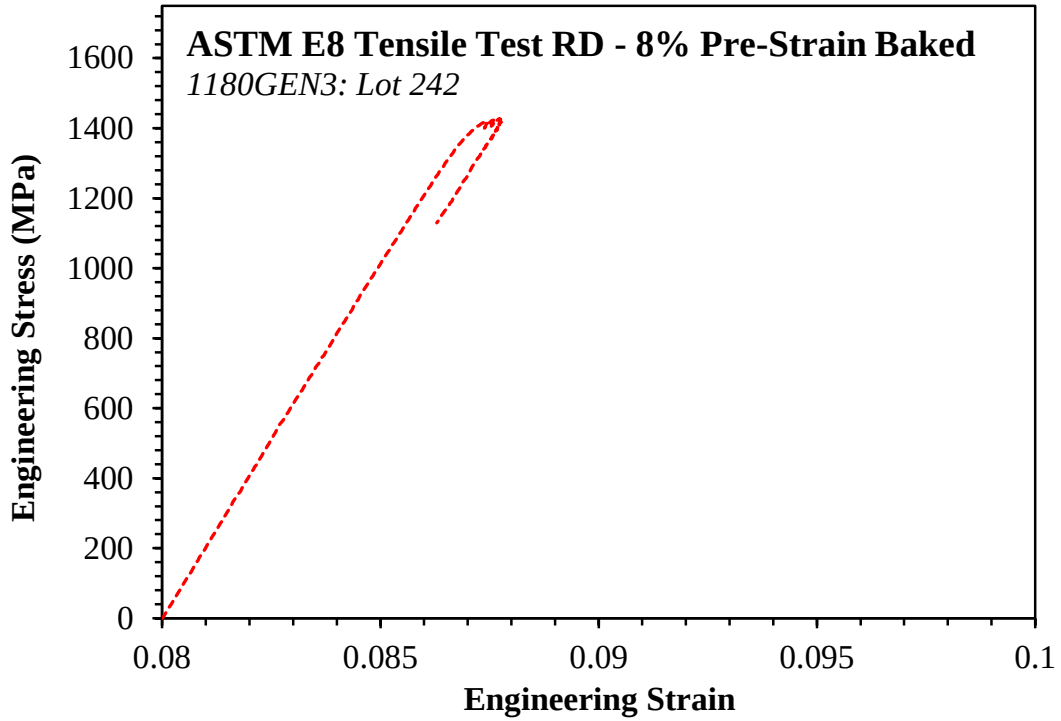


Baked Retest – Image before Fracture



Strain localized outside gauge at transition radius

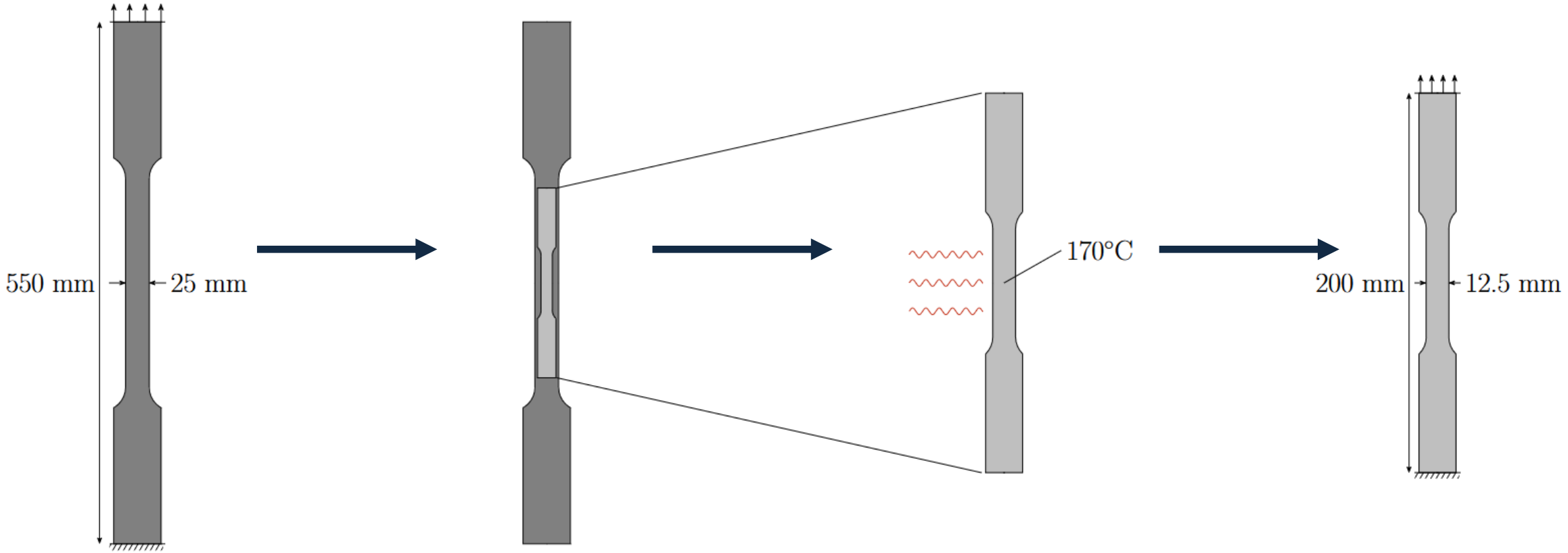
Baked Retest – Corresponding Stress Response



Developed KS-1B Methodology

- Developed by A/SP to promote characterization of BHI of 3G-AHSS for pre-strains greater than 2%
- Extraction of ASTM E8 coupon from pre-strained KS-1B sample provides a more uniform pre-strain field

1. Pre-strain KS-1B coupon (Specified %)
2. Extract ASTM E8 from KS-1B gauge
3. Paint bake extracted ASTM E8 coupon (170°C, 20 minutes)
4. Retest bake hardened coupon



Pre-Strain Levels

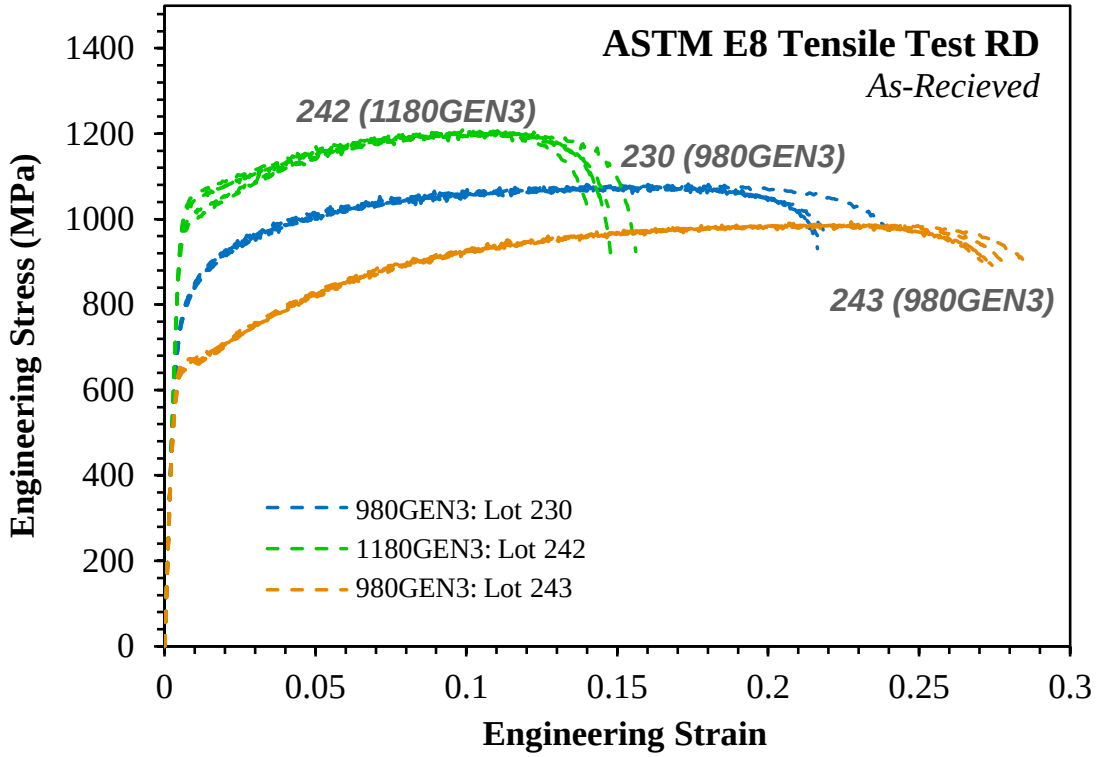
- KS-1B methodology applied to determine the effect of pre-strain on the BHI of considered GEN3 steels
- ASTM A653 methodology used to validate and contrast against KS-1B results for 2 and 8% pre-strain only

Pre-Strain	0%	2%	5%	8%	10%
KS-1B	X	✓	✓	✓	✓
ASTM A653	✓	✓	X	✓	X

Materials

Three commercial GEN3 Advanced High Strength Steels (AHSS) provided by the Auto/Steel Partnership considered

- 980GEN3: Lot #230 - 1.4 mm, Lot #243 - 1.6 mm
- 1180GEN3: Lot #242 - 1.2 mm

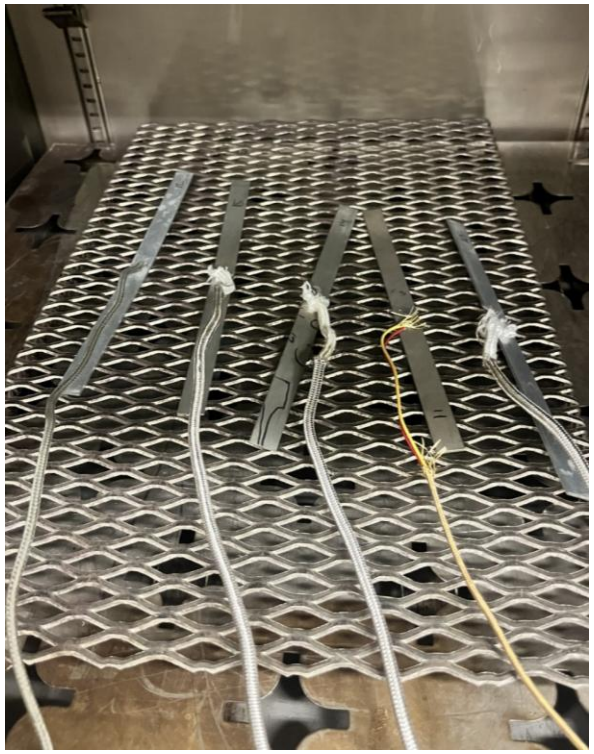


Material	980GEN3 Lot 230	1180GEN3 Lot 242	980GEN3 Lot 243
Yield Strength (MPa)	763 ± 6	1002 ± 24	644 ± 10
UTS (MPa)	1074 ± 4	1199 ± 2	985 ± 1
Uniform Elongation (%)	15.8 ± 0.4	10.7 ± 0.5	22.0 ± 0.6
True Strain at UE (%)	14.7 ± 0.3	10.2 ± 0.4	19.9 ± 0.5
Total Elongation (%)	22.2 ± 1.1	14.7 ± 0.6	27.6 ± 0.6

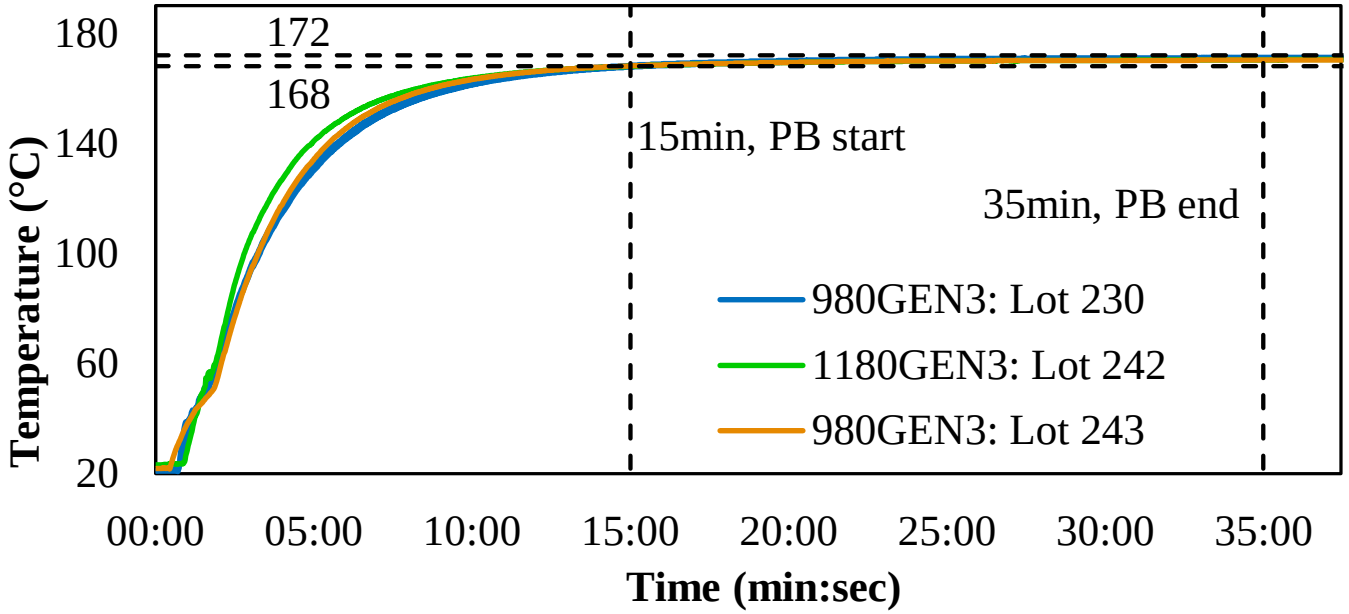
Simulated Paint Bake Cycle

- Furnace temperature and time required for samples to reach 170 ± 2°C calibrated with thermocouples
- Total furnace time of 35 min. → 15 min. for samples to reach 170°C followed by 20 min. of paint bake

Furnace Calibration

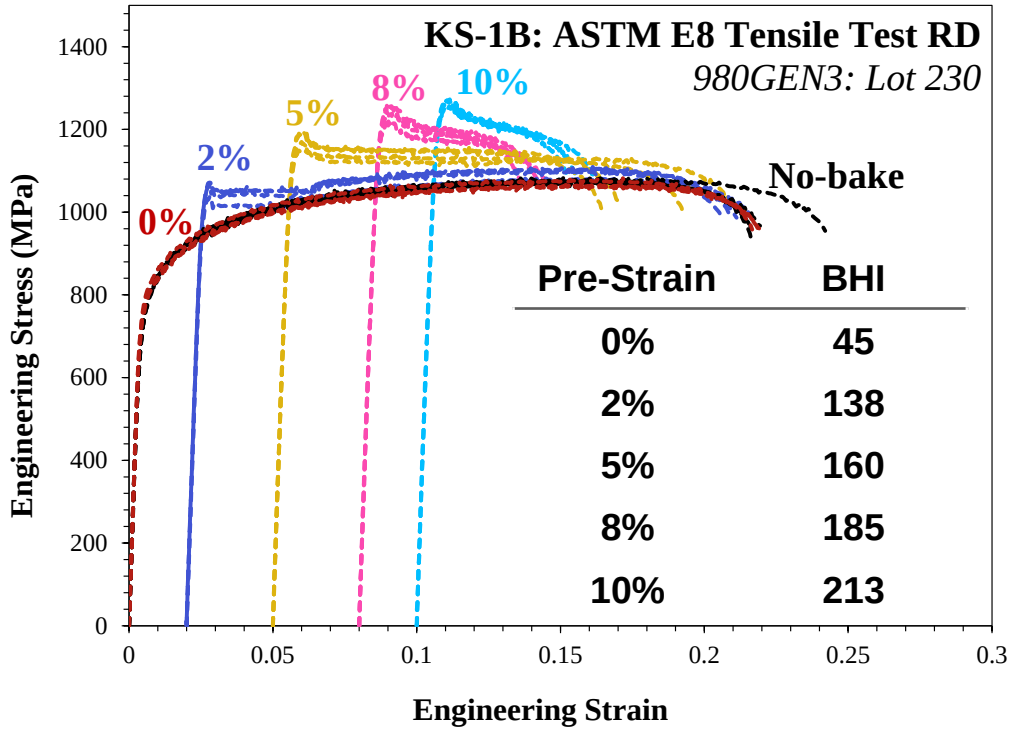


Paint Bake Temperature Profiles

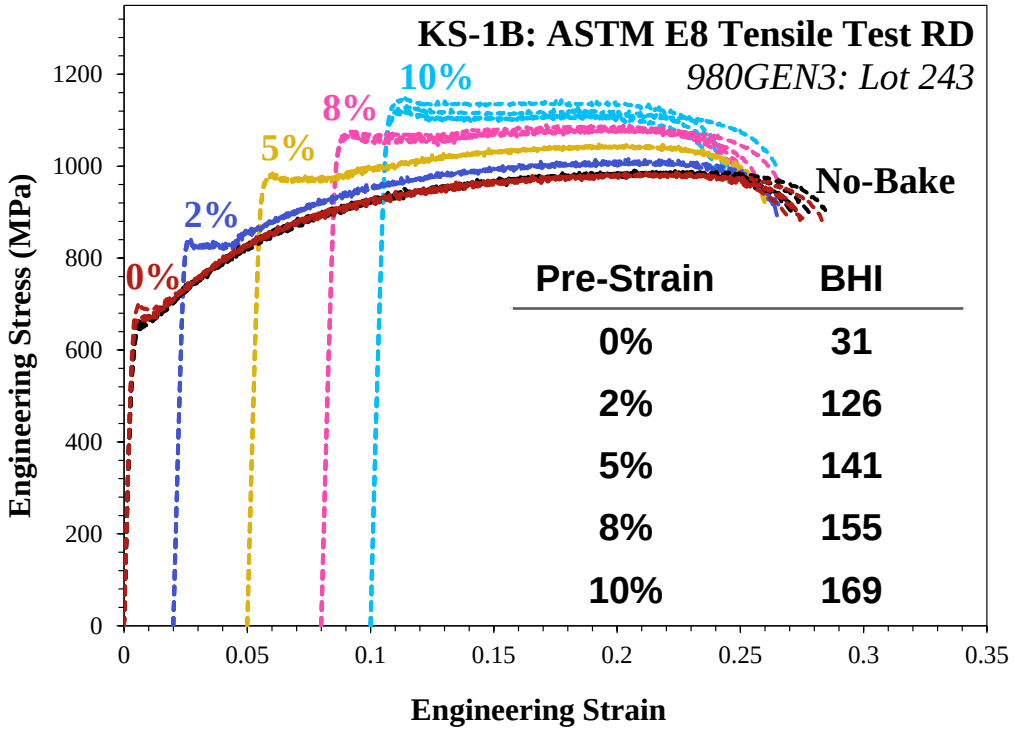


KS-1B Results: 980GEN3 Steels (Lot #230 & #243)

- The 980GEN3 steels exhibit significant bake hardening with the post-bake yield stress increasing with pre-strain
- Yield point elongation present in all bake hardened tests except for baking with no pre-strain for Lot 230



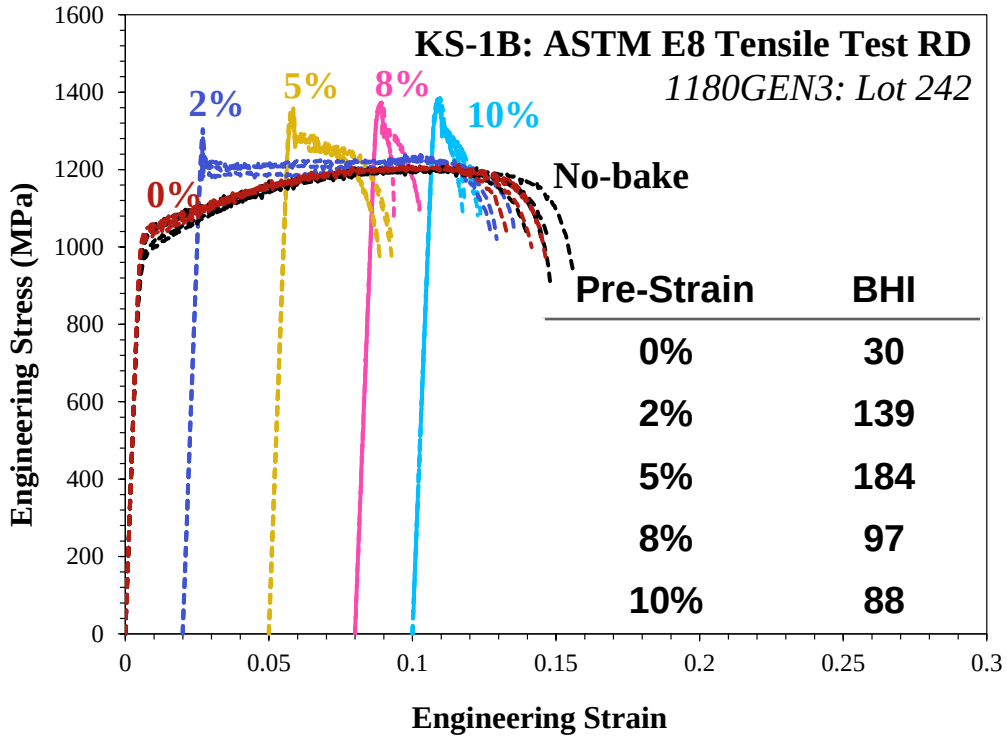
Pre-Strain	BHI
0%	45
2%	138
5%	160
8%	185
10%	213

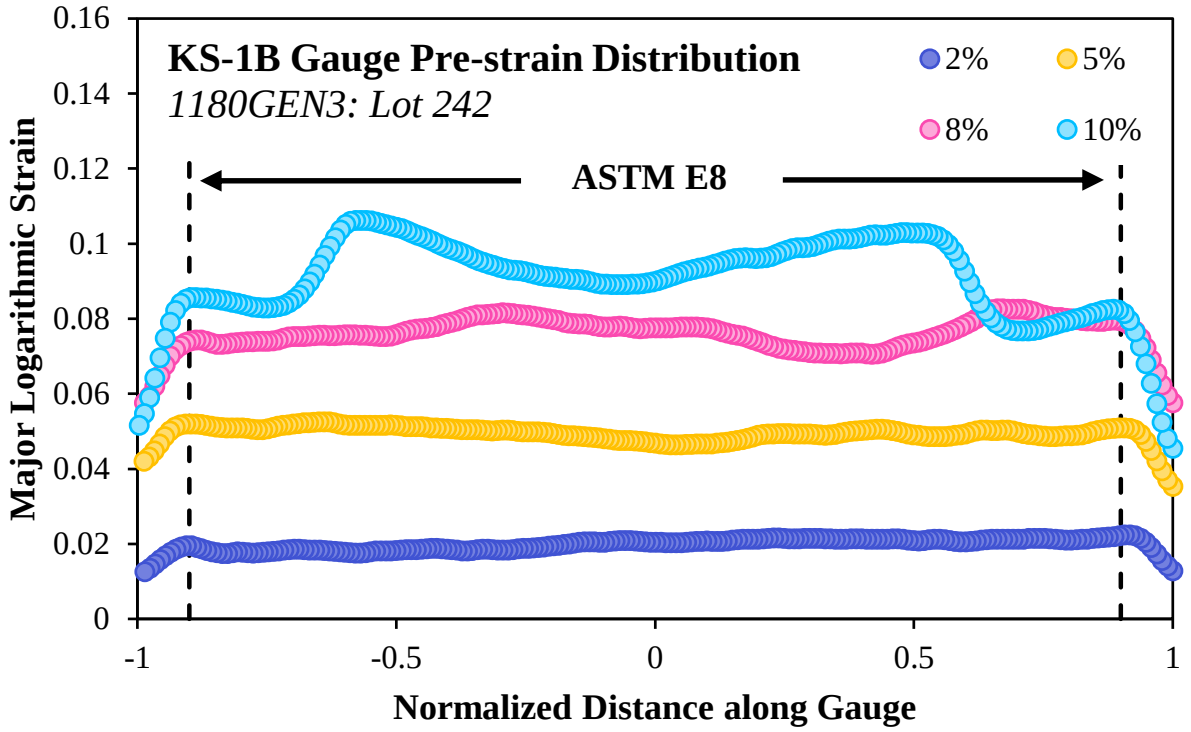


Pre-Strain	BHI
0%	31
2%	126
5%	141
8%	155
10%	169

KS-1B Results: 1180GEN3 (Lot #242)

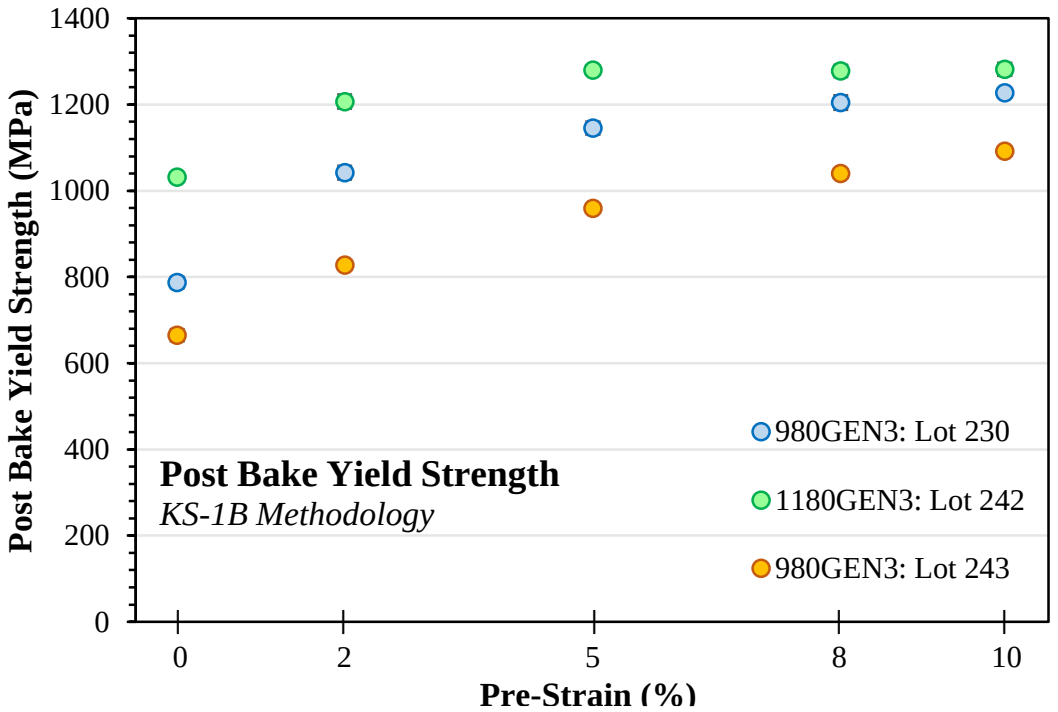
- The 1180GEN3 also shows significant sensitivity to the paint bake cycle and magnitude of pre-strain
- Strain localization occurs for 10% pre-strain as the uniform elongation of the base material is ~10%

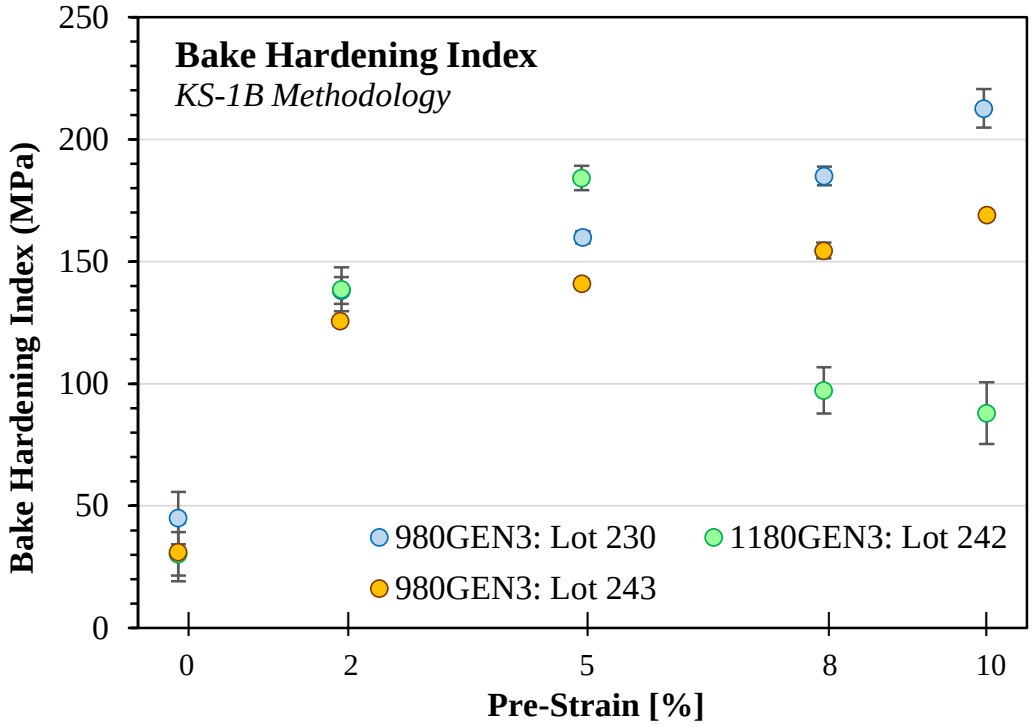




Summary of KS-1B Results

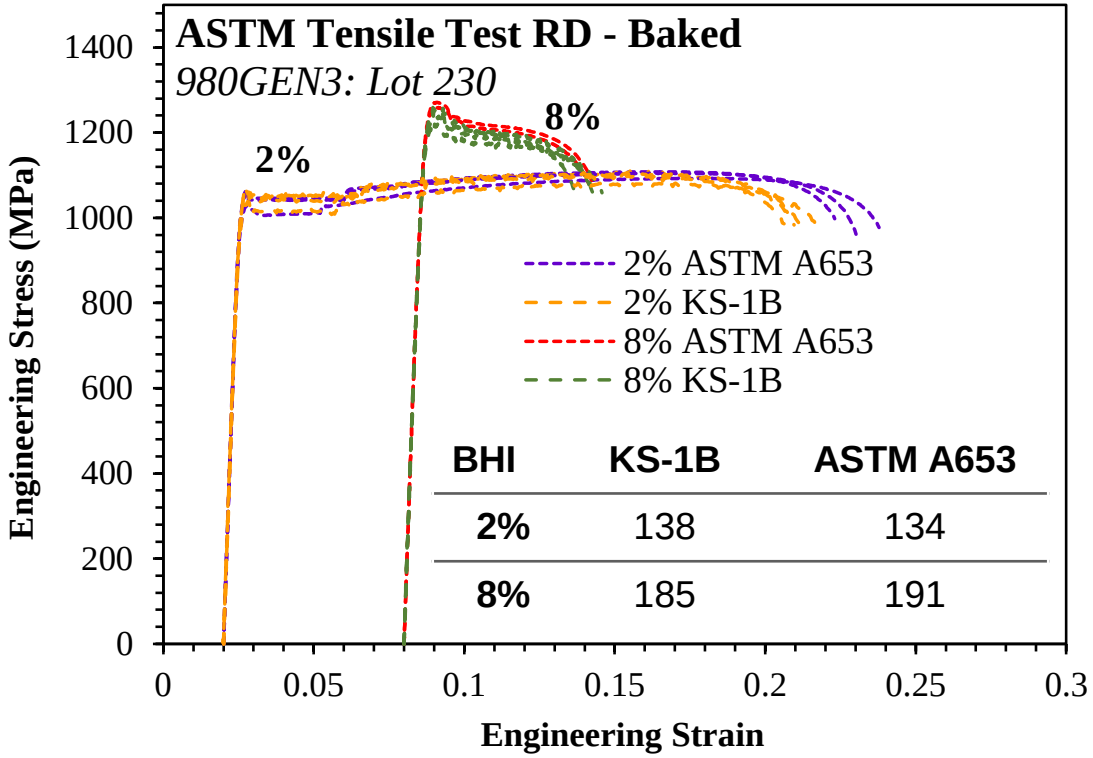
- The BHI of all three steels is significantly sensitive to the magnitude of applied pre-strain
- For the 980GEN3 steels, the BHI increase by 75 and 43 MPa (230, 243) from 2% to 10% pre-strain
- For the 1180GEN3 steel, the BHI increases from 2-5% pre-strain but drops for 8 and 10% due to a decreased hardening rate for strains exceeding 5%



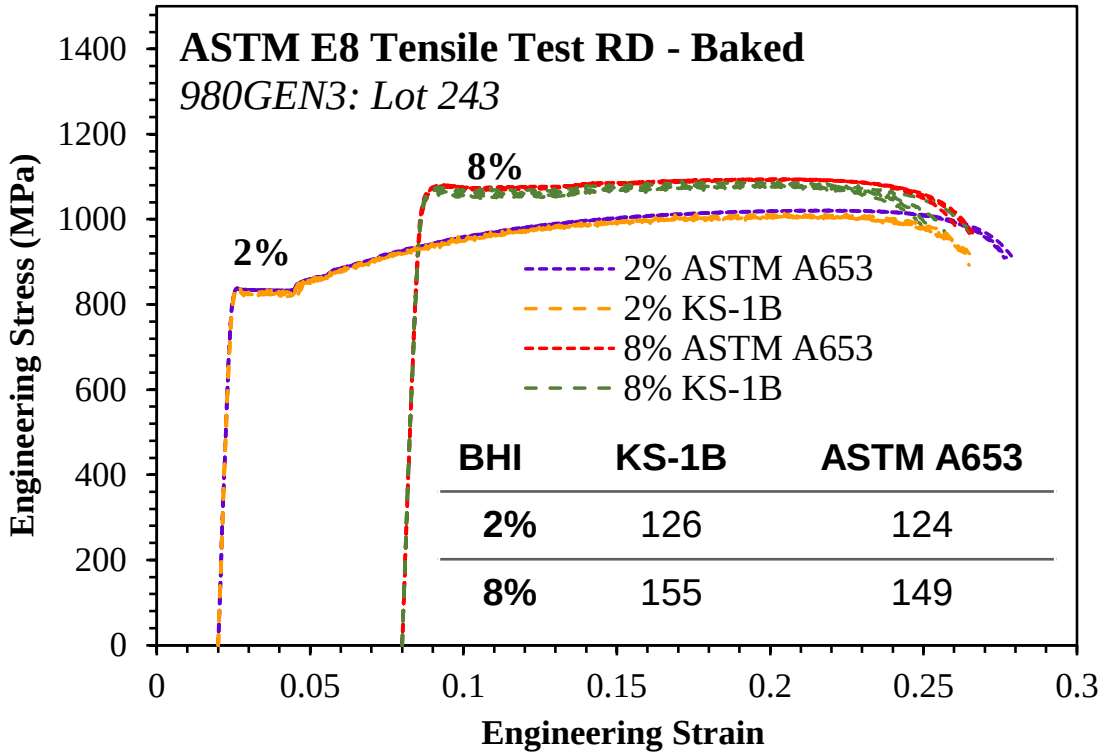


KS-1B & ASTM A653: 980GEN3 Steels (Lot #230 & 243)

- The bake hardening response and index (BHI) were consistent between methods for both 2 & 8% pre-strains



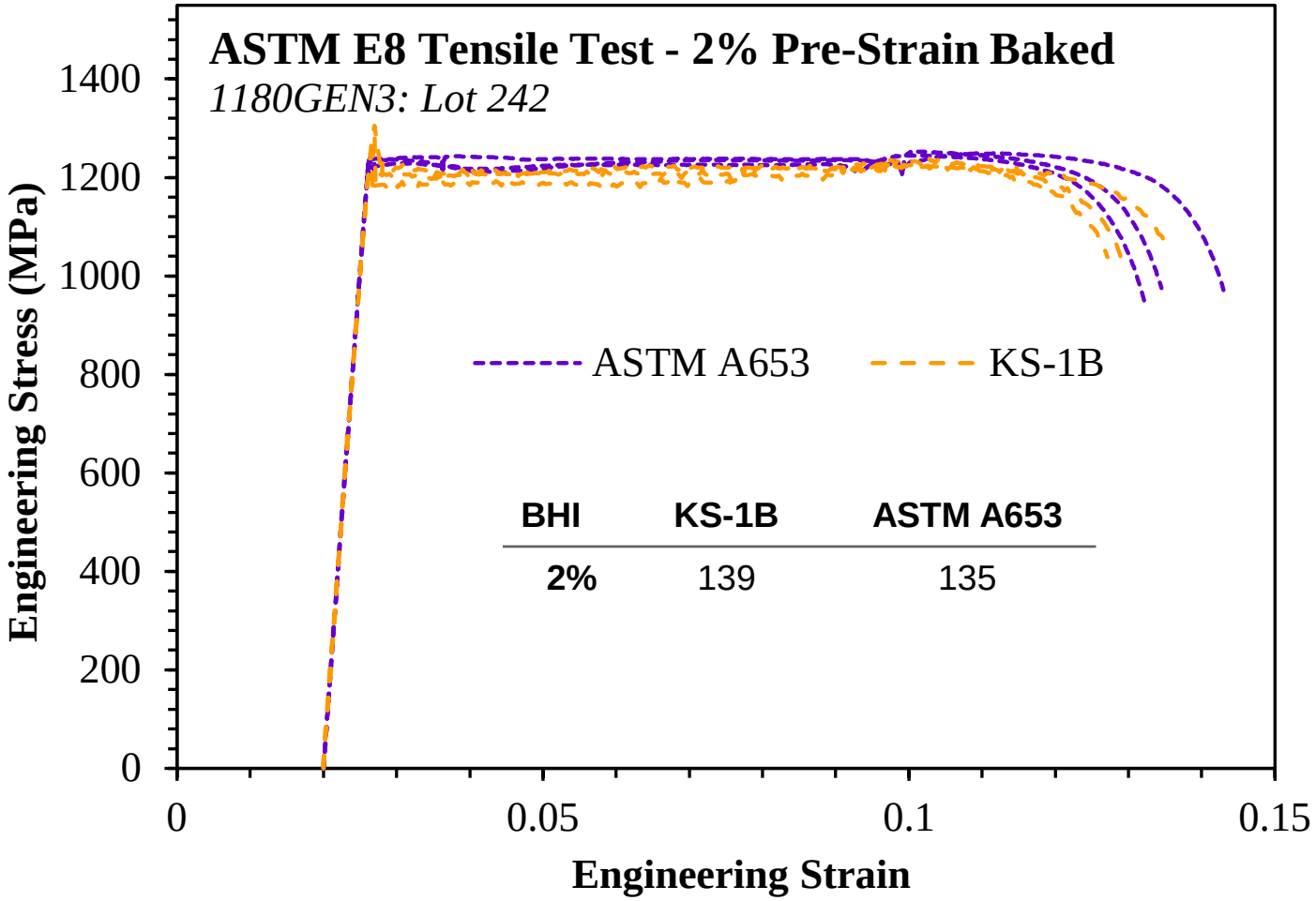
BHI	KS-1B	ASTM A653
2%	138	134
8%	185	191



BHI	KS-1B	ASTM A653
2%	126	124
8%	155	149

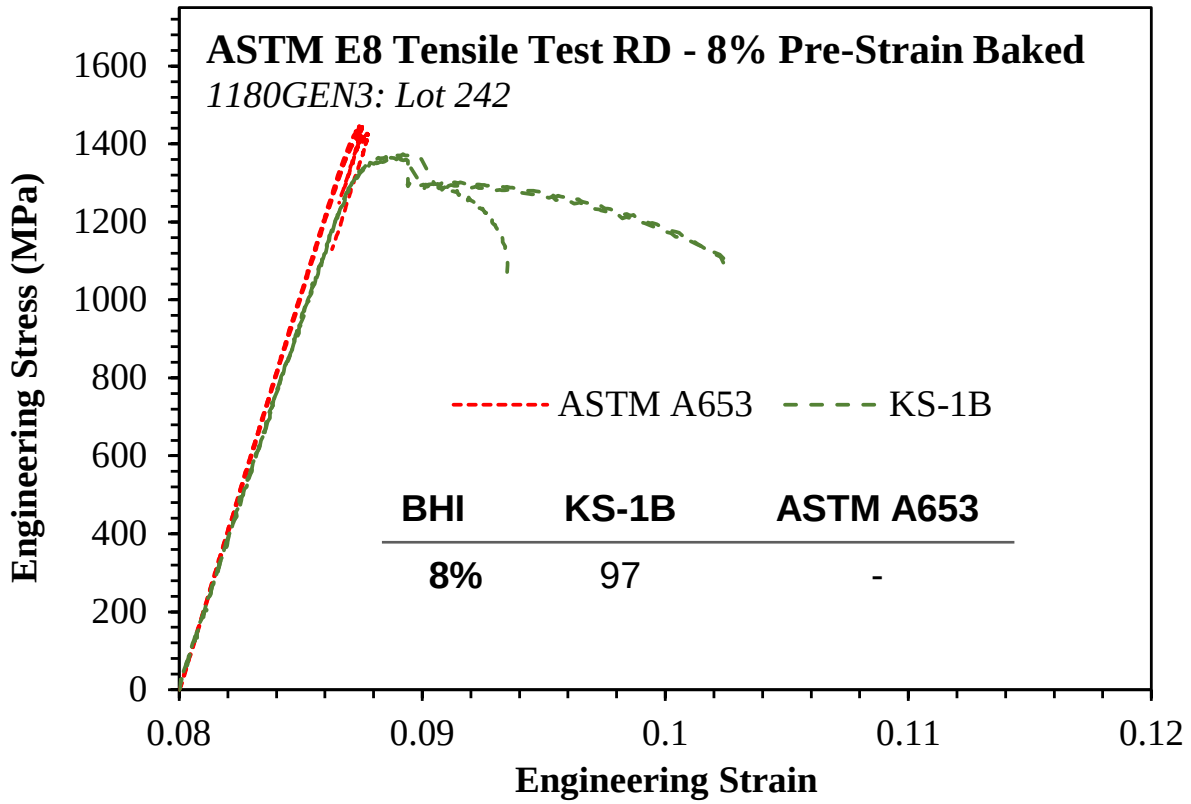
KS-1B & ASTM A653 : 1180GEN3 (Lot #242)

- For 2% pre-strain, the engineering stress response and corresponding BHI closely align for the 1180GEN3 steel

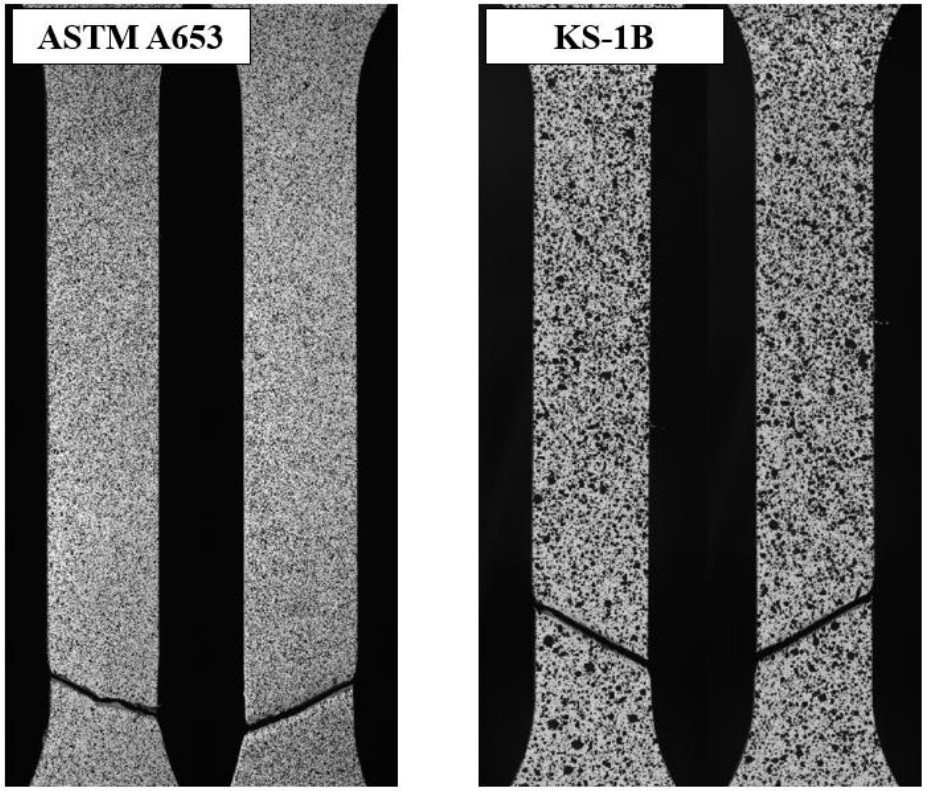


KS-1B & ASTM A653 : 1180GEN3 (Lot #242)

- For 8% pre-strain, ASTM A653 was unable to characterize the BHI as the bake hardened coupons fractured prematurely in transition radius



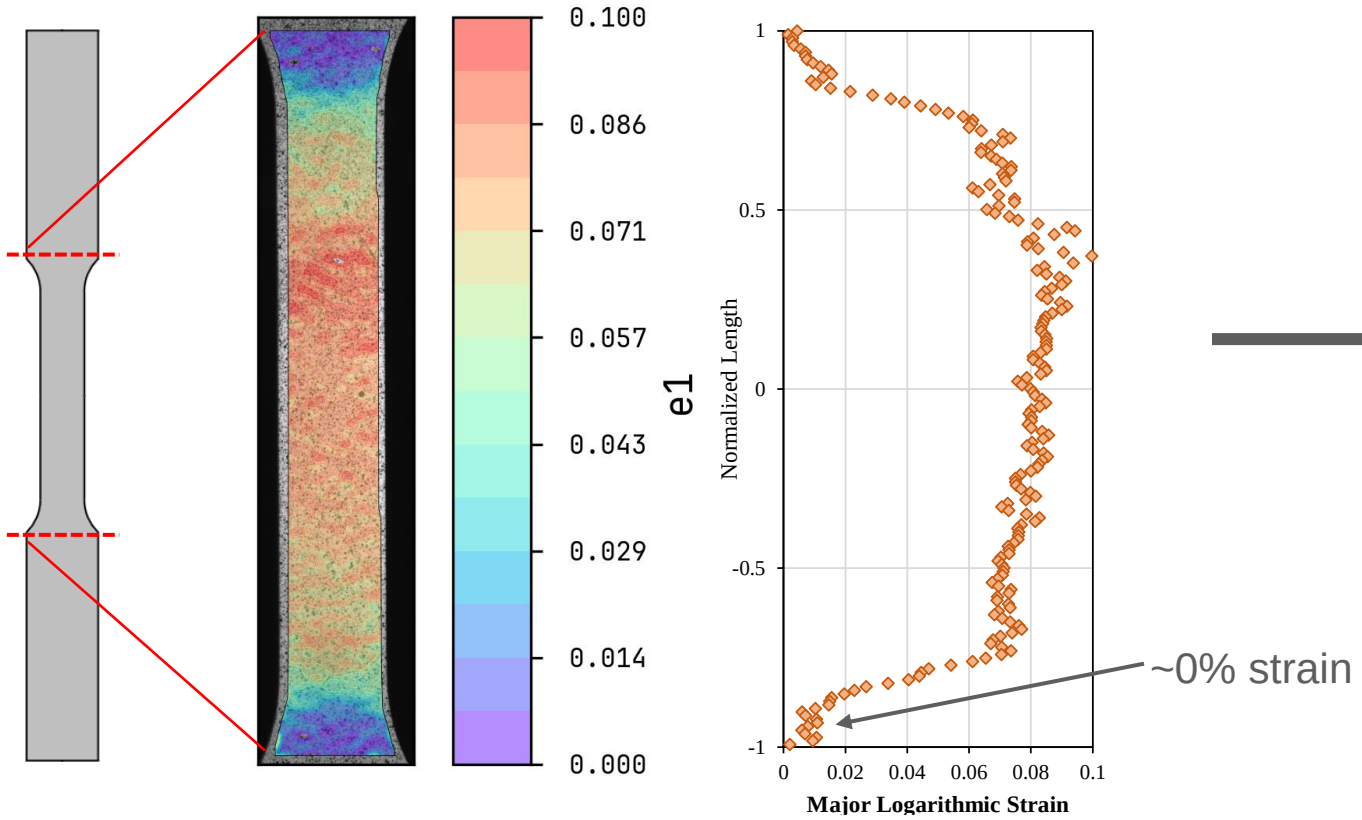
Bake Hardened Retests



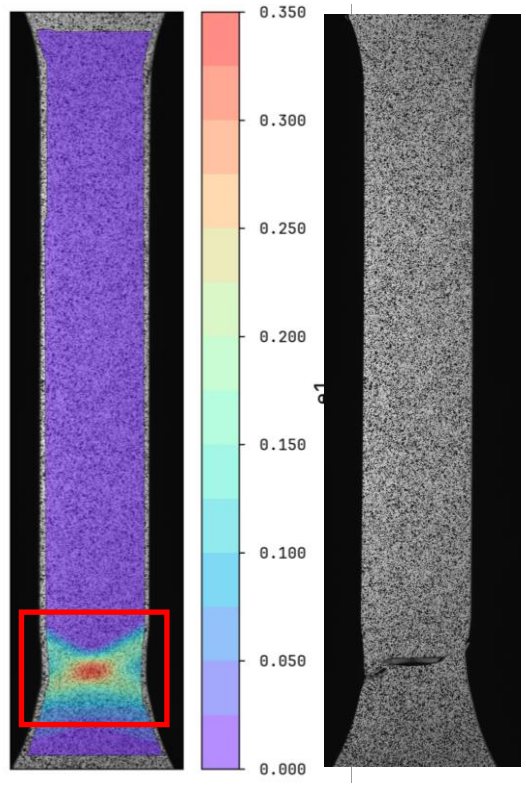
ASTM A653: 1180GEN3, 8% Pre-Strain

- Significant strain gradients at the transition radius of the pre-strained ASTM E8 coupons resulted in strain localizing in the soft transition radius during retesting of the bake hardened coupon

8% Pre-strain: ASTM E8



Bake Hardened Retest

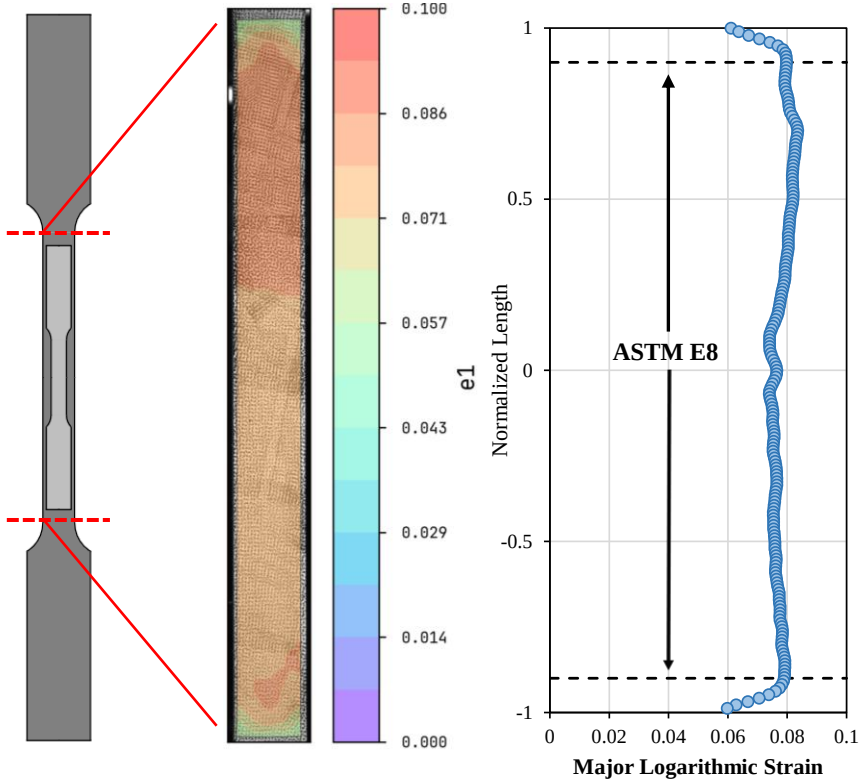


Localization

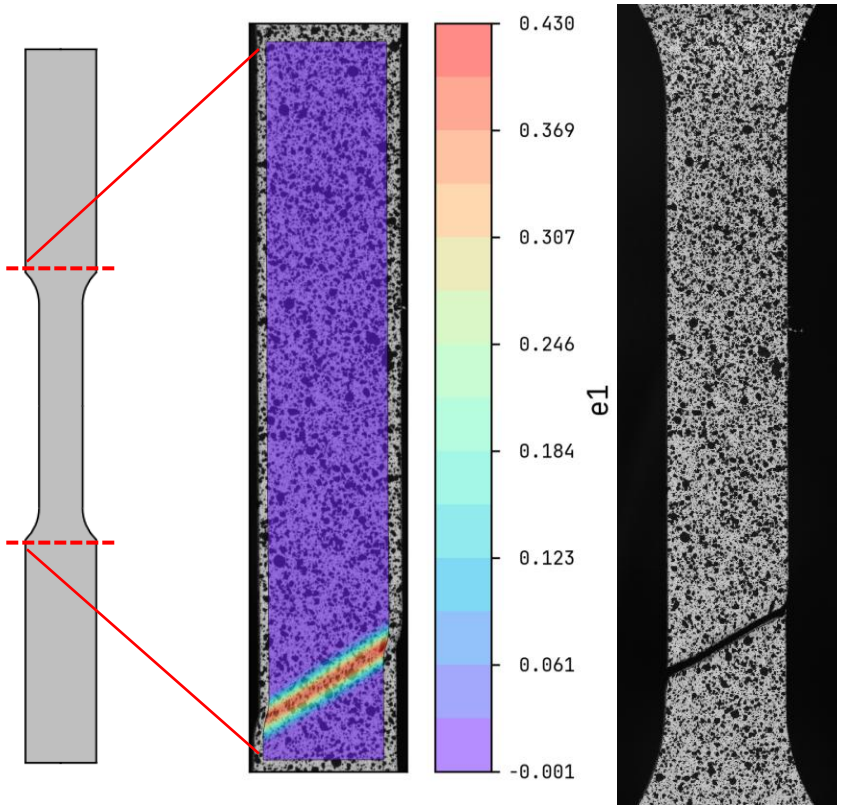
KS-1B: 1180GEN3, 8% Pre-Strain

- KS-1B resulted in a uniform pre-strain field and avoided strain localization outside of the gauge during retesting

8% Pre-strain: KS-1B

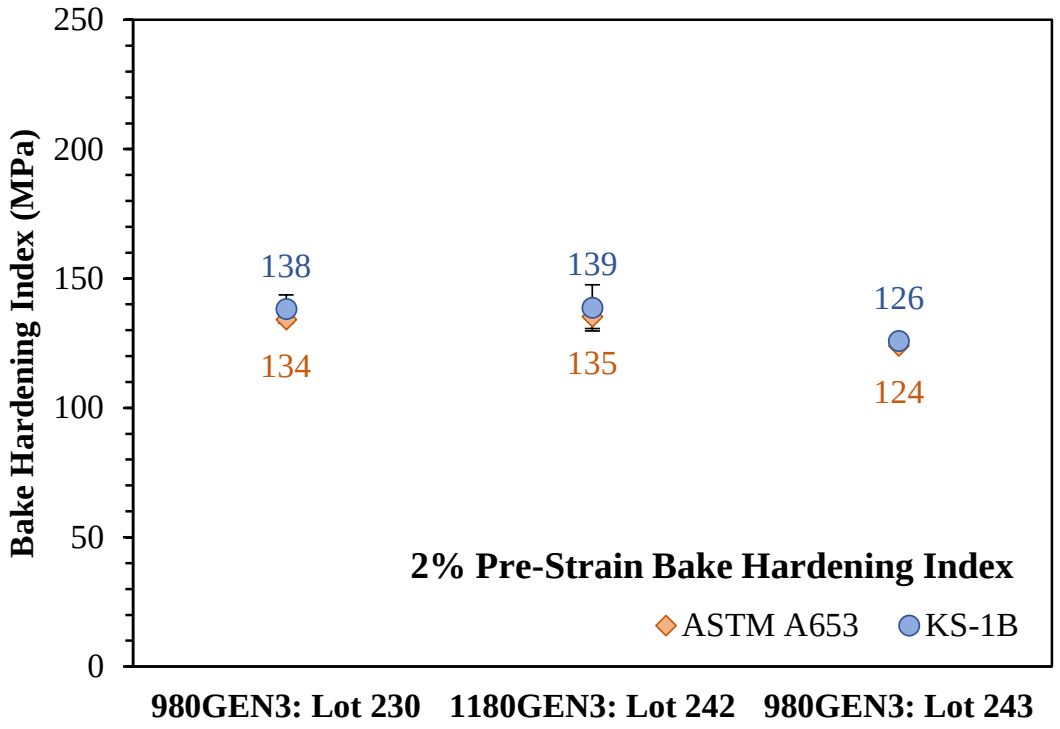


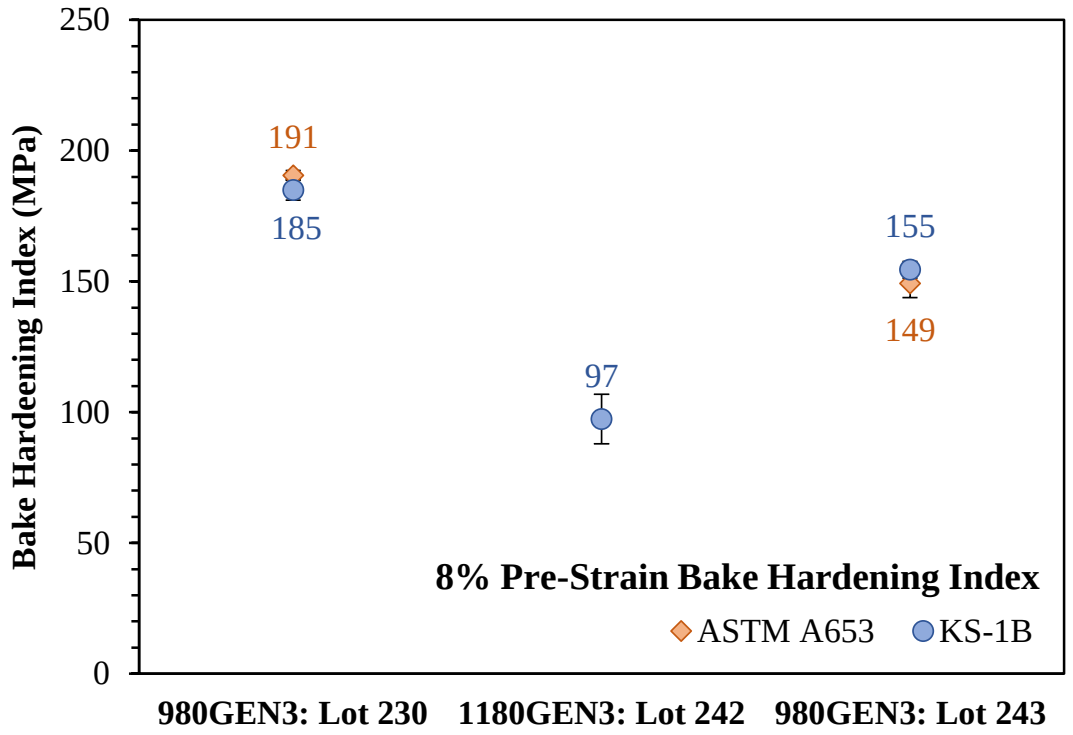
Bake Hardened Retest



KS-1B & ASTM A653 : BHI Comparison

- The ASTM A653 and KS-1B BHI are in agreement for 2% pre-strain for all considered steels
- For 8% pre-strain, the BHI determined from both methods align for the 980GEN3 steels
- For the 1180GEN3, only the KS-1B methodology is able to successfully characterize the BHI at 8% pre-strain





Influence of Significant Pre-Strain: Hole Punching

- Punching can induce significant local strain (up to 200%[1]) in the shear affected zone (SAZ)
- Effect of paint bake for extreme pre-strain evaluated with sheared edge conical hole expansion (HX)
- Machined edges considered to have negligible residual strain tested to provide a baseline

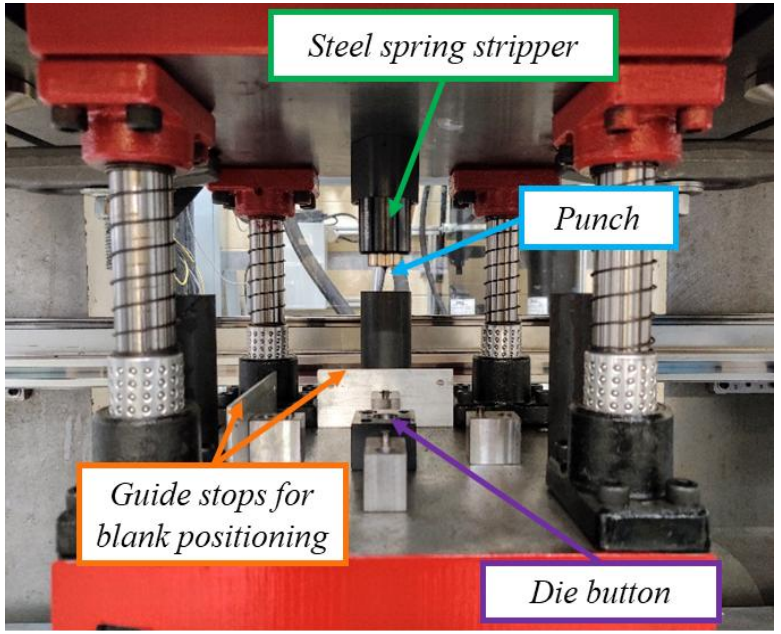
Test Parameters

- Hole diameter: 10 mm
- Punch Angle: 60° (conical)
- Punch Speed: 0.25 mm/s
- Binder Force: 640 kN

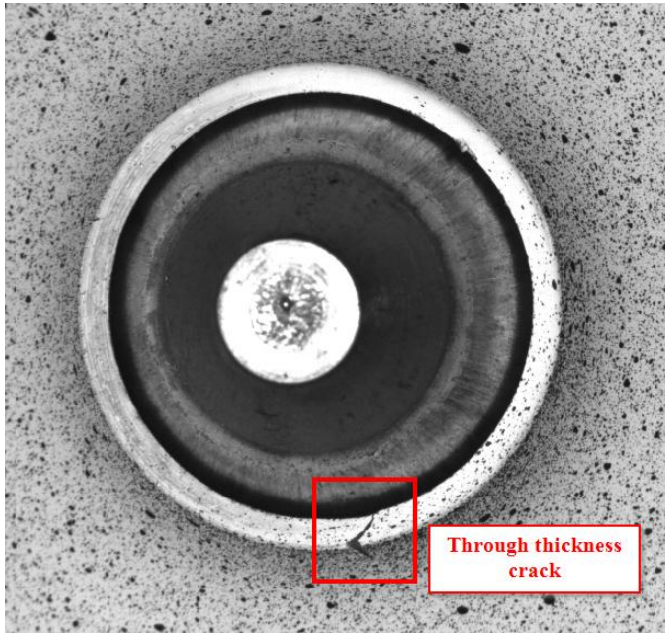
Punch Parameters

- Cutting clearance: 12%
- Cutting speed: 50 mm/s

Punching Tool



Fracture Image (Lot #243, Machined)

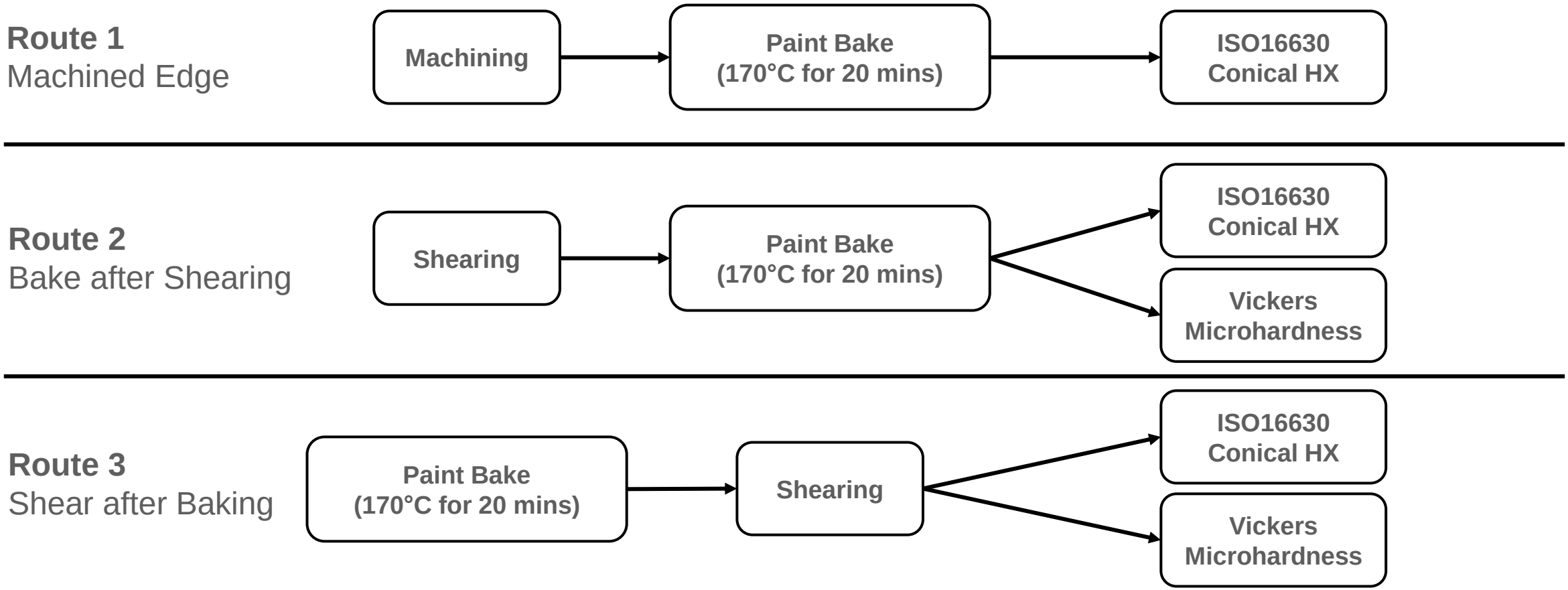


$$HER(\%) = \left(\frac{d_{inner}^{avg,\,fracture} - d_{initial}}{d_{initial}} \right) \times 100$$

[1] Pathak, N., Butcher, C., and Worswick, M., "Experimental Techniques for Finite Shear Strain Measurement within Two Advanced High Strength Steels," Experimental Mechanics 59, no. 2 (2018): 125-148. https://doi. org/10.1007/s11340-018-00448-1.

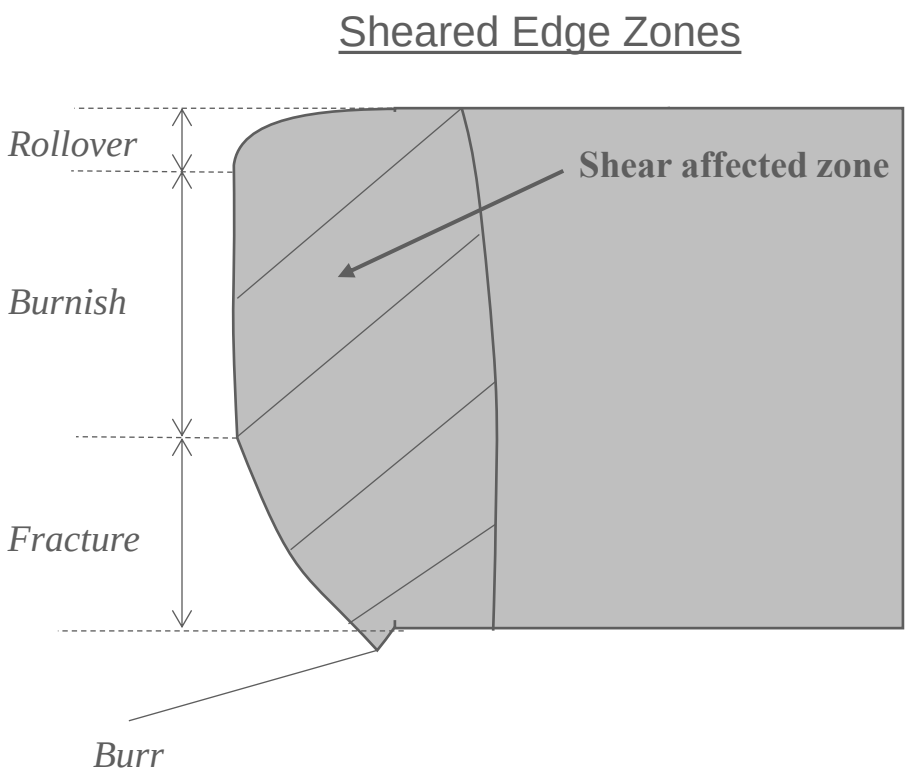
Conical HX Process Routes

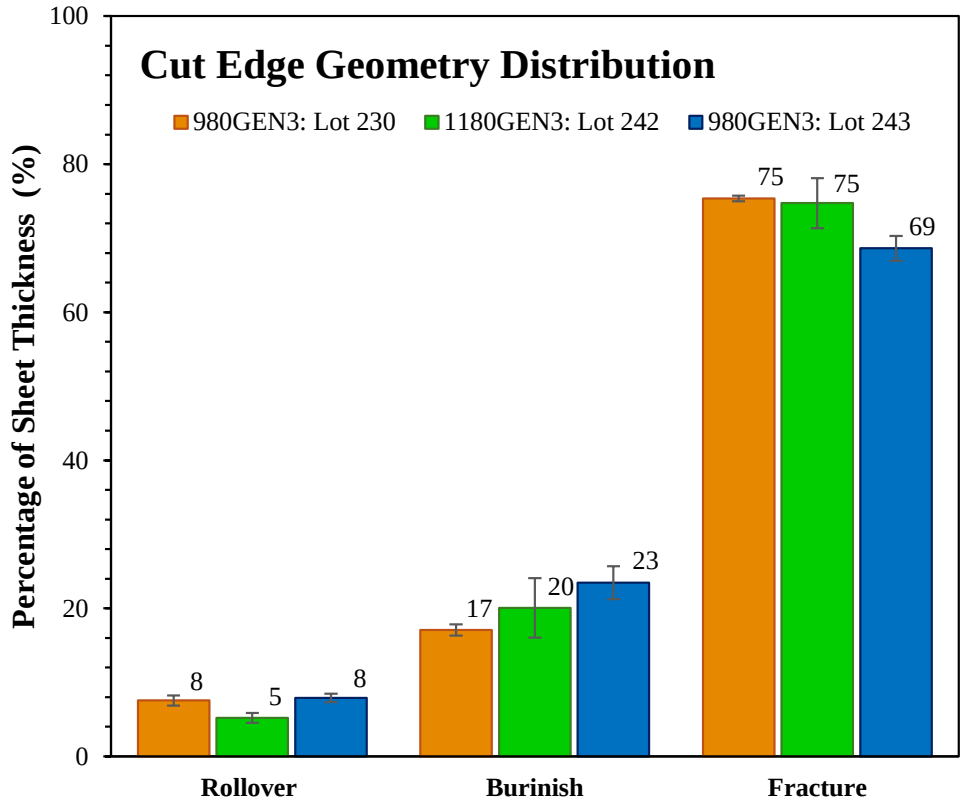
- Three process routes were considered, baseline tests also conducted on the materials without heat treatment for both machined and sheared edges



Sheared Edge Profiles

- Punched holes were sectioned to characterize the four sheared edge zones; rollover, burnish, fracture, and burr
- A negligible burr was observed on all samples attributed to the use of new/sharp punching tools



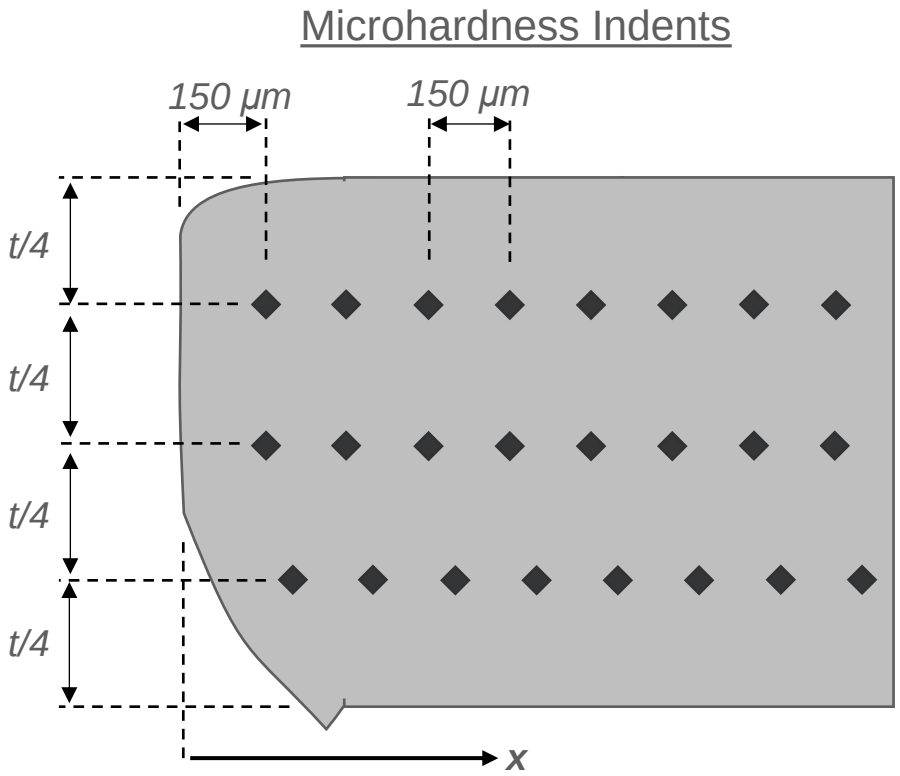


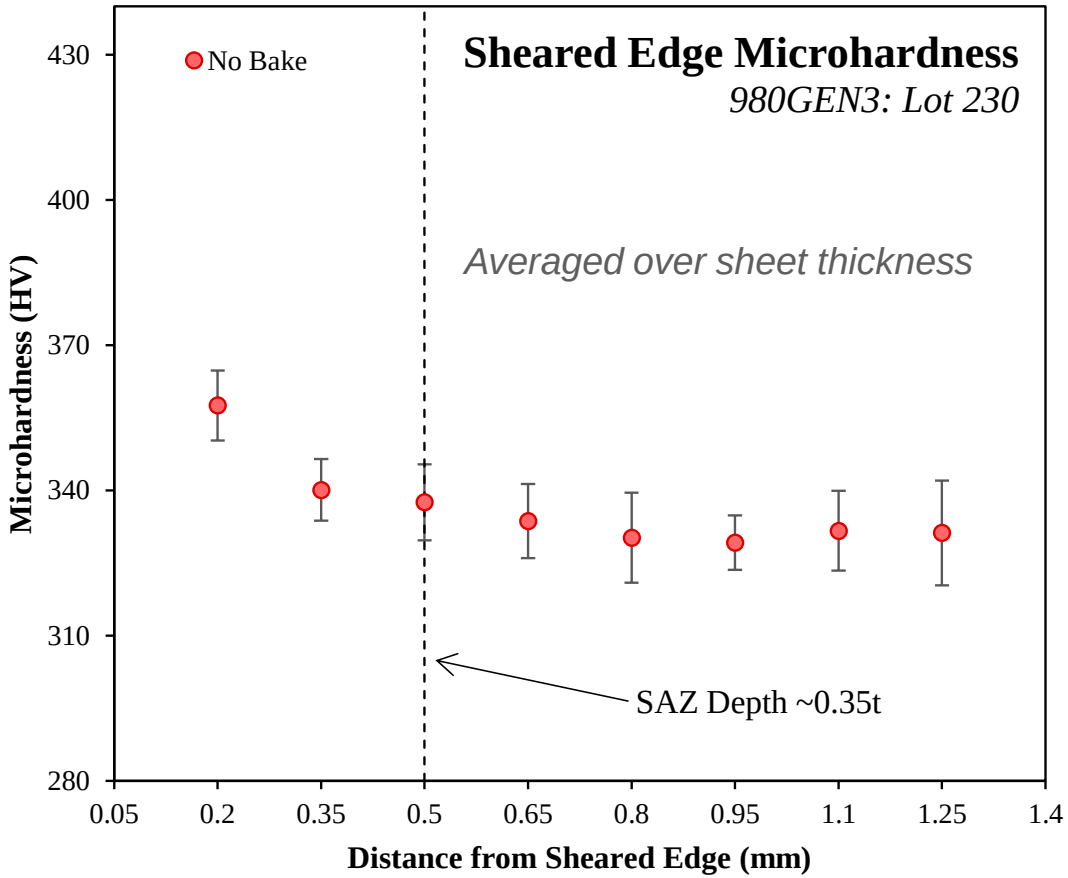
Shear Affected Zone Hardness Maps

- Vickers microhardness maps were created behind the sheared edge to quantify the SAZ depth and severity

Test Parameters

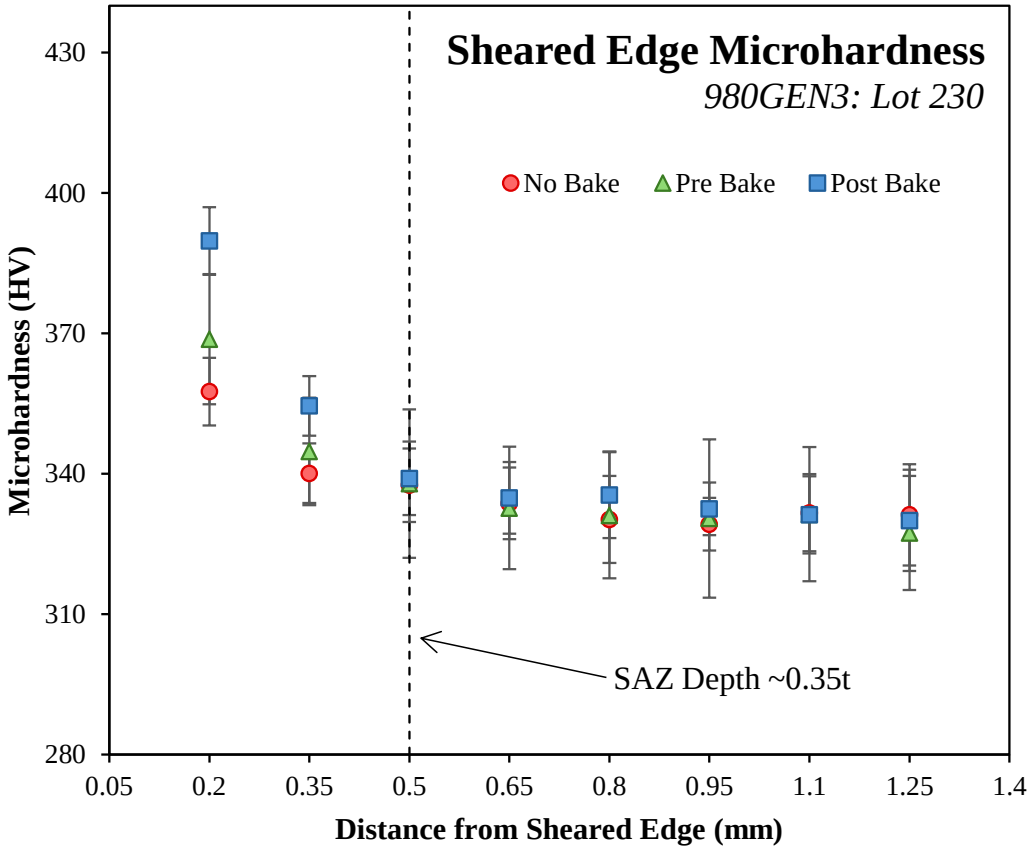
Indenter Load: 500 gf; Dwell Time: 10 s; Indent Pitch: 3x indent width

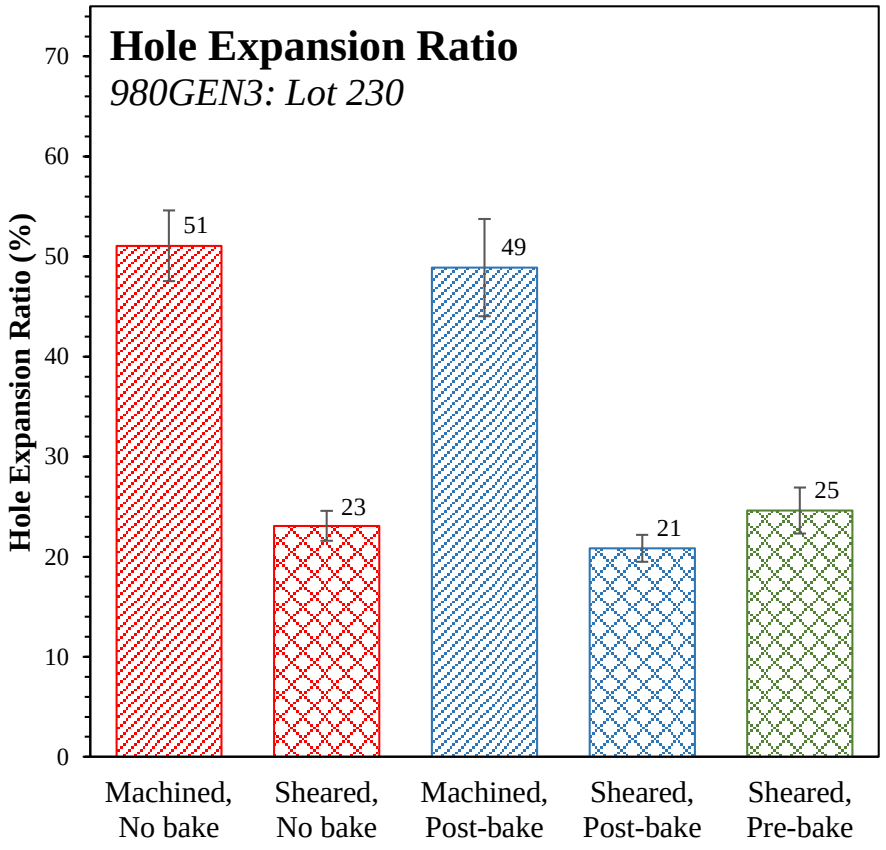




Conical HX: 980GEN3 (Lot #230)

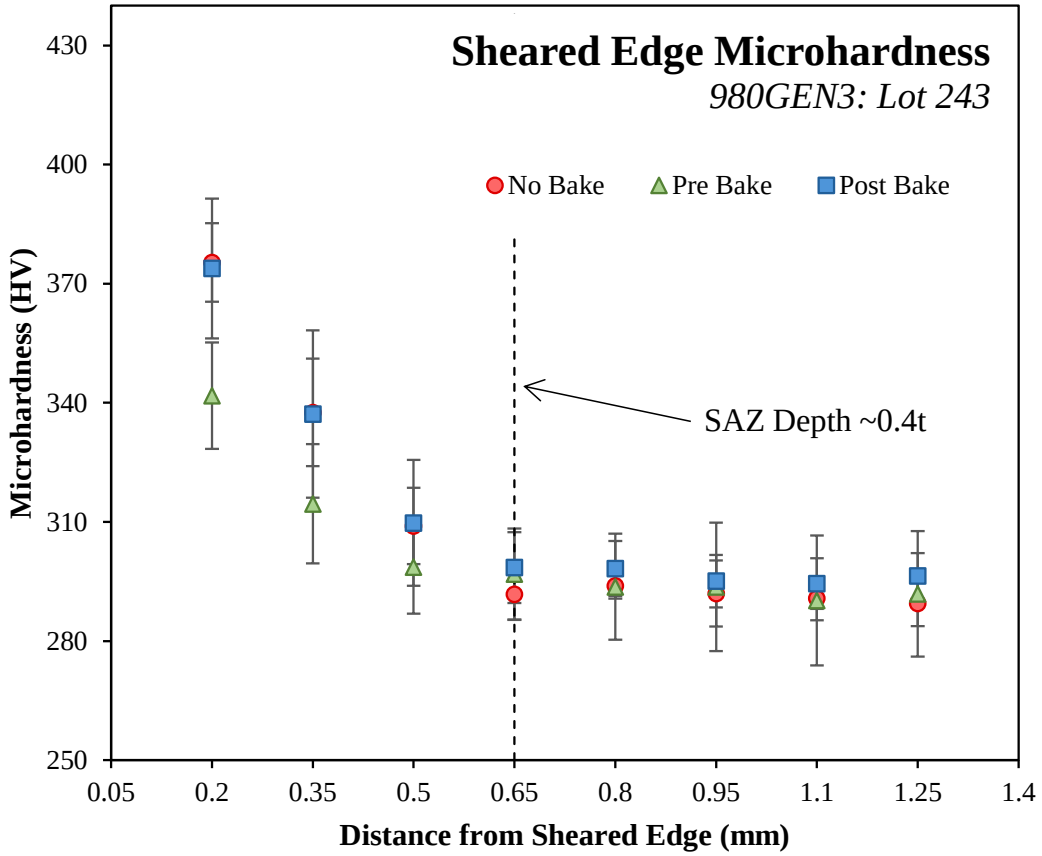
- The paint bake had minimal effect on the SAZ and base material hardness regardless of punch/bake sequence
- Paint bake cycle had a minimal effect on the HER consistent with the hardness trends

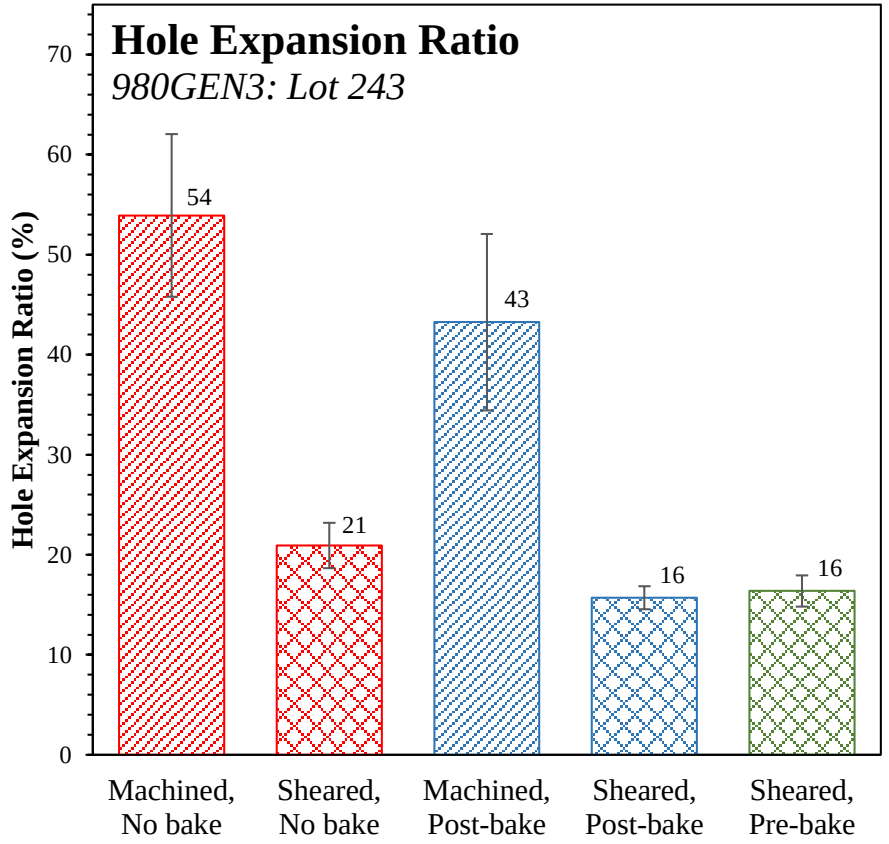




Conical HX: 980GEN3 (Lot #243)

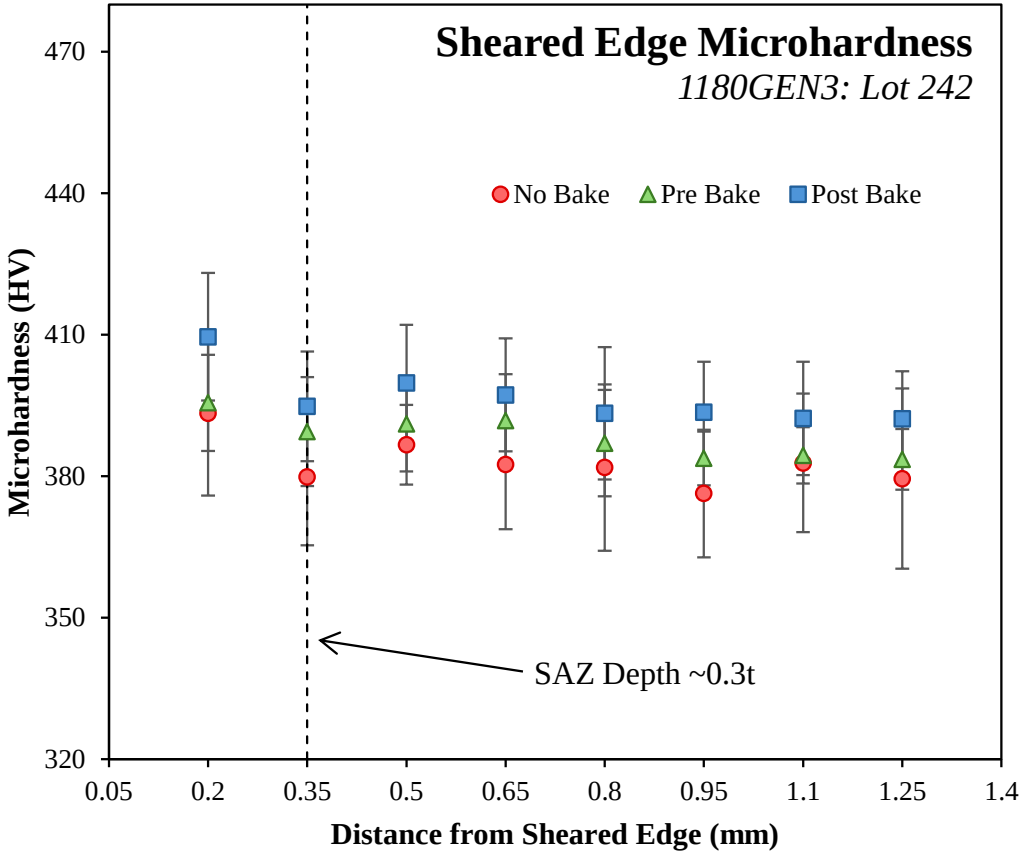
- Minor differences in the SAZ hardness profiles were observed for the different baking sequences
- Paint baking resulted in a minor decrease in the HER for both the sheared and machined edge

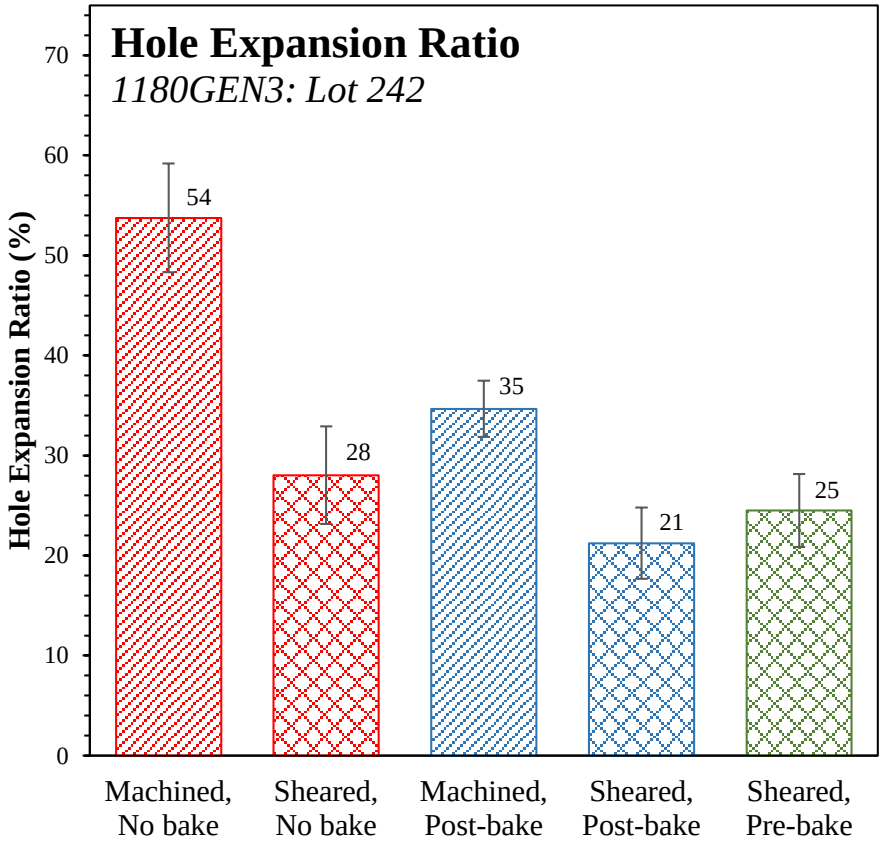




Conical HX: 1180GEN3 (Lot #242)

- The hardness profile behind the sheared edge was statistically similar regardless of paint bake cycle
- The sheared edge HER did not differ significantly for either baking sequence while the machined edge HER decreased significantly after bake hardening





Summary

- The bake hardening indices of the considered GEN3 AHSS grades changed significantly with the magnitude of applied tensile pre-strain
- The BHI determined with the KS-1B method for 2 & 8% pre-strain closely matched the ASTM A653 results for the considered 980GEN3 steels
- For 8% pre-strain, the ASTM A653 method was unable to characterize the BHI of the 1180GEN3 steel due to premature fracture while the KS-1B was successful in determining the BHI
- The sheared edge formability of the considered 3G steels did not appear to be affected by the paint bake cycle regardless of process sequence

For More Information

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