GREAT DESIGNS IN STEEL

# STRAIN AND BAKE PROPERTIES OF UHSS

## PROPOSAL FOR A NEW TEST PROCEDURE

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POSCO
On Behalf of Auto/Steel Partnership

2023

# PROJECT TEAM MEMBERS

GDIS

## Steel Testing & Harmonization Team

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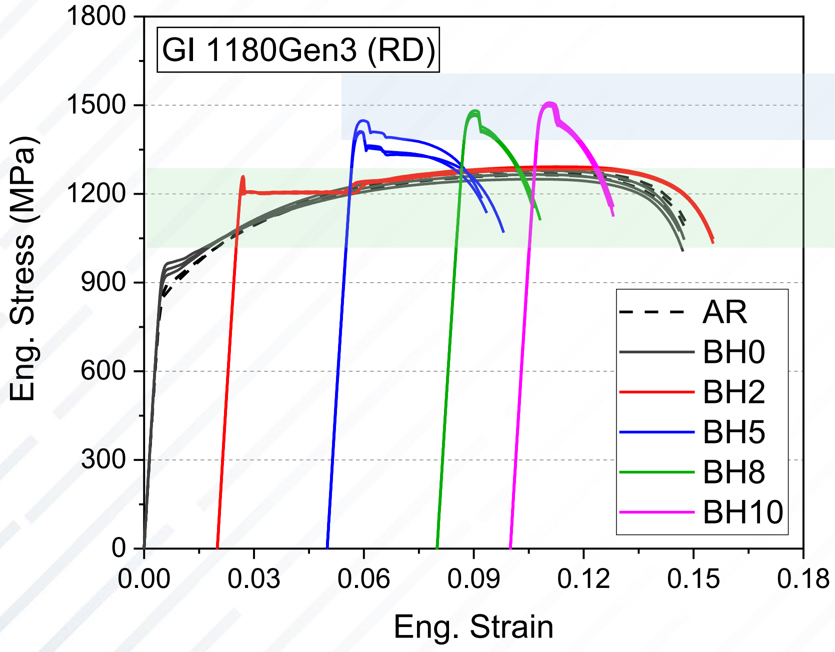
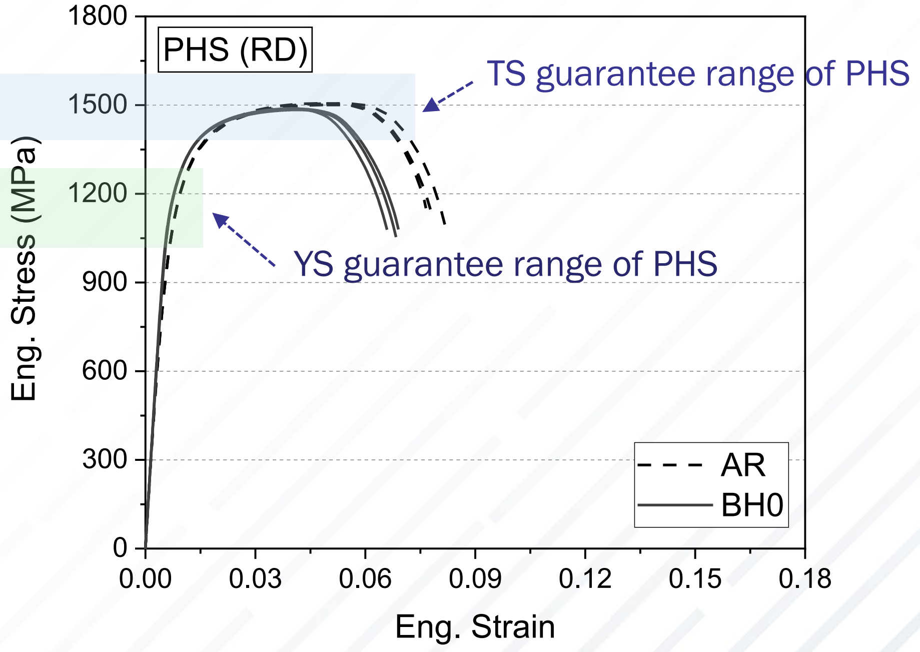
- R. Johnson, Stellantis
- E. McCarty, Auto/Steel Partnership
- E. Rodriguez, TERNIUM
- Dj Zhou, Stellantis

# BACKGROUND

- After pre-straining & baking, most automotive steels show hardening behavior
- Normally, as the pre-strain increases, the BH effect also increases
- This can be a strong point of AHSS, especially for the crash-resistant parts



# STANDARD FOR BHI EVALUATION

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| Standard | ASTM A653/A653M | BS EN 10325:2006 |
|---|---|---|
| Specimen | ASTM E8/E8M | BS EN 10002-1:2001 |
| Loading Dir. | Rolling Dir. | Transverse Dir. |
| Test Methods | ASTM A370 | BS EN 10002-1:2001 |
| Pre-strain | 2 % engineering pre-strain | 2 % platic(permanent) pre-strain |
| Baking Conditions | 170°C for a period of 20 min. | 170°C for a period of 20 min. (± 0.5 min) |
| Cooling Conditions | – | Air cooling to room temp. (23 ± 5 °C) |
| Cross sectional area after BH | The original test specimen cross section | The plastic pre-strained specimen cross section |
| Modulus of elasticity | – | 200 GPa |
| Bake hardening index | $BHI = B - A$ | $BH_2 = R_{eL,t}$ (or $R_{p0.2,t}$) $- R_{p2,r}$ |

※ Notation

*BHI* : Bake hardening index

*A* : Flow stress at 2 % extension under load

*B* : Yield strength [upper yield strength (BU) or lower yield stress (BL)] after baking at 340°F [170°C] for 20 minutes

$R_{p2,r}$ [MPa] : Stress corresponding to a 2 % platic prestrain measured on the test piece

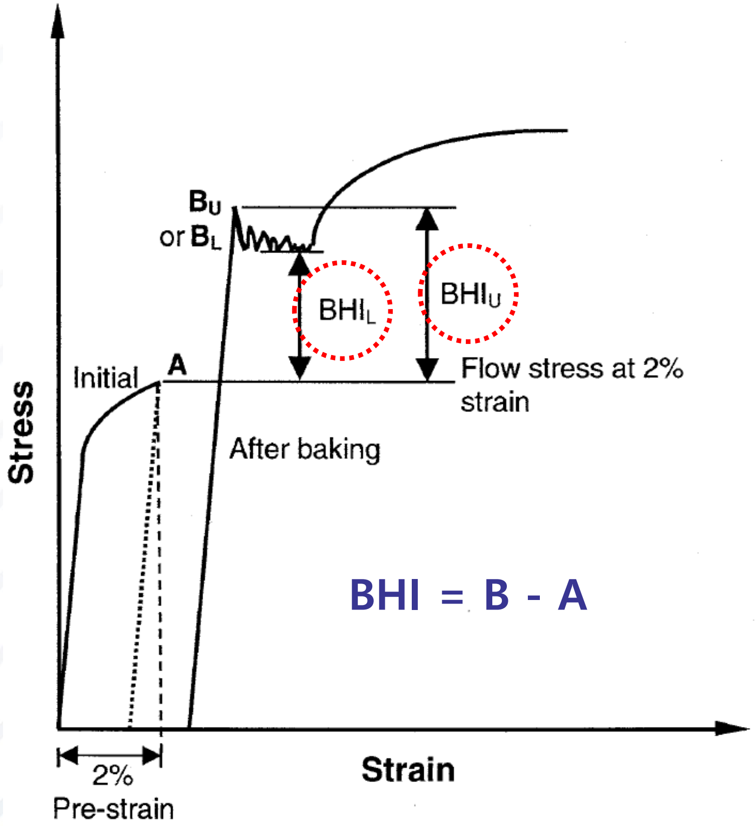
$R_{eL,t}$ [MPa] : Lower yield strength neasured on the test piece initially prestrained at 2 % end then heat treated

$R_{p0.2,t}$ [MPa] : 0.2 % proof strength measured on the test piece initially prestrained at 2 % and then heat treated

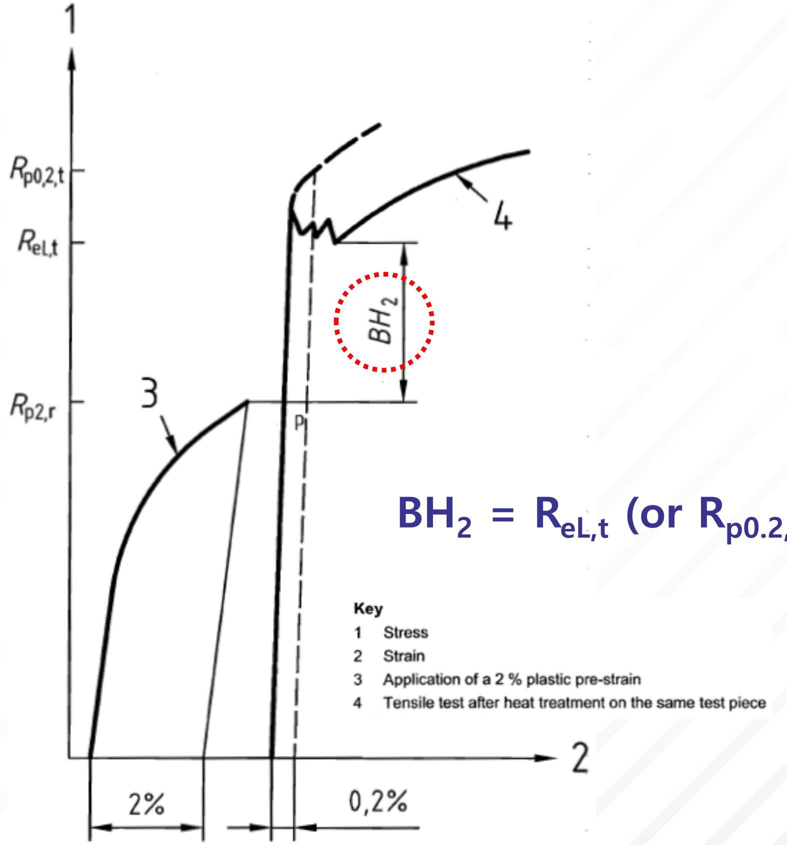
$BH_2$ [MPa] : Bake-Hardening-Index

# STANDARD FOR BHI EVALUATION

## Bake Hardening Index




[ASTM A653]
Representation of Bake Hardening Index (BHI)




[BS EN 10325:2006]
Illustration of the determination of $BH_2$

# ISSUE OF PRESENT TEST PROCEDURE

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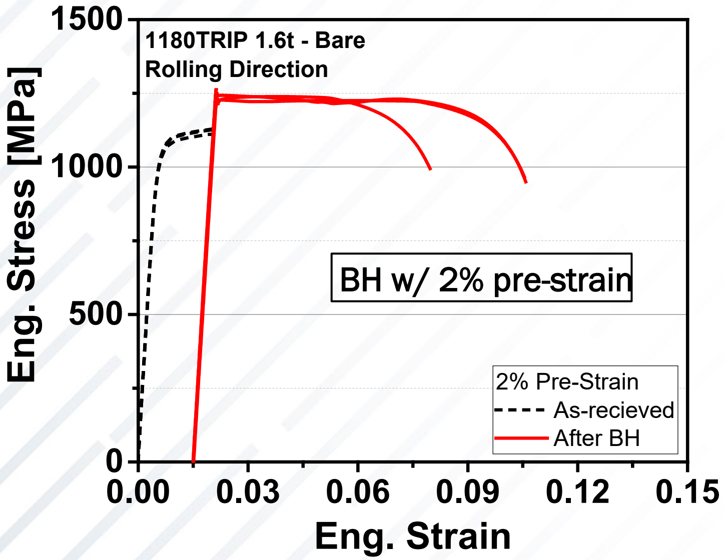
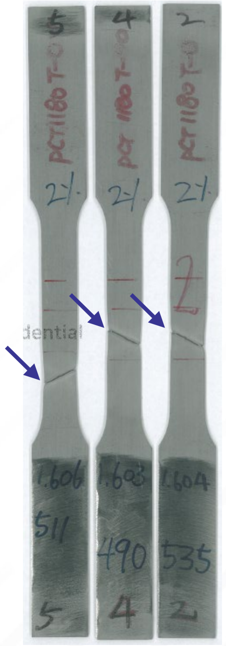
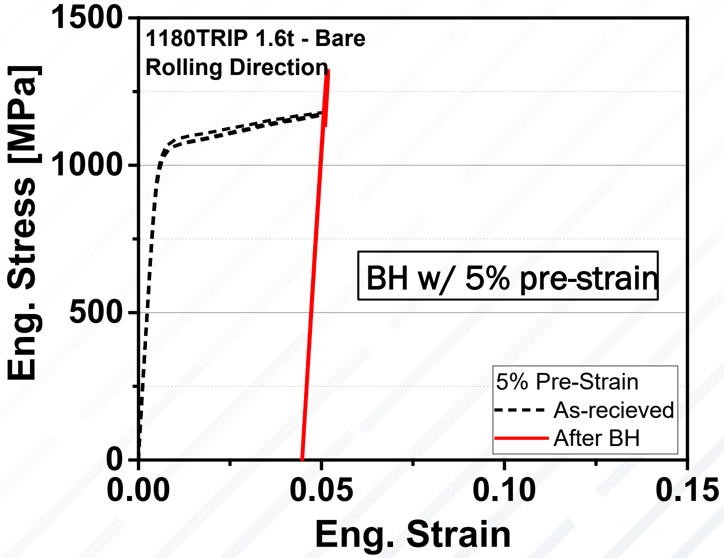
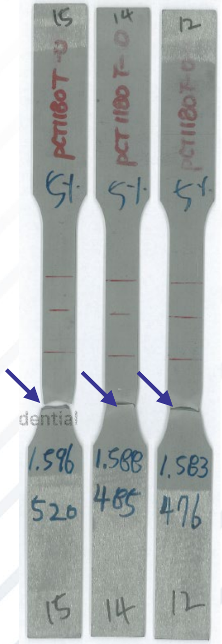
- High TS, low EL materials → unable to get BHI w/ large pre-strain condition
- Failure occurs outside of the gauge section due to a lack of remaining elongation
- Depending on the part design, large strains (5%~) are distributed after forming

**→ Need improved test procedure for large pre-strain cases to evaluate the BH effect**



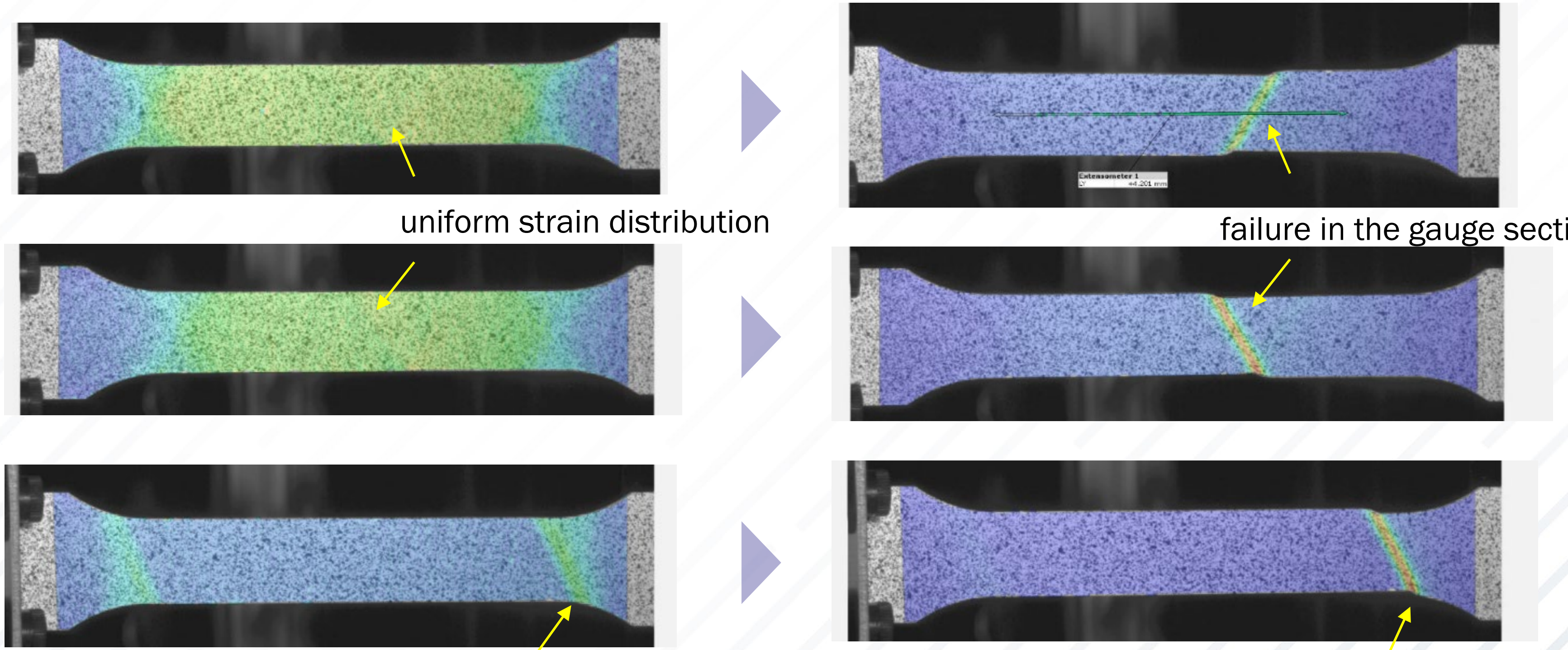


# ISSUE OF PRESENT TEST PROCEDURE

- High TS w/ large pre-strain → BH effect + low ductility → strain can not be propagated to the gauge section → failure occurs outside the gauge section

## e.g. 1500 Mart case



pre-strain : X
baking : X

uniform strain distribution

failure in the gauge section

pre-strain : 2%
baking : X

pre-strain : 2%
baking : O

strain concentrated on the shoulder

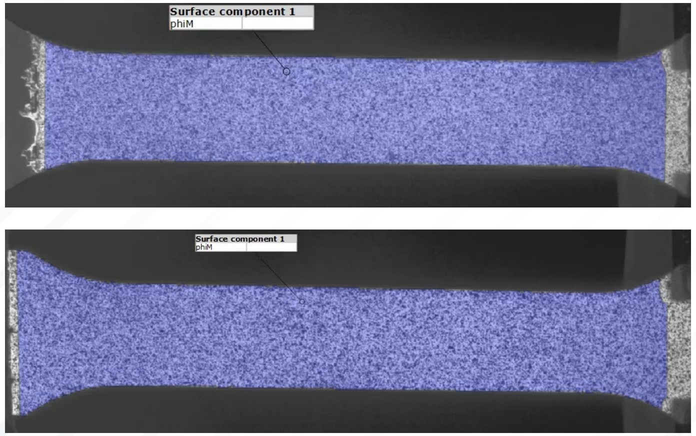
failure outside the gauge section

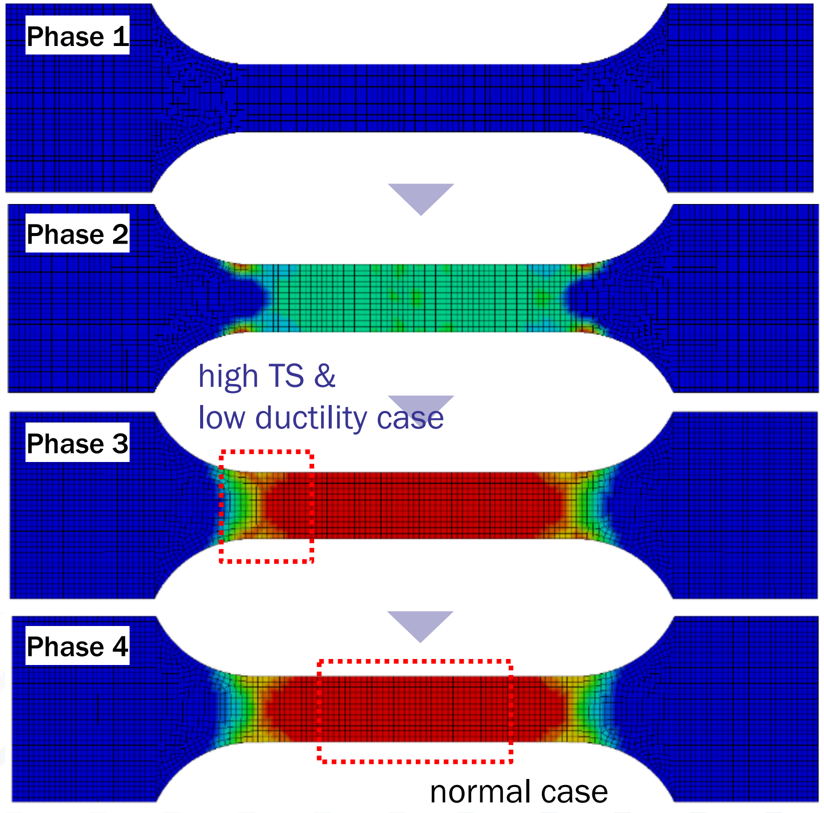
# ISSUE OF PRESENT TEST PROCEDURE

- Strain flow during tensile test
  - Normal case
    after hardening by BH, it progresses to phase 4
    → failure occurs in the gauge section
  - High TS w/ large pre-strain case
    high BH effect + low ductility
    → strain does not propagate to the gauge section
    → failure occurs near the shoulder area

[590DP AR]

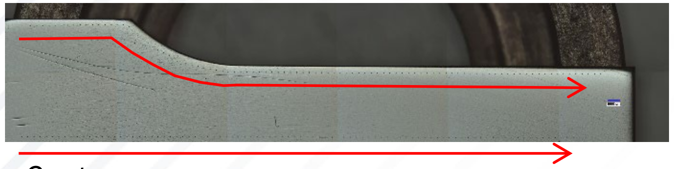
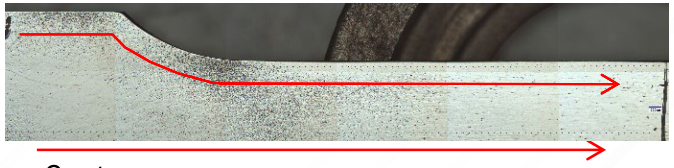
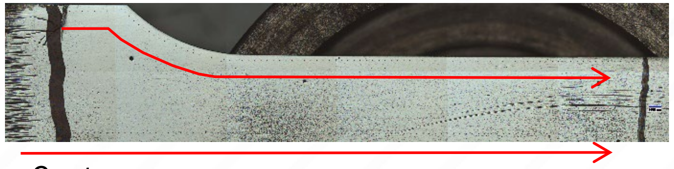
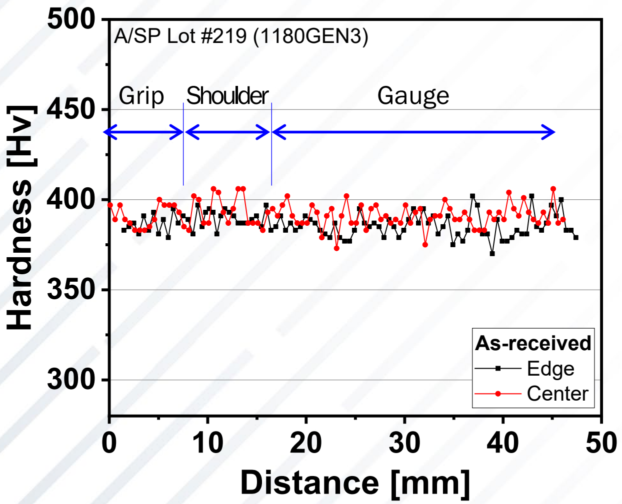
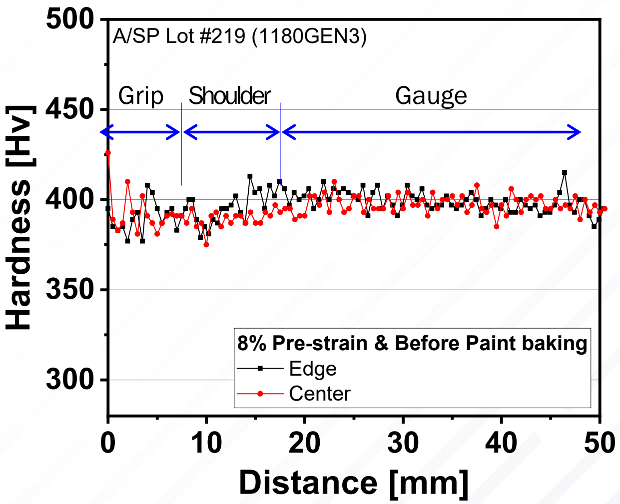
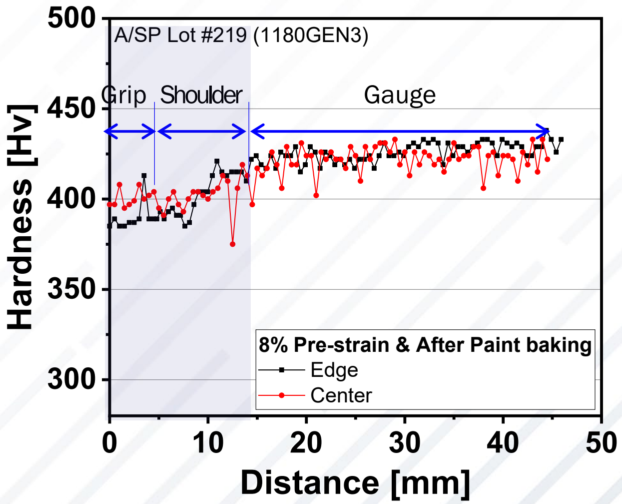
[1180Gen3 BH8]



# ISSUE OF PRESENT TEST PROCEDURE

## Hardness Distribution: 1180Gen3 1.0t case

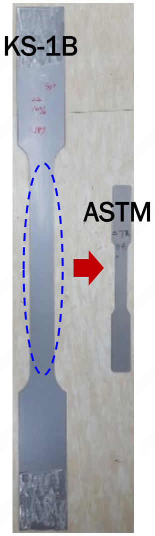
| As-received | 8% Pre-strain & Before Baking | 8% Pre-strain & After Baking |
| --- | --- | --- |
| Edge  Center | Edge  Center | Edge  Center |
| **As-received** | **Work Hardening** | **Work Hardening + Bake Hardening** |
|   |   |   |

# PROPOSAL FOR NEW TEST PROCEDURE

- **As-Is:** pre-strain → BH treatment → re-tension
- **To-Be:** pre-strain large specimen (e.g. KS-1B) → fabricate target specimen (e.g. ASTM E8) from the gauge section → bake treatment → re-tension

**Pre-strain is uniformly distributed in the target specimen**
**→ abnormal failure (due to the non-uniform strain field) can be avoided**

[Pre-straining]




[Specimen fabrication from gauge section]

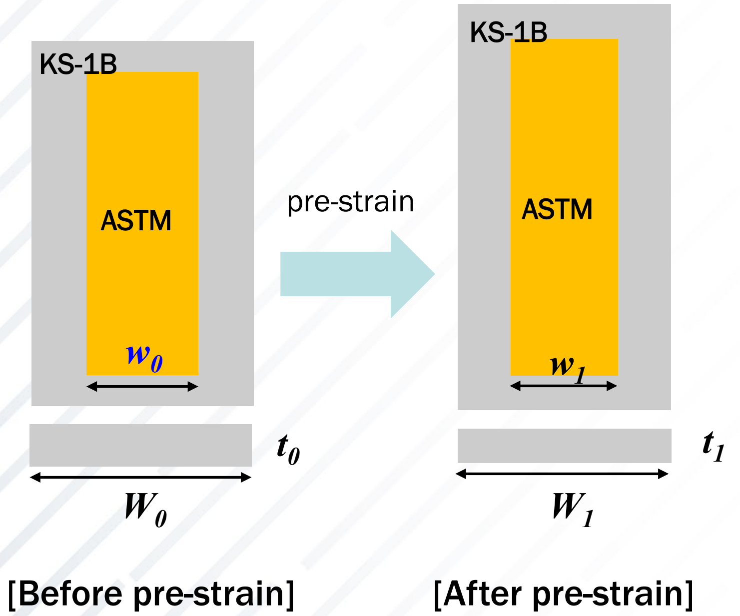
[Bake treatment (20 min @ 170°C)]


[Re-tension]

# PROPOSAL FOR NEW TEST PROCEDURE

## Calculation of Initial Width

The final specimen was machined from the pre-strained specimen
⟶ initial width of the final specimen should be calculated




### 1) Using width change ratio – Simple!

※ Initial width of ASTM specimen $w_0$

$$\frac{W_1}{W_0} = \frac{w_1}{w_0} \rightarrow w_0 = w_1 \times \frac{W_0}{W_1}$$

*where,*
$w_0$ = initial width of ASTM specimen
$W_0$ = width of big specimen
$t_0$ = initial thickness
$w_1$ = width of ASTM specimen after pre-strain
$W_1$ = width of big specimen after pre-strain

∴ Initial area of ASTM specimen :

$$\boldsymbol{A_{initial\_ASTM}} = w_0 \times t_0 = (\boldsymbol{w_1} \times \frac{\boldsymbol{W_0}}{\boldsymbol{W_1}}) \times \boldsymbol{t_0}$$

### 2) Using volumetric plastic strain condition

$$\varepsilon_l^p + \varepsilon_w^p + \varepsilon_t^p = 0$$

$$\varepsilon_w^p = -\varepsilon_l^p - \varepsilon_t^p = -\varepsilon_l + \varepsilon_l^e - \varepsilon_t^p = -\varepsilon_l + \frac{S(1+e_l)}{E} - \ln\left(\frac{t_1}{t_0}\right) = \ln(\frac{w_1}{w_0})$$

$$w_0 = \frac{w_1}{e^{-\varepsilon_l + \varepsilon_l^e - \varepsilon_t^p}} = \frac{w_1}{e^{-\varepsilon_l + \frac{S(1+e_l)}{E} - \ln(\frac{t_1}{t_0})}}$$

# PROPOSAL FOR NEW TEST PROCEDURE

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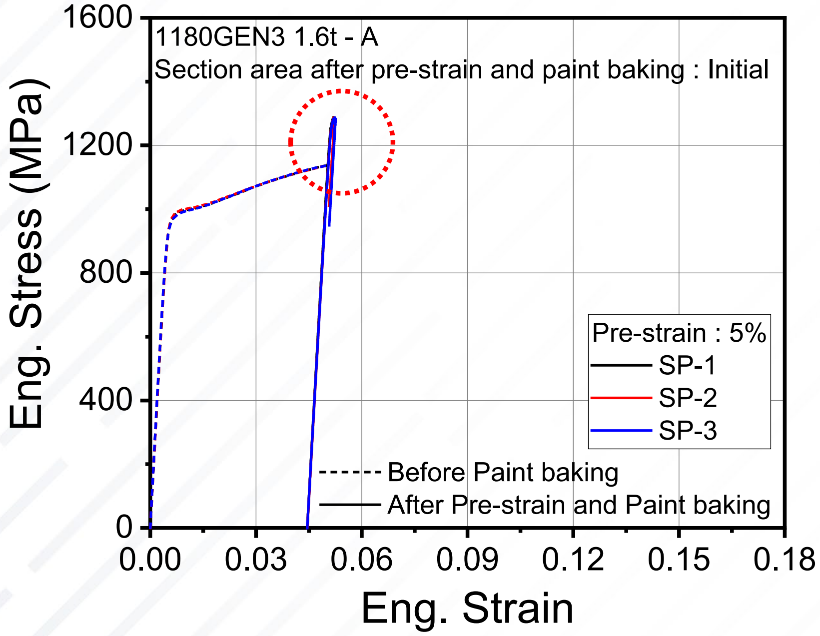
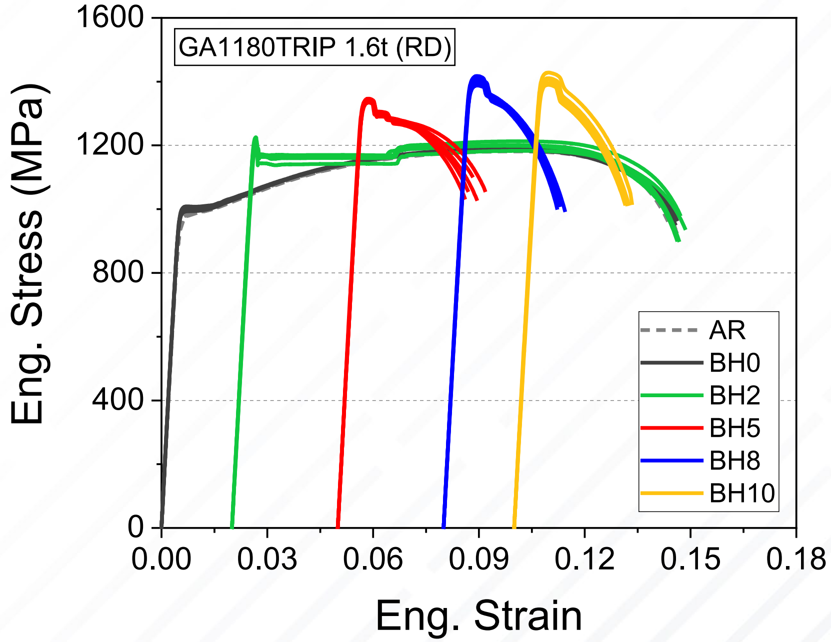
## Present Procedure (ASTM) vs. New Procedure

e.g. GA 1180Gen3 (EL ~15%)




**[Present Procedure]**

BH effect can not be evaluated w/ large pre-strain



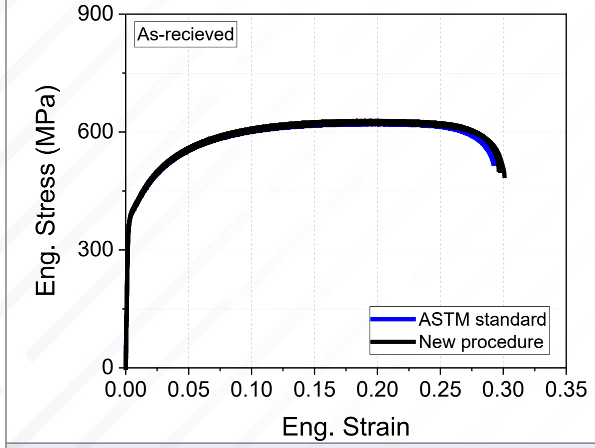

**[New Procedure]**

BH effect can be evaluated w/ large pre-strain

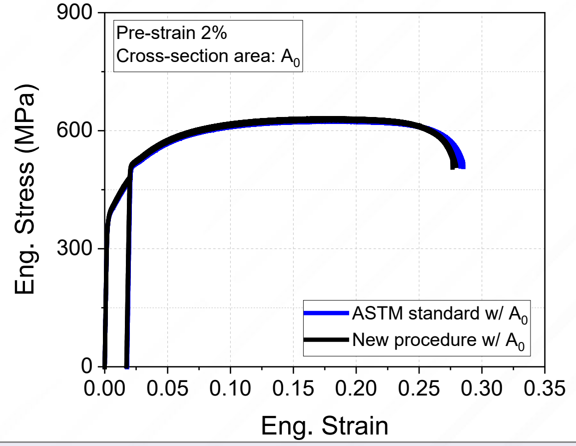
# VALIDATION OF NEW TEST PROCEDURE

Cross-validation using low TS, high EL material (CR590DP 1.4t)

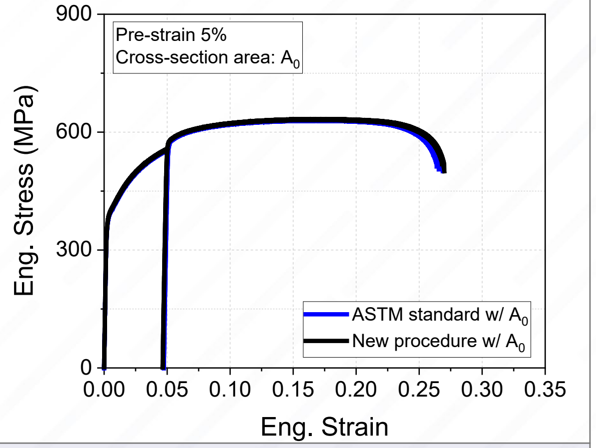
### As-received



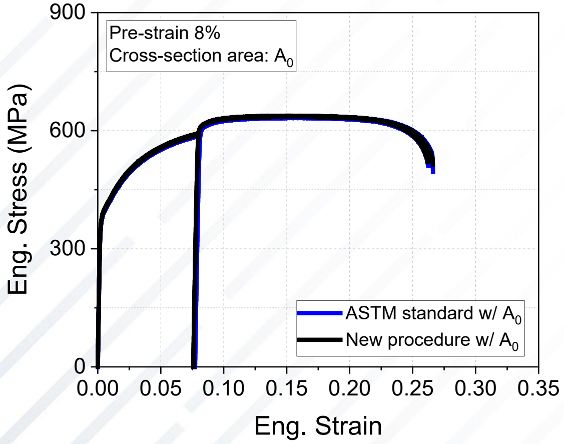

### BH2



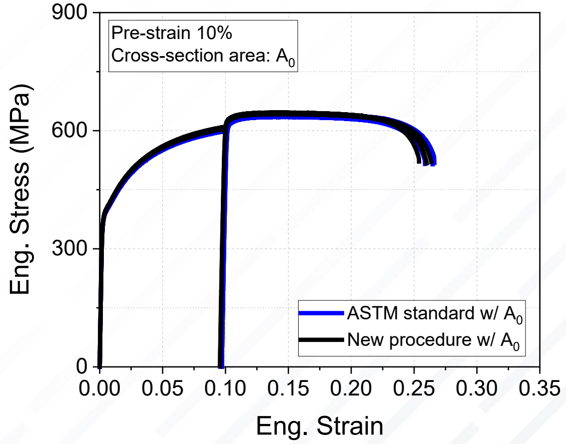

### BH5



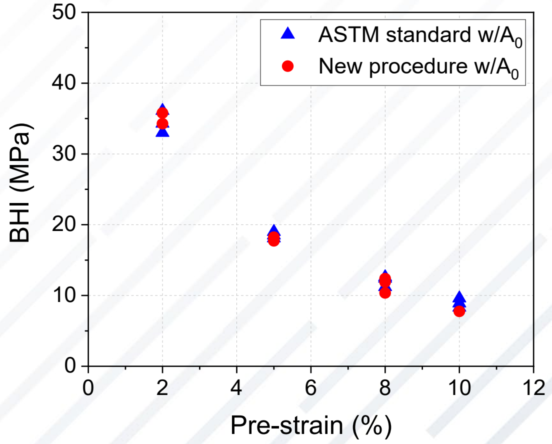

### BH8




### BH10




### BHI



# VALIDATION OF NEW TEST PROCEDURE

## BHI comparison: Present Procedure vs. New Procedure

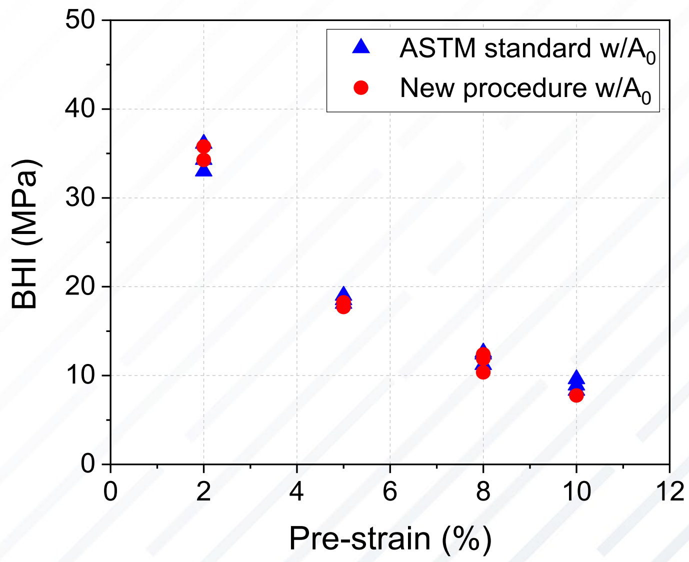
The error of BHI mean value is less than 5% (ASTM standard vs. New procedure)

| | | ASTM Standard | New Procedure |
|---|---|---|---|
| BH2 | 1 | 33 | 35.8 |
| | 2 | 34.3 | 34.7 |
| | 3 | 36.1 | 34.3 |
| | mean | 34.5 (±1.3) | 34.9 (±0.6) |
| BH5 | 1 | 18.1 | 17.7 |
| | 2 | 19 | 18.2 |
| | 3 | 18.5 | 17.3 |
| | mean | 18.5 (±0.4) | 17.7 (±0.4) |
| BH8 | 1 | 12.6 | 12.4 |
| | 2 | 12.4 | 11.9 |
| | 3 | 11.2 | 10.4 |
| | mean | 12.1 (±0.6) | 11.5 (±0.9) |
| BH10 | 1 | 9.6 | 8.0 |
| | 2 | 8.9 | 10.1 |
| | 3 | 8.3 | 7.8 |
| | mean | 8.9 (±0.5) | 8.6 (±1.0) |

(unit : MPa)

| | ASTM | New P | Error (%) |
|---|---|---|---|
| BH2 | 34.5 | 34.9 | 1.2 |
| BH5 | 18.5 | 17.7 | 4.3 |
| BH8 | 12.1 | 11.5 | 5.0 |
| BH10 | 8.9 | 8.6 | 3.4 |

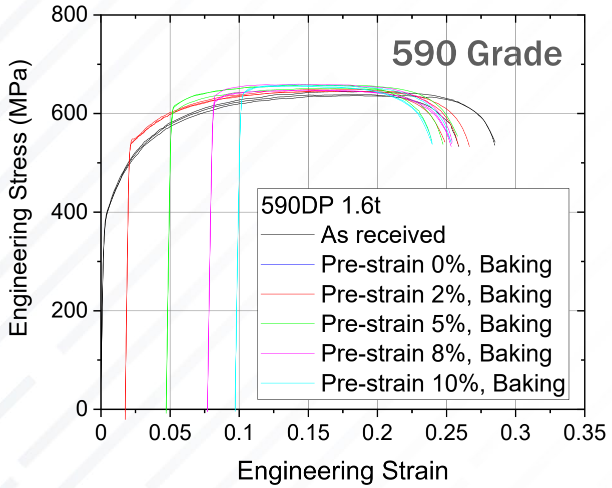
(unit : MPa)

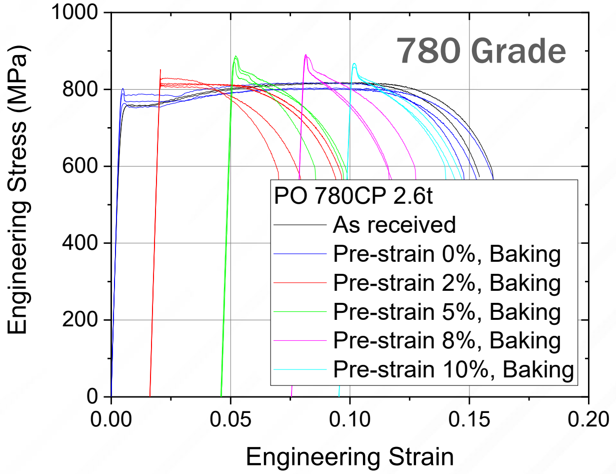


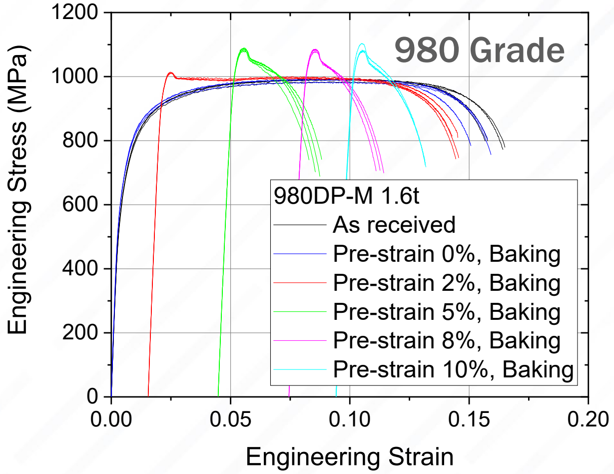
# TEST RESULTS OF VARIOUS MATERIALS

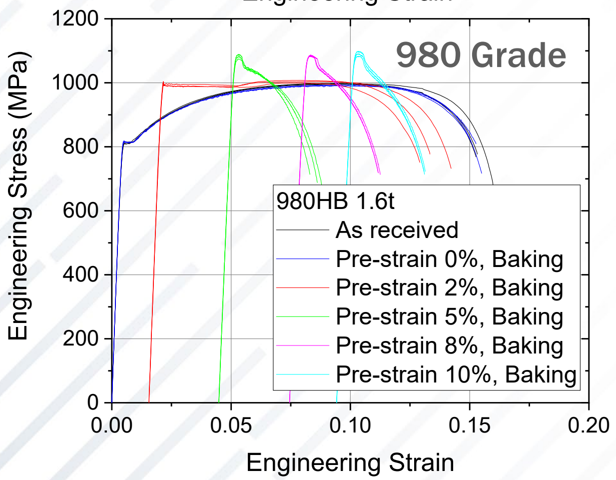
## Test results of 590~1180 grade steels by the new test procedure

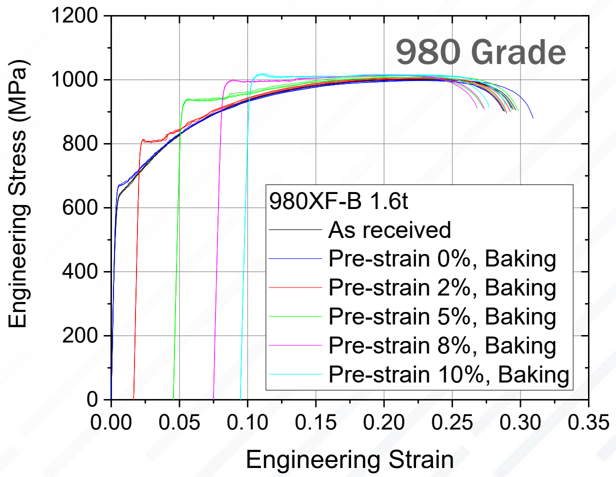
BHI can be determined for large pre-strain conditions compared to the present standard

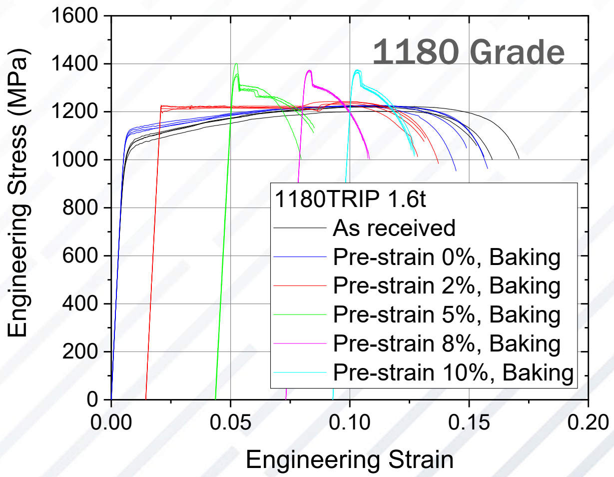


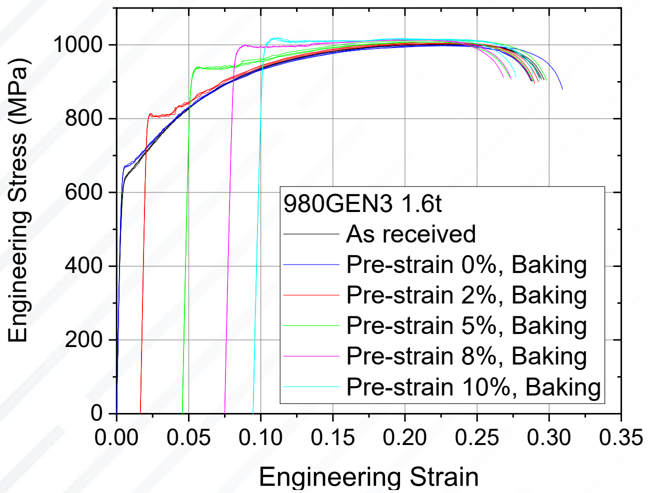
# SUMMARY

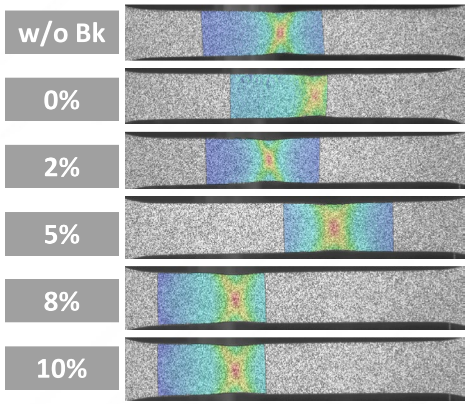
- An improved test method was suggested and validated to evaluate the BH effect of material with large pre-strain
- The new test method enables to obtain more accurate BH properties in large pre-strain conditions compared to the current test standard
- It is especially effective for AHSS because it makes to avoid abnormal failure after the pre-straining & bake hardening
- The accurate BH properties obtained by this procedure allow considering the forming history and baking effect in crash simulation
- Ultimately, it will be possible to design and simulate considering the final properties of each part

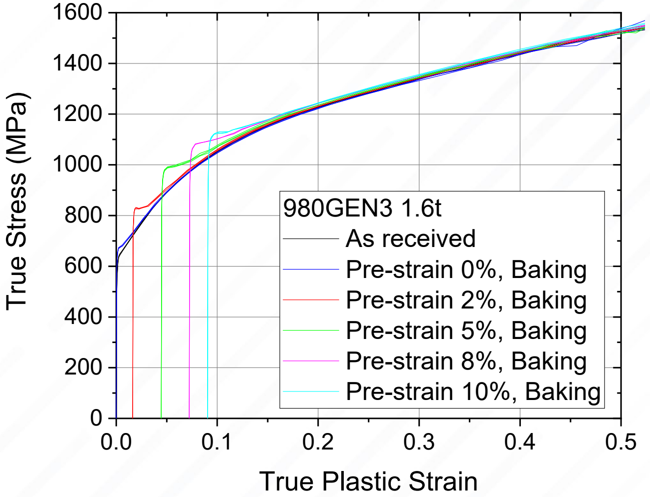
Pick up a copy of the draft test procedure at the Auto/Steel Partnership booth.

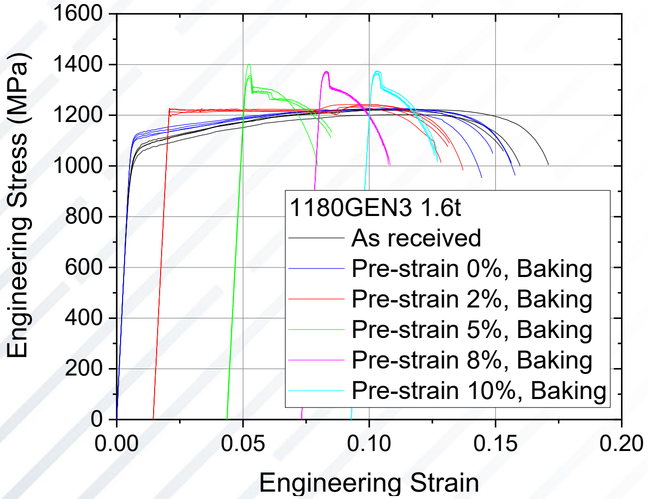
# DISCUSSION

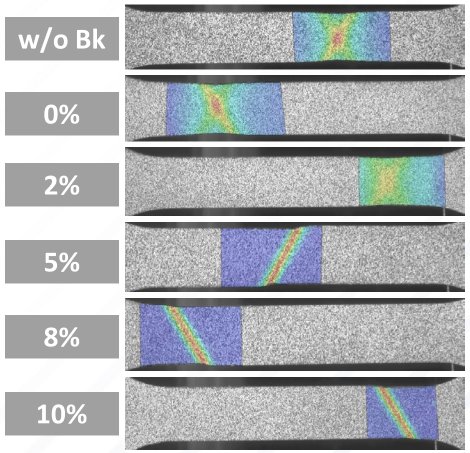
## Calculation of true stress-strain curve (DIC Inverse method, POSCO)

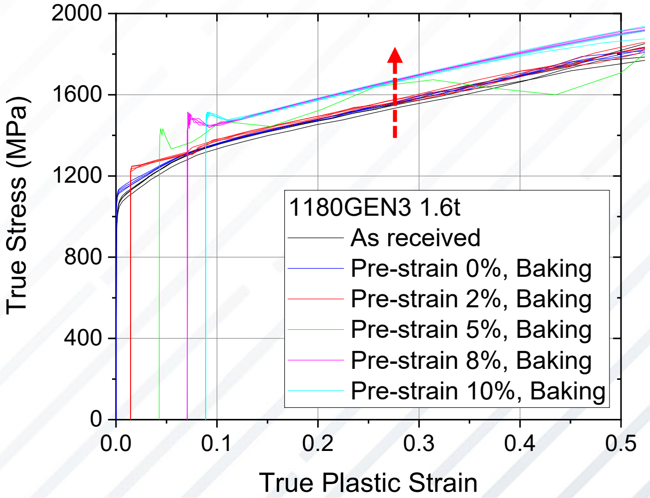


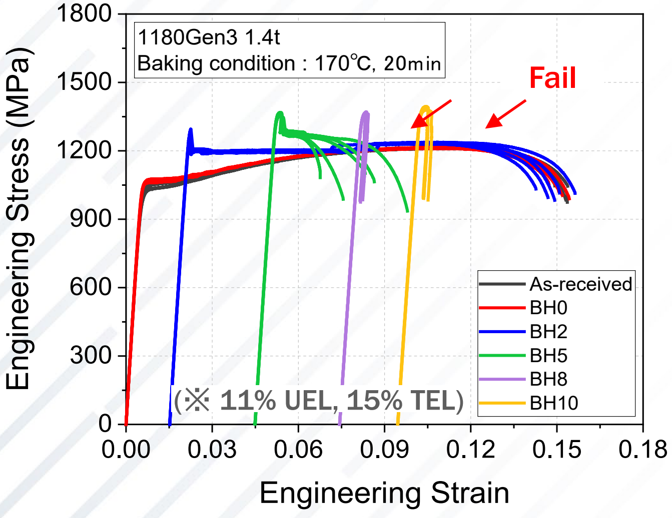
# DISCUSSION

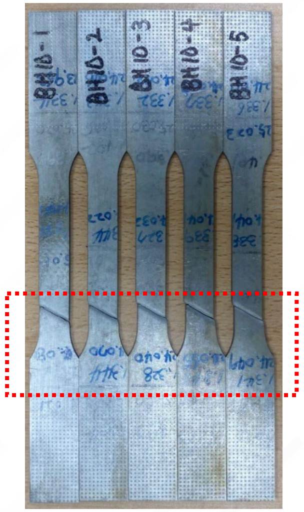
Even if the new procedure is applied, it is difficult to evaluate the BHI w/ pre-strain for some high TS, and low EL materials

– lack of remaining elongation margin after the pre-strain

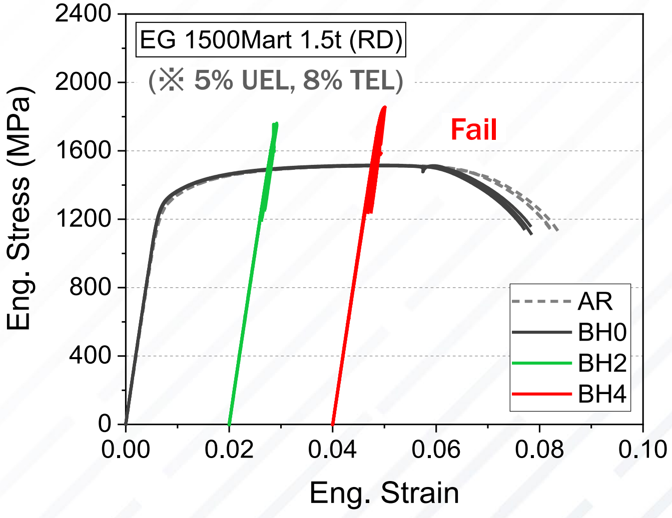
– e.g. 1180Gen3 w/ large pre-strain, 1500Mart cases

**→ Using DIC inverse method, eng. s-s curves can be calculated from true s-s curves**



**[1180Gen3 Case]**

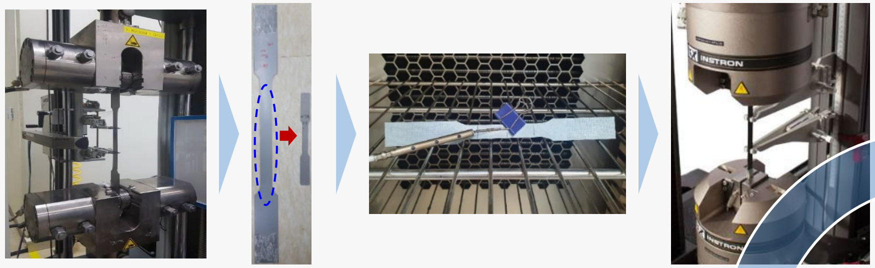



**[1500Mart Case]**

# INSIGHTS & TAKEAWAYS

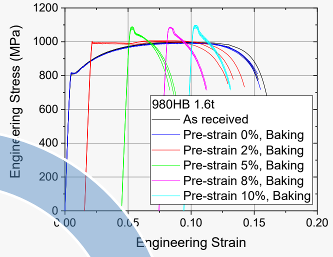
## The new test method can be the basis of simulations considering real-part properties

### Bake Hardening Test
– 2~10% Pre-strain & Bake Treatment

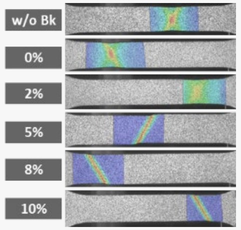



[Pre-tension] [Machining] [Baking] [Re-tension]

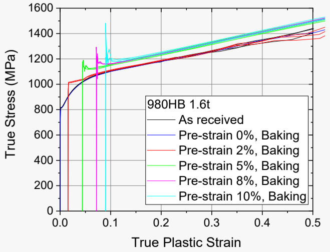
### Stress-Strain Curve Calculation
– DIC Inverse Method




[Eng. S-S Curve]

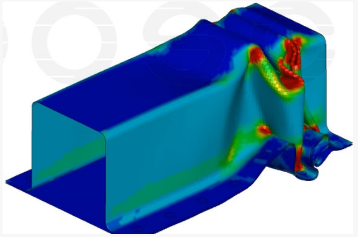



[DIC Image]




[True S-S Curve]

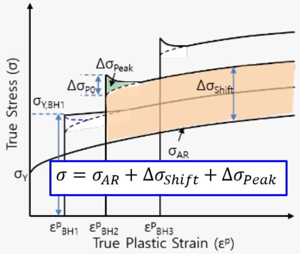
### Simulation Considering Forming & BH
– Work Hardening + Bake Hardening



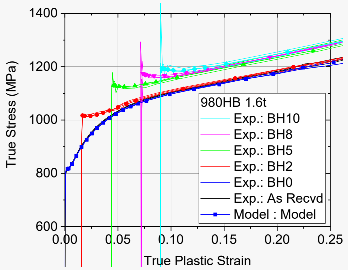
[Hat Crash with 5% Th. reduction]


[Energy Absorption]

### Flow Curve Modeling for BH Property
– Constitutive Eq. for Bake Hardening




[New model for WH and BH]




[Comparison of Exp. and Model]

# FOR MORE INFORMATION

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**More Questions?** Meet the speaker(s) at the Auto/Steel Partnership booth.

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