STRAIN AND BAKE PROPERTIES OF UHSS
PROPOSAL FOR A NEW TEST PROCEDURE

Haea Lee
POSCO
On Behalf of Auto/Steel Partnership
PROJECT TEAM MEMBERS

Steel Testing & Harmonization Team

Project Mentor: Dean Kanelos, Nucor Steel
Project Leads: Jugraj Singh, Stellantis and Derek Bross, Nucor Steel
Project Manager: Jonathan Smith, Auto/Steel Partnership

Project Team Members:
• D. Baker, General Motors
• M. Galant, General Motors
• J. Ha, POSCO America
• J. Herrera, TERNIUM
• R. Johnson, Stellantis
• E. McCarty, Auto/Steel Partnership
• E. Rodríguez, TERNIUM
• Dj Zhou, Stellantis
• 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

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

※ 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
- \( R_{p0.2,t} \) [MPa]: Stress corresponding to a 2 % platic prestrain measured on the test piece
- \( R_{eL,t} \) [MPa]: Lower yield strength measured 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

\[ BHI = B - A \]

Illustration of the determination of \( BH_2 \)

\[ BH_2 = R_{eLt} \text{ (or } R_{p0.2,t}) - R_{p2,r} \]

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

[BS EN 10325:2006]
Illustration of the determination of \( BH_2 \)
ISSUE OF PRESENT TEST PROCEDURE

• 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 $\rightarrow$ BH effect $+$ low ductility $\rightarrow$ strain can not be propagated to the gauge section $\rightarrow$ 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  
  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

<table>
<thead>
<tr>
<th>As-received</th>
<th>8% Pre-strain &amp; Before Baking</th>
<th>8% Pre-strain &amp; After Baking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As-received</td>
<td>Work Hardening</td>
<td>Work Hardening + Bake Hardening</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Grip Shoulder Gauge
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
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!

\[ \frac{W_1}{W_0} = \frac{w_1}{w_0} \rightarrow w_0 = w_1 \times \frac{W_0}{W_1} \]

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

\[ A_{initial\_ASTM} = w_0 \times t_0 = \left( w_1 \times \frac{W_0}{W_1} \right) \times t_0 \]

2) Using volumetric plastic strain condition

\[ \varepsilon^p_l + \varepsilon^p_w + \varepsilon^p_t = 0 \]

\[ \varepsilon^p_w = -\varepsilon^p_l - \varepsilon^e_l = -\varepsilon_l + \varepsilon^e_l - \varepsilon^p_l = -\varepsilon_l + \frac{S(1 + \varepsilon_l)}{E} - \ln \left( \frac{t_1}{t_0} \right) = \ln \left( \frac{w_1}{w_0} \right) \]

\[ w_0 = \frac{w_1}{e^{-\varepsilon_l + \varepsilon^e_l - \varepsilon^p_l}} = \frac{w_1}{e^{-\varepsilon_l + \frac{S(1 + \varepsilon_l)}{E} - \ln \left( \frac{t_1}{t_0} \right)}} \]
PROPOSAL FOR NEW TEST PROCEDURE

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

Eng. Stress (MPa) vs. Eng. Strain for different pre-strain levels (2%, 5%, 8%, 10%) and cross-section areas (A₀). Comparison between ASTM standard and new procedure.
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)

<table>
<thead>
<tr>
<th></th>
<th>ASTM Standard</th>
<th>New Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH2</td>
<td>34.5 (±1.3)</td>
<td>34.9 (±0.6)</td>
</tr>
<tr>
<td>BH5</td>
<td>18.5 (±0.4)</td>
<td>17.7 (±0.4)</td>
</tr>
<tr>
<td>BH8</td>
<td>12.1 (±0.6)</td>
<td>11.5 (±0.9)</td>
</tr>
<tr>
<td>BH10</td>
<td>8.9 (±0.5)</td>
<td>8.6 (±1.0)</td>
</tr>
</tbody>
</table>

(unit : MPa)

<table>
<thead>
<tr>
<th></th>
<th>ASTM</th>
<th>New P</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH2</td>
<td>34.5</td>
<td>34.9</td>
<td>1.2</td>
</tr>
<tr>
<td>BH5</td>
<td>18.5</td>
<td>17.7</td>
<td>4.3</td>
</tr>
<tr>
<td>BH8</td>
<td>12.1</td>
<td>11.5</td>
<td>5.0</td>
</tr>
<tr>
<td>BH10</td>
<td>8.9</td>
<td>8.6</td>
<td>3.4</td>
</tr>
</tbody>
</table>

(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.
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
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] [Retension]

**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

Haea Lee
POSCO
haealee@posco.com

Jiwoong Ha
POSCO
jiwoong.ha@posco.net

Daniel Baker
General Motors Company
dan.baker@gm.com

Jugraj Singh
Stellantis
jugraj.singh@stellantis.com

Jonathan Smith
Auto/Steel Partnership
jsmith@steel.org

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