High Strain Rate Behavior of Advanced High Strength Steels for Automotive Applications

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Purpose of the Work

• Generate high strain rate data for crash energy simulation
• Compare energy absorption capability of AHSS vs. conventional HSS
Steel Grades Tested

- 440W - GA - 1.40mm
- BH300 - GI - 1.43mm
- HSLA350 - GI - 1.60mm
- HSS590 - CR, bare - 1.40mm
- DP600 - GI - 1.25mm
- DP600 - HR - 2.62mm
- DP800 - GA - 1.19mm
Steel Grades Tested

- TRIP590 - EG - 1.45mm
- TRIP600 - CR, bare - 1.56mm
- TRIP780 - CR, bare - 1.56mm
- TRIP980 - CR, bare - 1.47mm
### Steels and Tensile Properties

Table 1 Tensile Properties (As received, ASTM E8, "L" direction)

<table>
<thead>
<tr>
<th>Group 1</th>
<th></th>
<th>Group 2</th>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BH300</td>
<td>440W</td>
<td>HSLA350</td>
<td>HSS590</td>
<td>DP600</td>
<td>DP600</td>
<td>TRIP590</td>
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<tr>
<td>YS (Mpa)</td>
<td>GI</td>
<td>GA</td>
<td>GI</td>
<td>GI</td>
<td>CR</td>
<td>GI</td>
<td>GI</td>
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<tr>
<td>309</td>
<td>326</td>
<td>356</td>
<td>431</td>
<td>412</td>
<td>437</td>
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<td>414</td>
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<tr>
<td>UTS (Mpa)</td>
<td>412</td>
<td>462</td>
<td>441</td>
<td>608</td>
<td>666</td>
<td>616</td>
<td>605</td>
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<tr>
<td>TE (%)</td>
<td>35.8</td>
<td>29.0</td>
<td>28.1</td>
<td>24.5</td>
<td>23.2</td>
<td>28.9</td>
<td>32.0</td>
</tr>
<tr>
<td>UE (%)</td>
<td>20.4</td>
<td>16.3</td>
<td>15.8</td>
<td>15.1</td>
<td>15.3</td>
<td>19.6</td>
<td>22.6</td>
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<tr>
<td>n (6-12)</td>
<td>0.19</td>
<td>0.18</td>
<td>0.13</td>
<td>0.17</td>
<td>0.16</td>
<td>0.22</td>
<td>0.20</td>
</tr>
</tbody>
</table>
# Steels and Tensile Properties

Table 1 Tensile Properties (As received, ASTM E8, "L" direction)

<table>
<thead>
<tr>
<th></th>
<th>Group 3</th>
<th></th>
<th>Group 4</th>
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<tbody>
<tr>
<td></td>
<td>DP800 GA</td>
<td>TRIP780</td>
<td>TRIP980 CR</td>
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<tr>
<td>YS (Mpa)</td>
<td>462</td>
<td>505</td>
<td>663</td>
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<tr>
<td>UTS (Mpa)</td>
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<td>793</td>
<td>984</td>
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<td>TE (%)</td>
<td>17.9</td>
<td>29.4</td>
<td>15.7</td>
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<tr>
<td>UE (%)</td>
<td>12.3</td>
<td>23.9</td>
<td>11.8</td>
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<td>0.13</td>
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Tensile Stress-Strain Curves

Engineering Stress, MPa

Engineering Strain

Group 1

Group 2

HSLA350-GI
BH300-GI
440W-GA
HSS590-CR
DP600-GI
TRIP590-EG
TRIP600-CR
DP600-HR
Tensile Stress-Strain Curves

- Group 3
- Group 4

Engineering Stress, MPa vs. Engineering Strain

- DP800-GA
- TRIP780-CR
- TRIP980-CR
Testing Methods

• Strain rates were selected to be from 0.001 to 1000/s to reflect the strain rates of the steel deformation during crash events
• Equipment were selected as following:
  ➤ Servohydraulic, tensile - 0.001 to 500 sec\(^{-1}\)
  ➤ Tensile Split Hopkinson Bar (SHB) - 500, 1000 sec\(^{-1}\)
Servo-hydraulic Testing System

- Load Measurement
  - Piezo-electric load cell
- Strain Measurement
  - Strain gage, <2%
  - Calculated from displacement, >2%
Split Hopkinson Bar System - Tensile

Incident Bar and Transmitter Bar - 1” in dia. x 8”
Typical Testing Results

440W

Engineering Stress (MPa)

Engineering Strain

- 0.005/s
- 10/s
- 0.1/s
- 100/s
- 500/s
- 1000/s HSB
SHB vs. Servo-hydraulic

**440W**

- **Engineering Strain**
- **Engineering Stress (MPa)**

Graph showing the comparison between 500/s and 500/s HSB conditions.
Stress-Strain Curves at High Strain Rates

BH300 Smoothed

True Stress (MPa)

True Strain

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

0 100 200 300 400 500 600 700

- 0.00S/s
- 0.1/s
- 10/s
- 100/s
- 500/s
- 1000/s SHB

www.autosteel.org
• High strain rate is available for all steel grades tested
• Contact steel company representatives or AISI for data requests
Some Important Results
BH300

Engineering Stress (MPa) vs. Engineering Strain

E = 206,486 MPa

Modulus at High Strain Rates
YS vs. Strain Rate
UTS vs. Strain Rate

![Graph showing the relationship between Tensile Stress (MPa) and Strain Rate (1/s) for various materials. The graph includes lines for BH300, HSLA350, A490, HSS390, TRIP590, DP600, and DP900 materials. Each line represents a different material, with distinct markers and colors for easy identification. The y-axis represents Tensile Stress in MPa, ranging from 200 to 1100, and the x-axis represents Strain Rate in 1/s, ranging from 0.001 to 10000.]
## Increase of UTS with Strain Rate

Increase of UTS per Order of Magnitude Increase in Strain Rate  
(Average from 0.001/s to 1000/s, in MPa)

<table>
<thead>
<tr>
<th>Material</th>
<th>Increase in Strain Rate (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH300</td>
<td>20.3</td>
</tr>
<tr>
<td>440W</td>
<td>22.3</td>
</tr>
<tr>
<td>HSLA350</td>
<td>22.2</td>
</tr>
<tr>
<td>HSS590</td>
<td>23.0</td>
</tr>
<tr>
<td>DP600-GI</td>
<td>24.8</td>
</tr>
<tr>
<td>DP600-HR</td>
<td>19.3</td>
</tr>
<tr>
<td>DP800-GA</td>
<td>18.8</td>
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<tr>
<td>TRIP590-EG</td>
<td>15.3</td>
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<tr>
<td>TRIP600-CR</td>
<td>20.6</td>
</tr>
<tr>
<td>TRIP780-CR</td>
<td>20.3</td>
</tr>
<tr>
<td>TRIP980-CR</td>
<td>17.0</td>
</tr>
<tr>
<td>Average</td>
<td>20.4</td>
</tr>
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</table>
Increase of UTS vs. UTS

The graph shows the increase of UTS (UTS at 0.005/s, MPa) plotted against UTS at 0.005/s, MPa. The data points are indicated by squares, showing the relationship between the two variables.
UE vs. Strain Rate

![Graph showing UE vs. Strain Rate for different steel grades.](image-url)
n-value vs. Strain Rate

- HSLA350
- HSS590
- TRIP590
- DP600
- DP800

Strain Rate (1/s)

n-value

0.001 0.01 0.1 1 10 100 1000

0 0.05 0.1 0.15 0.2 0.25

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Energy Absorption - $E_{\text{necking}}$ and $E_{10\%}$

$E_{\text{necking}} = (YS + UTS) \times UE / 2$

HSLA350
Comparison of $E_{\text{necking}}$ vs. $E_{10\%}$
• Many experimental results show no correlation between $E_{\text{necking}}$ and the energy absorption by a columnar structure during crush

• There is much better relation between $E_{\gamma_0}\%$ and energy absorption by a columnar structure

• $E_{10\%}$ is an arbitrary number. It can be used to compare material performance in a structure in general

• $E_{\text{necking}}$ show the potential capability of energy absorption for a steel
Energy Absorption at 10% Strain

E_{10\%} vs. Strain Rate
$E_{10\%}$ vs. Quasi-static UTS

![Graph showing the relationship between $E_{10\%}$ and quasi-static UTS.](image-url)
Increase of $E_{10\%}$ vs. UTS

Graph showing the relationship between UTS at 0.005/s, MPa, and the increase of $E_{10\%}$, J/mm$^3$. The graph plots UTS values on the x-axis ranging from 200 to 1100 MPa and $E_{10\%}$ values on the y-axis ranging from 0 to 0.004 J/mm$^3$. The data points are scattered, indicating a trend in the relationship between the two variables.
Energy Absorption of HSLA350 vs. AHSS at 500/s, in J/mm³

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>E\textsubscript{necking}</th>
<th>E\textsubscript{necking} Normalized</th>
<th>E\textsubscript{10%}</th>
<th>E\textsubscript{10%} Normalized</th>
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</thead>
<tbody>
<tr>
<td>HSLA350-GI</td>
<td>0.080</td>
<td>1.00</td>
<td>0.0527</td>
<td>1.00</td>
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<tr>
<td>HSS590-CR</td>
<td>0.121</td>
<td>1.51</td>
<td>0.0596</td>
<td>1.13</td>
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<tr>
<td>DP600-GI</td>
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<td>1.86</td>
<td>0.0697</td>
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<td>DP600-HR</td>
<td>0.144</td>
<td>1.80</td>
<td>0.0590</td>
<td>1.12</td>
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<tr>
<td>TRIP590-EG</td>
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<td>2.00</td>
<td>0.0606</td>
<td>1.15</td>
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<td>TRIP600-CR</td>
<td>0.189</td>
<td>2.36</td>
<td>0.0640</td>
<td>1.21</td>
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</table>
• Overall, AHSS exhibited improved crash energy absorption over conventional HSS

• Using $E_{\text{necking}}$, the AHSS in Group 2 exhibit 50-60% higher energy absorption potential for DP steel and over 100% for TRIP steels. Using $E_{10\%}$, the AHSS in Group 2 shows 10 to 30% higher energy absorption.
• The project was funded and completed under the AISI/DOE Technical Road Map Program #0038
• Work was coordinated and results were analyzed by Ispat Inland Research
• Support from AISI AAC member companies is greatly appreciated.