Challenges and Advances in Welding of a New Generation of High Strength Steels

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CAFE Standard: 54.5 MPG in 2025

New CAFE Standards

2012-2016 and 2017-2025

mass reduction
Advanced High Strength Steels

![Diagram of Advanced High Strength Steels](image)

(auto/steel partnership)
Future Steel Vehicle – Phase 2

FSV BEV Steel Types
as % of Body Structure Mass

- HSLA 450, BH 340, 400 - 32.7%
- DP 500, 600 - 11.8%
- DP 800 - 9.5%
- DP 1000 - 10%
- Mild Steels - 2.6%
- TRIP 980 - 9.5%
- TWIP 980 - 2.3%
- CP 1000 - 1470 - 9.3%
- HF 1500 - 11.1%
- MS 1200 - 1.3%

(WorldAutoSteel 2011)
2013 Ford Escape

Material - BIW

- Mild Steel
- BH – HSLA (YS < 300)
- HSLA (YS > 300)
- DP 600
- DP 800
- DP 1000
- Boron - Martensitic

(Morgans, GDIS 2013)
### Future Steel Vehicle – Phase 2, Steel Portfolio

<table>
<thead>
<tr>
<th>Designator</th>
<th>Classification</th>
<th>Designator</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild 140/270</td>
<td>DP 350/600</td>
<td>TRIP 600/980</td>
<td></td>
</tr>
<tr>
<td>BH 210/340</td>
<td>TRIP 350/600</td>
<td>TWIP 500/980</td>
<td></td>
</tr>
<tr>
<td>BH 260/370</td>
<td>SF 570/640</td>
<td>DP 700/1000</td>
<td></td>
</tr>
<tr>
<td>BH 280/400</td>
<td>HSLA 550/650</td>
<td>HSLA 700/780</td>
<td></td>
</tr>
<tr>
<td>IF 260/410</td>
<td>TRIP 400/700</td>
<td>CP 800/1000</td>
<td></td>
</tr>
<tr>
<td>IF 300/420</td>
<td>SF 600/780</td>
<td>MS 950/1200</td>
<td></td>
</tr>
<tr>
<td>DP300/500</td>
<td>CP 500/800</td>
<td>CP 1000/1200</td>
<td></td>
</tr>
<tr>
<td>FB 330/450</td>
<td>DP 500/800</td>
<td>DP 1150/1270</td>
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</tr>
<tr>
<td>HSLA 350/450</td>
<td>TRIP 450/800</td>
<td>MS 1150/1400</td>
<td></td>
</tr>
<tr>
<td>HSLA 420/500</td>
<td>CP 600/900</td>
<td>CP 1050/1470</td>
<td></td>
</tr>
<tr>
<td>FB 450/600</td>
<td>CP 750/900</td>
<td>HF 1050/1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MS 1250/1500</td>
<td></td>
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</table>

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(WorldAutoSteel 2011)
Future Steel Vehicle – Phase 2
Steel Technologies & Joining Technologies

Table 1-4: FSV’s Steel Technologies

<table>
<thead>
<tr>
<th>Steel Technologies</th>
</tr>
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<tbody>
<tr>
<td>Conventional Stamping</td>
</tr>
<tr>
<td>Laser Welded Blank</td>
</tr>
<tr>
<td>Tailor Rolled Blank</td>
</tr>
<tr>
<td>Induction Welded Hydroformed Tubes</td>
</tr>
<tr>
<td>Laser Welded Hydroformed Tubes</td>
</tr>
<tr>
<td>Tailor Rolled Hydroformed Tubes</td>
</tr>
<tr>
<td>Hot Stamping (Direct &amp; In-Direct)</td>
</tr>
<tr>
<td>Laser Welded Blank Quench Steel</td>
</tr>
<tr>
<td>Tailor Rolled Blank Quench Steel</td>
</tr>
<tr>
<td>Rollforming</td>
</tr>
<tr>
<td>Laser Welded Coil Rollformed</td>
</tr>
<tr>
<td>Tailor Rolled Blank Rollformed</td>
</tr>
<tr>
<td>Rollform with Quench</td>
</tr>
<tr>
<td>Multi-Walled Hydroformed Tubes</td>
</tr>
<tr>
<td>Multi-Walled Tubes</td>
</tr>
<tr>
<td>Laser Welded Finalised Tubes</td>
</tr>
<tr>
<td>Laser Welded Tube Profiled Sections</td>
</tr>
</tbody>
</table>

Table 3-9: FSV Joining Technologies Summary

<table>
<thead>
<tr>
<th>Joining Technologies</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of spot welds</td>
<td>1023</td>
</tr>
<tr>
<td>Length of laser welds</td>
<td>83.6 m</td>
</tr>
<tr>
<td>Length of laser braze</td>
<td>3.4 m</td>
</tr>
<tr>
<td>Length of hem flange</td>
<td>2 m</td>
</tr>
<tr>
<td>Length of hem adhesive</td>
<td>2 m</td>
</tr>
<tr>
<td>Length of structural adhesive</td>
<td>9.8 m</td>
</tr>
<tr>
<td>Length of anti-flutter adhesive</td>
<td>6.5 m</td>
</tr>
</tbody>
</table>
Advanced High Strength Steels

Future Opportunity
Third Generation AHSS
AHSS Developments

- Enhanced Dual-Phase (DP)
- Modified TRIP
- Ultrafine Bainite
- Quenching and Partitioning (Q&P)
- Lower Mn TRIP/TWIP
- Higher Mn TRIP

(Branagan, GDIS 2013)
3rd Generation AHSS Future Opportunity

Tensile Strength (MPa) vs. Elongation (%)

- NanoSteel (NS)
- IF
- IF-HS
- Mild
- ISO
- BH
- CMn
- TRIP
- HSLA
- DP, CP
- MA
- L-IP
- AUST. SS
- TWIP

(Branagan, GDIS 2013)
Growth of AHSS in Automotive Architecture

Growth of AHSS

Source: Ducker Worldwide
Advanced High Strength Steels

Chemical composition + steel processing

↓

desired microstructure

↓

desired material properties
Advanced High Strength Steels

- Dual Phase – ferrite+martensite
- Ferritic-Bainitic/Stretch Form - fine f + bainite
- Complex Phase – f/b matrix + m, austenite, pearlite
- Martensitic
- TRIP (Transformation - Induced Plasticity)
  - C, Al/Si; f + a ($\geq 5\%$) (+ m + b)
- Hot Formed (Press Hardenable, Hot Stamped)
  - C, B; martensitic after heat treatment
- TWIP (Twinning – Induced Plasticity) – C, $\sim 20\%$ Mn; austenitic
- Quench & Partition – C, Mn or Al/Si; f + m + a
- Nanosteel – extremely fine grains, unique compositions
Principal Types of Resistance Welds

- Spot Weld
- Projection Weld
- Seam Weld
- High-Frequency Weld
- Butt Weld
- Flash Weld
Resistance Spot Welding AHSS

- Increased electrical resistivity
- **Heat balance**
  - As strength ↑, composition ↑, and thickness ↑, more pronounced changes in welding behavior occur.
- Increased force and longer welds times typical
- Increased weld hardness
- Weld fracture modes
- Pulsation and/or post weld tempering
- Joint fatigue, fracture, stress concentration, crash integrity, modeling
Cooling Rate as a Function of Gauge, Steel and Welding Process

- Implied cooling rates for different processes
  - Closed-form models
- Critical cooling rates
  - Martensite transformation
  - Microstructural modeling
- Hardenability of AHSS
- Martensite formation resulting from welding
- Hardness of martensite/effective fracture toughness
Microstructure of a resistance spot weld on 0.8-mm IF (0.007% C, 0.14% Mn) steel

- 0.8-mm IF steel
  - Hardness profile indicates non-martensitic decomposition
  - Better fit with model by Li
RSW Microstructure and Hardness

Microstructure of a resistance spot weld on 1.6-mm DP980 (0.15% C, 1.4% Mn) steel

- 1.6-mm DP 980
  - “Top Hat” hardness profile
  - Indicative of isothermal transformation
  - Martensitic reaction predicted by either model
RSW Hardness Profiles for Dual Phase Steels

(Tumuluru, SMWC II, 2006)
## Fracture Modes for RSW (AWS D8 and A/SP)

### Peel and Chisel Criteria - Failure Modes

<table>
<thead>
<tr>
<th>Fracture Mode</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Button pulled without evidence of interfacial fracture</td>
<td></td>
</tr>
<tr>
<td>Partial thickness fracture with button pull</td>
<td></td>
</tr>
<tr>
<td>Partial thickness fracture with no button pull</td>
<td></td>
</tr>
<tr>
<td>Interfacial fracture with button pull and partial thickness fracture</td>
<td></td>
</tr>
<tr>
<td>Interfacial fracture with partial thickness fracture</td>
<td></td>
</tr>
<tr>
<td>Full interfacial Fracture</td>
<td></td>
</tr>
<tr>
<td>No fusion</td>
<td></td>
</tr>
</tbody>
</table>

![Image of Peel and Chisel test with various fracture modes](image-url)
Potential Solutions to Improving Peel Behavior of AHSS Spot Welds

- **Passive methods**
  - Long weld time
  - Pre/post pulsing
  - Short hold time
  - Increased minimum weld size

- **Active methods**
  - Weld and temper
  - Dilution (patented)
Force and Current Profiles for RSW of AHSS

Spot Welding of Galvanized TRIP 400/700
parameters settings, schematic

V1
- 4kN
- Squeeze time 50 cyc.
- Hold time 15 cyc.
- Weld time 12 cyc.
- Conventional

V2
- 4kN
- Squeeze time 50 cyc.
- Pause 2 cyc.
- Hold time 15 cyc.
- Weld time 9 cyc.

V3
- 4kN
- Squeeze time 50 cyc.
- Hold time 15 cyc.
- Weld time 12 cyc.
- 5kN

V4
- 4kN
- Squeeze time 50 cyc.
- Hold time 15 cyc.
- Cooling time $t_1$
- $t_2 = 1.2 \times t_1$
- Weld time 12 cyc.
- Post weld heat treatment 20 cyc.

(WorldAutoSteel 2009)
RSW Current Range Behavior of Dual Phase Steels

1.6 mm HDGA DP steels

(Tumuluru, 2006)
TSS & CTS Behavior of Spot Weld Joints

(Matsushita, JFE Tech. Report, 2013)
Tensile Shear Strength of High-Strength Steels vs. Thickness

![Graph showing the relationship between tensile shear strength and thickness for different materials.]
Static-Cross Tension Strength of HSS vs. Carbon, Thickness

![Graph showing weld strength vs. C content and cross tension strength vs. thickness.](image-url)
Effect of Fracture Appearance on Absorbed Energy

<table>
<thead>
<tr>
<th>Fracture Appearance Rating</th>
<th>Energy (in-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>&gt;10%</td>
<td>20%</td>
</tr>
<tr>
<td>&gt;30%</td>
<td>30%</td>
</tr>
<tr>
<td>&gt;50%</td>
<td>40%</td>
</tr>
</tbody>
</table>

**Tensile Shear Test**

**Dynamic Cross Tension Test**
Effect of Steel Strength on Peak Load in Weld Cross-Tension Impact Behavior of RSW
Effect of Steel Strength on Absorbed Energy in Weld Cross-Tension Impact Behavior of RSW
General Characteristics of In-Situ Tempering of Spot Welds

- Overall J-shaped curve
- Two distinct regions
  - Steady state
  - Transient
  - (Short time, high current)
- Correlations between hardness and weld failure morphology
Spike Temper Characteristics of 1.0mm DP780 HDG

Temper Time (Cycles)

Temper Current (% Expulsion Limit)

Distance, m

HV (1Kg, 15sec.)

28 Rc
30
32
34
36
38
Effect of In-Process Tempering on TRIP 700 Spot Welds

Fig. 7. Appearance of welds subjected to peel tests in 1.05mm EZ coated TRIP700 welded with 4kN electrode force, 12 cycles weld time, 6.6kA welding current and 10 cycles hold time (scale in mm):

a) Without in-process tempering - showing mainly interface fracture, cracked on testing

b) With in-process tempering of 20 cycles cool time, 4.9kA tempering current and 25 cycles temper time - showing complete plug fracture

(Shi, TWI 2005)
Tensile Shear Fatigue Behavior of Steel Spot Welds

[Graph showing Delta-K (MPa*m^1/2) vs. Cycles to Failure for different steel types and weld parameters.]
Fatigue Performance of AHSS Spot Welds – Microstructural Effects

- Weld cracks within weld indentation area had no effect on fatigue life.
- FGHAZ orientation had a large effect on fatigue performance.
Fusion Zone Hardness in AHSS Spot Welds

\[ CE_Y = C + A(C) \cdot \left\{ \frac{5B + \frac{Si}{24} + \frac{Mn}{6}}{\frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr + Mo + Nb + V}{5}} \right\} \]

where

\[ A(C) = 0.75 - 0.25 \tan h \{20(C - 0.12)\} \]

Yurioka CE

(Khan, Mat. Trans., 2008)
PREDICTION OF POST WELD HARDNESS OF ADVANCED HIGH STRENGTH STEELS FOR AUTOMOTIVE APPLICATION USING A DEDICATED CARBON EQUIVALENT NUMBER

a) Eq. (10) for RSW with forced cooling and experimental results

b) Eq. (11) for RSW without forced cooling and experimental results

(den Uijl, WiW 2008)
Resistance Butt Welding of AHSS

- Steel grades commonly resistance butt welded
  - 600 MPa
  - 800 MPa
  - 1000 MPa
- Process requirements
  - Short cycle times
  - High currents
  - Fast reacting force systems
- Metallurgical response
  - Constrained heat affected zones
  - Minimized extent of HAZ softening
  - Mechanical constraint to provide properties
- Effect of parent material strength
- Typical scrap levels today for AHSS: 0.2 – 2%

Developing temperature distribution during resistance butt welding mild steel

Distribution of effective strain through a cross section of a resistance butt welded mild steel
Weld hardness of a high frequency weld in a DP 280/600 tube.
Hardness variation across induction welds for various types of steel
Flash-Butt Welding of High Strength Steels

Fig. 1  Effect of preheating and upsetting length on weld crack length (Steel A)

X80 steel, 12mm
Increasing upset length and preheating reduced weld defects.

(Ichiyama, Nippon Steel Tech. Report, 01/2007)
Flash-Butt Welding of High Strength Steels

980HT steel, 13mm
Increasing upset current (and hence upsetting displacement) improved weld toughness by removal of bondline oxides and steel inclusions.

(Ichiyama, Nippon Steel Tech. Report, 01/2007)
Higher than Expected Strengths from Dissimilar Configuration
Advanced High Strength Steel Spot Welds

Example of dissimilar configuration with CTS matching the “minimum rule”

Cross-tension strength for TRIP800 configurations, showing “positive deviation”

For AHSS/AHSS configurations, cross-tension strength is always higher than the strength expected from the lower strength material in the joint.

(Biro, SMWC XV, 2012)
Resistance Spot Welding of 1.4 mm DP980 & TWIP980 Steels

Table 1  Chemical composition (mass%).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Etc.</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP980</td>
<td>0.115</td>
<td>0.35</td>
<td>2.6</td>
<td>Cr, Mo, Ni, Cu, V</td>
<td>Bal.</td>
</tr>
<tr>
<td>TWIP980</td>
<td>0.60</td>
<td>—</td>
<td>18.0</td>
<td>Al</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

- TWIP microstructure fully austenitic in BM, HAZ & FZ
- Current range much narrower for TWIP vs. DP

(Yu, Mat. Trans 53 (11), 2012)
Constant Power Control produced wider current range and slower nugget growth rate

(Yu, WJRS, 03/2014)
Pulse Spot™ Welding of 1180 MPa AHSS

Fig. 4 Current and Electrode force pattern of Pulse Spot™ welding

Nugget diameter, $d$

<table>
<thead>
<tr>
<th>$3\sqrt{t}$</th>
<th>Conventional spot welding</th>
<th>Pulsed Spot™ welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\sqrt{t}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$5\sqrt{t}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$t$=Thickness of sheet

Photo 2 Comparison of fracture pattern between conventional spot welding and Pulse Spot™ welding

Fig. 6 Comparison of cross tension strength between of conventional spot welding and of Pulse Spot™ welding at each diameter

(Matsushita, JFE Tech. Report 2013)
Resistance Spot Welding of a 1.6mm, Q&P 980 Steel

Table 1 Chemical compositions of current-generation Q&P steels

<table>
<thead>
<tr>
<th>Chemical composition, wt%</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.15-0.30</td>
<td>1.5-3.0</td>
<td>1.0-2.0</td>
<td>0.02-0.06</td>
<td>&lt;0.015</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Table 5 Spot weld strength for 1.6 mm (0.06 in.) Q&P 980

<table>
<thead>
<tr>
<th>Point</th>
<th>Button size</th>
<th>Tensile shear strength</th>
<th>Cross-tension strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>in.</td>
<td>kN</td>
</tr>
<tr>
<td>A</td>
<td>6.5</td>
<td>0.256</td>
<td>26.7</td>
</tr>
<tr>
<td>B</td>
<td>6.2</td>
<td>0.244</td>
<td>26.0</td>
</tr>
<tr>
<td>C</td>
<td>6.0</td>
<td>0.236</td>
<td>23.9</td>
</tr>
</tbody>
</table>

Fig. 10 Resistance spot welding pulsed current profile. Pulse 1 = pulse 2, $I_1 = I_2$; cooling 1 = 20 ms, cooling 2 = 200 ms; pulse 3 = 100 ms, $I_3 = 4.3$ kA; hold time = 100 ms

Resistance spot welding of a complicated joint in new advanced high strength steel

HSLA 300, 2.2 mm

DP800 GI, 1.6 mm

IF GI, 0.8 mm

(den Uijl, Tata Steel online report)