Fatigue of Spot-Welded Sheet Steel Joints: Physics, Mechanics, and Process Variability

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Sheet Fatigue Team Members

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**Staff Members**
- Bart Clark | A/SP
Motivation

- **Weight reduction**

What are the implications of replacing heavier gage components made of low carbon and HSLA materials with thinner AHSS parts?

- **Over 5000 spot welds in a typical uni-body structure fastens panels and components together. Fatigue resistance of these joints impart significant influence on durability of a vehicle.**
## Grades & Gages

<table>
<thead>
<tr>
<th>Gage mm</th>
<th>IF GI</th>
<th>DQSK GI</th>
<th>CQSK Bare 1.83 GI 1.74</th>
<th>HSLA 340 GI 1.78</th>
<th>DP 600 GA 1.61</th>
<th>DP 980 Bare 1.55</th>
<th>TRI P 600 Bare 1.64</th>
<th>TRI P 800 EG 1.53</th>
<th>RA 830 GI 1.39</th>
<th>MS 1300 Bare 1.60</th>
<th>Boro n Bare 1.74-1.47</th>
</tr>
</thead>
<tbody>
<tr>
<td>YS, MPa</td>
<td>178</td>
<td>170</td>
<td>156</td>
<td>370</td>
<td>432</td>
<td>414</td>
<td>702</td>
<td>421</td>
<td>510</td>
<td>901</td>
<td>1156</td>
</tr>
<tr>
<td>UTS MPa</td>
<td>306</td>
<td>308</td>
<td>350</td>
<td>448</td>
<td>671</td>
<td>782</td>
<td>1057</td>
<td>672</td>
<td>839</td>
<td>895</td>
<td>1355</td>
</tr>
<tr>
<td>UE, %</td>
<td>21.7</td>
<td>20.5</td>
<td>14.5</td>
<td>15.9</td>
<td>13.6</td>
<td>12.7</td>
<td>7.1</td>
<td>20.6</td>
<td>22.3</td>
<td>0.8</td>
<td>3.2</td>
</tr>
<tr>
<td>TE, %</td>
<td>32.2</td>
<td>32.5</td>
<td>22.7</td>
<td>31.7</td>
<td>22.1</td>
<td>19.5</td>
<td>11.4</td>
<td>29.3</td>
<td>27.2</td>
<td>6.7</td>
<td>5.1</td>
</tr>
</tbody>
</table>

YS: Yield Strength (MPa), UTS: Ultimate Tensile Strength (MPa), UE: Elongation (%), TE: Reduction in Area (%)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squeeze time</td>
<td>99 cycles</td>
</tr>
<tr>
<td>Weld time</td>
<td>22 cycles</td>
</tr>
<tr>
<td>Hold time</td>
<td>90 cycles</td>
</tr>
<tr>
<td>Electrode force</td>
<td>1500 lb (DQSK, IF ~1100lb)</td>
</tr>
<tr>
<td>Cap size, truncated</td>
<td>7.9mm</td>
</tr>
</tbody>
</table>

**Target Button Size:** 7.0 mm

**Weld Current Adjusted for Each Material**
Fatigue Specimen Designs

### Tensile Shear

- 188 mm
- 70 mm
- 38 mm
- 5 mm

**Spacer**

### Coach Peel

- 160 mm
- 80 mm
- 38 mm

- 25 mm
- $R = 2.5t$
- 12.5 mm
- $t$

[www.autosteel.org](http://www.autosteel.org)
All Spot Weld Results
(nominal -1.6mm)

Load, N

Load Amplitude (N)


Failure cycles

Tensile Shear

Coach Peel

Thickness effect
No mean stress effect

DQSK-R0.1
DQSK-R0.3
CQSK-R0.1
CQSK-R0.3
IF-R0.1
IF-R0.3
HSLA340-R0.1
HSLA340-R0.3
DP600-R0.1
DP600-R0.3
DP800-R0.1
DP800-R0.3
DP980-R0.1
DP980-R0.3
TRIP600-R0.1
TRIP600-R0.3
TRIP800-R0.1
TRIP800-R0.3
RA830-R0.1
RA830-R0.3
MS1300-R0.1
MS1300-R0.3
Boron-R0.1
Boron-R0.3

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Location of Crack Initiation and Growth

1.78mm HSLA-340Y-GI sheet.

- Tested Nugget
- Typical Fatigue fracture
Effects of Prestrain

Minimal effect of pre-strain when thickness of formed sheet is accounted for

Normalized using Rupp parameter

Raw Fatigue Data

Difficulty of pre-strain when thickness of formed sheet is accounted for


Failure cycles
Spot Weld, Bond-Only, & Weld Bonded

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**Load, N**

- **blue** – weld-bonded
- **red** – bond only
- **black** – spot weld

**Failure cycles**

- **Tensile shear**
- **Coach peel**

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*Symbols:*
- SW = Spot Weld
- Bond = Bond Only
- WB = Weld Bond

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**Materials:**
- HSLA340TS01 SW
- HSLA340TS03 SW
- HSLA340CP01 SW
- HSLA340CP03 SW
- HSLA340TS01 Bond
- HSLA340TS03 Bond
- HSLA340CP01 Bond
- HSLA340CP03 Bond
- HSLA340TS01 WB
- HSLA340TS03 WB
- HSLA340CP01 WB
- HSLA340CP03 WB
- DP600TS01 SW
- DP600TS03 SW
- DP600CP01 SW
- DP600CP03 SW
- DP600TS01 Bond
- DP600TS03 Bond
- DP600CP01 Bond
- DP600CP03 Bond
- DP600TS01 WB
- DP600TS03 WB
- DP600CP01 WB
- DP600CP03 WB
Multiparameter Study: Hold Time, Heat Treatment, w/ Weld-bond

Heat Treatment: Paint & Bake Cycle

Hold Time: Thought to be detrimental for AHSS

Weld Bond: Load transfer over a larger region

HSLA 340 (1.78mm) – Button Dia: 7 mm
Tensile Shear Specimens, 1.78 mm HSLA 340-GI, R = 0.1

HSLA 340 1.78 mm – Button Dia: 4.9 mm
Tensile Shear Specimens, 1.78 mm HSLA 340-GI, R = 0.1

For HSLA 340:
• Effect of HT or heat treatment – small for 7.0 mm & more (longer HT – better lives) for 4.9 mm welds
• More scatter for 4.9 mm welds
• Weld bond improves fatigue life
Multiparameter Study:
Hold Time, Heat Treatment, w/ Weld-bond

For DP 600:
• Effect of HT or heat treatment – small for 7.0 mm & more (shorter HT – better lives) for 4.9 mm welds
• More scatter for 4.9 mm welds
• Weld bond improves fatigue life
Evaluation of Fatigue Damage Parameters

Uncertainty of Analysis or Scatter of Data due to Geometric Variability of Spot Welds Joints?

Bonnen et al., SAE Paper No. 2006-01-0978.

Minimal effect of center-to-grip distance variation for current data

Center to Grip Distance
Effect of thickness variation for current data

Sheet Thickness

Fatigue Strength Variability

Maximum Applied Load, N

Cycle to Failure

TS Specimens: $R^2 = 0.76$

CP Specimens: $R^2 = 0.38$

- DP600 - 0.93
- DP600-1.54
Fatigue Strength Variability

**Flange Length in CP specimens**

![Diagram showing flange length in CP specimens](image)

**DP 600 – 0.93 mm**

- Load vs Life
- Moment vs Life

**R = 2.5t**

- 25mm
- 160mm
- 80mm
- 38mm

**R² = 0.94**

- 1.E+05
- 1.E+04
- 1.E+03
- 1.E+02

**Cycles to Failure**

- 1.E+02
- 1.E+03
- 1.E+04
- 1.E+05
- 1.E+06
- 1.E+07

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Crucial Geometric Parameters

**Von Mises Stress**

\[ \sigma_M = \left( \sigma_x^2 + 3\tau_{xz}^2 \right)^{1/2} \]

**Axial Stress**

**Tensile Shear**

\[ \sigma_x = \frac{6M}{bt^2} \]

**Coach Peel**

\[ \sigma_x = \frac{6M}{bt^2} \]

**Shear Stress**

**Tensile Shear**

\[ \tau_{xz} = \frac{4Q}{\pi D^2} \]

**Coach Peel**

\[ \tau_{xz} = \frac{P}{Dt} \]
Fatigue Strength Variability

Maximum Load - Tensile Shear
Fatigue Strength Variability

Effective Stress - Tensile Shear

R² = 0.89

Cycles to failure, cycles

von Mises Stress, MPa

- DP600-0.93
- DP600-1.54
- TRIP600-1.64
- HSLA-1.78
- RA830-1.35
- MS1300-1.60
- IF-1.60
- DQSK-1.60
- DP800-1.60
Fatigue Strength Variability

Stress Intensity Range (ΔKI), N/mm²⋅1.5

Cycles to failure, cycles

R² = 0.90


Stress Intensity Factor Range - Tensile Shear
Fatigue Strength Variability

Maximum Load - Coach Peel

![Graph showing the relationship between cycles to failure and maximum applied load for different steels. The graph includes data points for DP600-0.93, DP600-1.54, TRIP600-1.64, HSLA-1.78, DQSK-1.60, and DP800-1.60. The R² value is 0.49.](image-url)
Fatigue Strength Variability

R² = 0.81

Effective Stress - Coach Peel

Cycles to Failure

von Mises Stress, MPa

DP600-0.93
DP600-1.54
TRIP600-1.64
HSLA-1.78
DQSK-1.60
DP800-1.60
Fatigue Strength Variability

Stress Intensity Range ($\Delta K_I$), N/mm$^1.5$

R$^2 = 0.83$

Cycles to failure, cycles

Stress Intensity Factor Range - Coach Peel

- DP600-0.93
- DP600-1.54
- TRIP600-1.60
- HSLA-1.78
- DQSK-1.60
- DP800-1.60
Conclusions

1. Spot weld fatigue performance of studied steels (AHSS, HSLA, low carbon) appears to be insensitive to base metal composition, microstructure, and strength.

2. Spot weld fatigue behavior is mainly controlled by geometric factors such as sheet thickness and weld diameter.

3. Spot weld fatigue behavior is largely mean stress insensitive, for the mean stresses examined.

4. No effect of weld hold time (between 1 and a 90 cycles).
5. No effect of paint bake cycle.

6. Adhesive bonding and weld bonding significantly improve fatigue behavior over spot welding alone, although this improvement is in keeping with the actual increase in joint area gained by the addition of the adhesive layer.

7. Prestraining or stretch-forming the parent metal before spot welding has no impact on the fatigue performance of spot welded joints.

8. Principal spot weld damage parameters (Rupp, Dong, Swellam, Kang, & Sheppard) predict A/SP data equally well.

9. Crucial parameters controlling the mechanics and physics uncovered, thus reducing uncertainty in prediction.
A/S-P spot weld fatigue knowledge base
(including detailed fatigue data, report, microstructure, tensile data, etc.)

freely available at:

http://www.a-sp.org

http://www.a-sp.org/database/custom/ASP%20Spot%20Weld%20Fatigue%20Project%202-7-06v1c.exe
Acknowledgements

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