GAS METAL ARC WELDING OF ADVANCED HIGH STRENGTH STEEL

DEVELOPMENTS FOR OPTIMIZED WELD CONTROL AND IMPROVED WELD QUALITY

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Drivers for GMAW AHSS
Collaborative Work

**Benefit**
- AHSS (DP600) – Higher strength vs. mild steel/HSLA allows reduced gauge of steel for frame weight save

**Concern**
- AHSS sensitive to heat input – HAZ more significant – mechanical property (in particular, fatigue) loss is greater

**Customers:**
- Ford Product Development – F150 Successor

**Partners:**
- The Lincoln-Electric Co. – Welding Equipment Supplier
- Metro Technologies – Tooling & Process Development
- AET Integration – Welding Optimization & Fatigue Analysis

www.autosteel.org
Factors influencing GMAW Quality, Productivity & Cost

Design
- Base Material Type and Thickness
- Coating Type and Thickness
- Joint Design
- Fixturing and Joint Fit-Up

Equipment Selection
- Power Source Type
- Consumable Type
- Welding Progression
- Weld Length
- Welding Parameters (Current, Voltage, etc.)

Process Set-Up
- Electrode Alignment
- Torch Angle/Push-Drag Angle
- Tip to Work Distance (CTWD)
- Part Cleanliness
- Equipment Maintenance

Production Control

Area of concentration
Effect of GMAW on Weld Quality

- Arc Welding affects Micro-Structure and Mechanical Properties
  - Effects vary with material chemistry, strain and bake temperatures
- Thermal Cycle results in a Heat Affected Zone (HAZ)
  - HAZ size depends on heat input and thermal transfer from joint
  - HAZ is more pronounced for higher strength grades
  - HAZ with hard/soft regions may act as metallurgical notch
Considerations for AHSS Weld Quality

• Carbon Steels up to and including HSLA
  – welded w/ high heat inputs
    • AHSS more sensitive to heat input, compounded by potential for thinner gauges
  – always resulted in weld wire being the strongest – with AHSS may not be
    • Consider higher strength wires, but weld metal may be susceptible to brittle failure, or cored wires – new development
  – impurities part of process
    • AHSS more sensitive to impurities
Factors:
- Wire Feed Speed (WFS) @ 159-201 mm/s (375-475”/min)
- Travel Speed (TS) @ 13.5-24.1 mm/s (32-57”/min)
  - (Actual variable SQRT WFS/TS (2.89-3.45))
- Voltage (varied with WFS)
  - 23.8V @ 159; 24.5V @ 182; 25.0V @ 201 mm/s WFS
- Contact Tip to Work Distance (CTWD) @ 12.5-19.0 mm (0.50-0.75”)
- Torch Angle (25-55° from vertical)
- Push/Drag Angle (5-25° from vertical)
- Wire Placement (0-2 wire diameters from joint)

Response:
- Weld Profile from Laser Scan (Leg Size/Bead Convexity/Toe Angle)
- Weld Dimensions from Section (Toe Angle & Penetration)
- Load to Failure (Tensile Lap-Shear)
- Fatigue Life (Tensile Shear - 3 Loads, 3 Replicates, R=0.1)
- Micro-Hardness Traverse/Micro-Structure
Results of DOE #1 – Tensile Lap-Shear

- 97% of the 174 samples broke at base metal (Ave load 36 kN ≡ MS UTS)
- 3% remaining broke between weld metal and HAZ on MS side at lower load (Ave 33 kN)
  - due to lack of fusion caused by extreme welding parameters.

Samples were only runs welded with at least 4 of 5 factors below:
- All 4 were the smallest weld size
- All 4 welded at highest travel speeds (23-24 mm/s or 54-57 in/min)
- All 4 welded w/ -2 wire placement (wire center 2 diameters from upper plate)
- 3 of 4 welded w/ 25° from vertical torch angle (directs arc force/heat to bottom plate)
- 3 of 4 welded w/ 5° push angle (directs more of arc force/heat into bottom plate)

- Combination of small weld with high travel speed results in lower heat input and less penetration. Locating arc out 2 wire diameters, a 25° torch angle and 5° push angle all direct less heat into upper plate.
**DOE #1 Results – Weld Size and Profile**

<table>
<thead>
<tr>
<th>Run</th>
<th>Factor 1 WFS mm/s (“/min)</th>
<th>Travel Speed mm/s (“/min)</th>
<th>Factor 2 SQRT(WFS/TS)</th>
<th>Factor 3 CTWD mm (”)</th>
<th>Factor 4 Torch Angle °</th>
<th>Factor 5 Push/Drag Angle °</th>
<th>Factor 6 Wire Placement diams.</th>
<th>Voltage V</th>
<th>Average Current A</th>
<th>Heat Input J/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>159 (375)</td>
<td>19.1 (45.0)</td>
<td>2.89</td>
<td>19.1 (0.75)</td>
<td>55</td>
<td>5</td>
<td>-2</td>
<td>23.8</td>
<td>267</td>
<td>335.34</td>
</tr>
<tr>
<td>50</td>
<td>201 (475)</td>
<td>16.9 (40.0)</td>
<td>3.45</td>
<td>14.2 (0.56)</td>
<td>55</td>
<td>25</td>
<td>0</td>
<td>25.0</td>
<td>342</td>
<td>505.69</td>
</tr>
<tr>
<td>19</td>
<td>191 (450)</td>
<td>16.1 (38.0)</td>
<td>3.45</td>
<td>12.5 (0.50)</td>
<td>25</td>
<td>5</td>
<td>0</td>
<td>24.2</td>
<td>361</td>
<td>545.68</td>
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Weld Size linked to heat input (controlled by WFS, TS and CTWD); Profile influenced by all factors

Toe-angle deemed critical for mechanical performance – assuming adequate penetration in both substrates
DOE #1 – Micro-Hardness

No significant change in DP600 hardness at HAZ - exists for all samples (range 165-188 HV)

Heat input influences weld hardness, but not HAZ

### Microhardness Traverse of Samples with Three Different Heat Inputs

**Heat Input**

- A-14 Lowest Heat Input
- A-50 Best High Cycle Fatigue
- A-19 Highest Heat Input

### Table

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DOE #1 – Micro-Structure

Heat input threshold for influence on grain structure?
DOE #1 – Tensile Lap-Shear Fatigue relative to Heat Input

Fatigue Life of Samples with Three Different Heat Inputs

3 load levels: 8.9 kN (2000 lbf), 11.1 kN (2500 lbf) and 15.6 kN (3500 lbf) w/ R=0.1 & frequency=10 Hz

- Run #19 – highest heat input - 8 of 9 samples broke at toe on DP600 side
- Run #14 – lowest heat input - 7 of 9 samples broke at toe on DP600 side
- Run #50 – high heat input – 5 of 9 broke at DP600 and showed highest fatigue life
Fatigue S-N Curve for all samples

\[ \log_{10}(S) = 3.094 - 0.2163 \log_{10}(N) \]

Regression

95% CI
95% PI

Equal distribution of Type A (DP600) & B (mild steel) failures

S 0.0444567
R-Sq 80.3%
R-Sq(adj) 80.2%
DOE #1 – Effect of Weld Geometry and Heat Input on Fatigue Life

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<td>3.45</td>
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<td>55</td>
<td>25</td>
<td>0</td>
<td>25.0</td>
<td>342</td>
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<td>25</td>
<td>5</td>
<td>0</td>
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<td>361</td>
<td>545.68</td>
</tr>
<tr>
<td>36</td>
<td>201 (475)</td>
<td>24.1 (57.0)</td>
<td>2.89</td>
<td>19.1 (0.75)</td>
<td>25</td>
<td>5</td>
<td>-2</td>
<td>25.7</td>
<td>318</td>
<td>339.69</td>
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</table>
1. Correlation of Fatigue Life to Weld Dimensions
   – Input: Vertical Leg Size, Toe Angle, Max Top Plate Penetration, Max Bottom Plate Penetration, Horizontal Leg Size, Upper Fusion-Line Angle
   – Output: Fatigue Life/Location at 8.9, 11.1, 15.6 kN (2000, 2500, 3500 lbf)

2. Correlation of Weld Dimensions to Welding Variables
   – Output: Vertical Leg Size, Horizontal Leg Size, Toe Angle, Max Bottom Plate Penetration, Max Top Plate Penetration, Undercut, Upper Fusion-Line Angle, Min Hardness in DP600 HAZ region

3. Correlation of Fatigue Life to Welding Variables
   – Input: WFS, TS, CTWD, Torch Angle, Push Angle, Wire Placement
   – Output: Fatigue Life at 8.9, 11.1, 15.6 kN (2000, 2500, 3500 lbf)
DOE #1 – Model (#1) relating Effect of Weld Geometry on Fatigue Life

- **Fatigue life – 8.9 kN (2000 lb) load** (Response Surface Linear Model R-Sq = 0.65) increases with:
  - increasing vertical leg size
  - decreasing bottom plate (DP600) penetration
  - decreasing top plate (Mild Steel) penetration
  - decreasing upper fusion line angle

- **Failure location at 8.9 kN (2000 lb) load** more likely to be in mild steel base metal with:
  - decreasing vertical leg size
  - increasing horizontal leg size

- **Fatigue life – 15.6 kN (3500 lb) load** (Response Surface Linear Model R-Sq = 0.56) increases with:
  - increasing vertical leg size
  - increasing bottom toe angle
  - decreasing bottom plate (DP600) penetration

- **Failure location at 15.6 kN (3500 lb) load** more likely to be in mild steel base metal with:
  - decreasing vertical leg size
  - increasing bottom toe angle
  - increasing bottom plate (DP600) penetration
  - increasing horizontal leg size
Primary crack initiates at weld toe on DP600 and propagates in DP600 (Type A)

Sample ID: 50 A-3

Vertical Leg 3.89 mm; Horizontal Leg 5.87 mm;
Toe Angle 129°; Bottom Plate Penetration 47%
Top Plate Penetration 0.59 mm

High Cycle Fatigue: 221,112 cycles
Failure Location: DP600 Toe
Primary crack initiates at weld root and propagates in HAZ and/or weld metal on mild steel side (Type B)

Sample ID: 32B-6

Vertical Leg 3.86 mm; Horizontal Leg 6.10 mm; Toe Angle 137°; Bottom Plate Penetration 53%; Top Plate Penetration 0.66 mm

High Cycle Fatigue: 198,503 cycles
Failure Location: Weld Root & Mild Steel HAZ
• Optimization of Weld Dimensions for Highest Fatigue Life
  – Min vertical leg size (90% of 3.4 mm) = 3.1 mm
  – Max bottom plate penetration (70% of 3.4 mm) = 2.4 mm
• For Fatigue Life
  – 12,500 cycles min @ 15.6 kN (3500 lb) max load
  – 39,000 cycles min @ 11.1 kN (2500 lb) max load
  – 81,000 cycles min @ 8.9 kN (2000 lb) max load
  • Minimum bottom toe angle = 120º
  • Back angle = 98º max
  • Top plate penetration = 1.1 mm max
**Model #2 Summary - Effect of Weld Variables on Weld Dimensions**

- **Bottom Plate Penetration** (linear model R-Sq = 0.78) decreases with:
  - decreasing wire feed speed (WFS)
  - increasing contact tip to work distance (CTWD)
  - increasing torch angle
  - increasing push/drag angle
  - decreasing wire placement away from joint

- **Vertical leg size in mild steel** (linear model R-Sq = 0.39) increases with:
  - increasing WFS/TS ratio
  - decreasing wire placement away from joint

- **Horizontal Leg** (2 factor interaction R-Sq = 0.79 - lack of fit) increases with:
  - decreasing WFS
  - increasing WFS/TS Ratio
  - increasing push angles
  - increasing wire placement away from joint

- **Bottom Toe Angle - DP600** (quadratic model R-Sq = 0.76) increases with:
  - decreasing WFS
  - increasing WFS/TS ratio at larger torch angles
  - increasing CTWD
Toe Angle increases with lower WFS and higher WFS/TS ratios

Toe Angle
X = A: Wire Feed Speed
Y = B: SQRT(WFS/TS)

Actual Factors
C: CTWD = 12.50
D: Torch Angle = 40
E: Push/Drag Angle = 15
F: Wire Placement = -2

ANOVA for Response Surface Reduced Cubic Model
Analysis of variance table [Partial sum of squares]

<table>
<thead>
<tr>
<th>Source</th>
<th>Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>P Value</th>
<th>Prob &gt; F</th>
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<tbody>
<tr>
<td>Model</td>
<td>6522.46</td>
<td>28.00</td>
<td>232.95</td>
<td>13.86</td>
<td>&lt; 0.0001</td>
<td>significant</td>
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<tr>
<td>A</td>
<td>485.35</td>
<td>1</td>
<td>485.35</td>
<td>28.88</td>
<td>&lt; 0.0001</td>
<td></td>
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<tr>
<td>B</td>
<td>481.18</td>
<td>1</td>
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<td>28.63</td>
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<td>C</td>
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<td>28.03</td>
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<td>6.06</td>
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<tr>
<td>E</td>
<td>598.50</td>
<td>1</td>
<td>598.50</td>
<td>35.62</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1012.71</td>
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<td>1012.71</td>
<td>60.26</td>
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<tr>
<td>Lack of Fit</td>
<td>416.63</td>
<td>23</td>
<td>18.11</td>
<td>1.68</td>
<td>0.2960</td>
<td>not significant</td>
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<tr>
<td>Pure Error</td>
<td>53.90</td>
<td>5</td>
<td>10.78</td>
<td>1.36</td>
<td>0.2960</td>
<td>not significant</td>
</tr>
</tbody>
</table>

Std. Dev. = 4.10
Mean = 127.37
C.V. = 3.22

R-Squared = 0.93
Adj R-Squared = 0.87
Pred R-Squared = 0.69

"Pred R-Squared" of 0.6883 is in reasonable agreement with "Adj R-Squared" of 0.8654.
DOE #1 – Model (#3) relating Effect of Weld Variables on Fatigue Life

- Fatigue life at 8.9 kN (2000 lb) load (RSM 2FI Model R-Sq = 0.73) increases with:
  - decreasing WFS
  - increasing WFS/TS ratio (decreasing travel speed)
  - increasing torch angle at high push angles
  - increasing push angle at higher WFS/TS ratios and/or torch angles
  - wire placement based on WFS/TS ratio

- Fatigue life at 15.6 kN (3500 lb) load (Response Surface 2FI Model R-Sq = 0.73) increases with:
  - decreasing WFS
  - increasing WFS/TS ratio (decreasing TS - more so at larger wire placements)
  - increasing CTWD
  - increasing torch angle
  - increasing push angle at high torch angles
  - wire placement based on WFS/TS ratio
  - increasing wire placement at large push angles
**DOE #1 – Process Window (WFS/TS) w/ defined Weld Leg for max Fatigue Strength (8.9 kN)**

Weld Leg (Upper) Size and Toe Angle both significant as regards Fatigue Life.
Conclusions

• Fatigue Life of Lap welded joint between DP600 3.4 mm and Mild Steel 3.8 mm increased by:
  – decreasing Wire Feed Speed
  – decreasing Travel Speed
  – Increasing CTWD
  – Increasing Torch Angle
  – Increasing Push Angle
  – Increasing Wire Placement away from joint (linked to other parameters)

Further Work

• Continued DOE’s using DP600 to thicker (4.7 mm) and thinner (2.7 mm) mild steel, and DP600 to itself –
  – Based on process optimization from DOE #1
Thank You