Developments in friction stir & spot welding: tailored blanks & Al/Steel joining techniques

Global Automotive Lightweight Materials 2015

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NRC-Saguenay
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Who’s NRC?

NRC:
- 4000 employees across Canada

NRC (Saguenay):
- 35 employees

Shaping
- Extrusion
- Hot/warm/cold forming
- Hydroforming
- Semi-solid casting (SEED)

Joining
- Structural adhesives
- Welding processes
- GMAW/GTAW
- Laser & H-LAW welding
- Friction stir welding
- Surface treatment
- Environmental durability
- Hybrid joining

Corrosion

NRC-Saguenay (Aluminium Technology Centre)
Outline

Tailor welded blanks: FSW & laser comparison

Planning,
Stirring
Drawing out

Robotic FSW/FSSW systems

FSW
Al/Steel:
techniques & joint performance

Gantry systems

Hybrid joining: welding processes + adhesives

FSSW: techniques & joint performance

Automobile et transport de surface / Automotive and Surface Transportation
Tailor welded blanks: FSW & laser comparison

- Interesting lightweighting possibility (body-in-white & structural parts)
- Goal: Increase productivity without decreasing formability

Friction stir welding

- High productivity
- Hard to control geometrical defects
- Hot cracking sensitivity

Autogenous laser welding

<table>
<thead>
<tr>
<th>Thickness ratio</th>
<th>Approximate weight savings (part)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 : 1</td>
<td>≈ 15 %</td>
</tr>
<tr>
<td>2 : 1</td>
<td>≈ 30 %</td>
</tr>
</tbody>
</table>
Tailor welded blanks: FSW & laser comparison

**Cold forming**
Room temperature

**Warm forming**
200°C @ 350°C

**Hot stamping**
400°C @ 530°C

- Solution heat treatment
- Quench
- Artificial aging

Materials:
- 5052-O
- 5754-O
- 5182-O (+ Mn)
- 6016-T4
- 6111-T4
- 7075-T6

Room temperature: 200°C @ 350°C

Hot stamping temperature:
- 5754-O: 505°C
- 7075-T6: 470°C
Tailor welded blanks: FSW & laser comparison

Good weldability at high travel speed: at least 3.0 m/min

Pin tool (Φ 8.5 mm)

2000 RPM, 1.0 m/min, 5.5 kN

2000 RPM, 2.3 m/min, 6.25 kN

2000 RPM, 3.0 m/min, 6.8 kN

Pin tool (Φ 12.0 mm)

2000 RPM, 1.0 m/min, 6.0 kN

2000 RPM, 2.3 m/min, 10.0 kN

2000 RPM, 3.0 m/min, 11.5 kN
Tailor welded blanks: FSW & laser comparison

- **Robot (single pass)**
  - First pass: 7.5 kW, 7.0 m/min
  - Second pass: 4.0 kW, 2.0 m/min

- **‘Remote on the fly’ (double-pass)**
  - First pass: 7.5 kW, 7.0 m/min
  - Second pass: 4.0 kW, 2.0 m/min

- Increased productivity
- More stable welding parameters
- Increased possible undercut defect
- Smoother surface finish
- Limitation of undercuts
Tailor welded blanks: FSW & laser comparison

Increased formability with FSW

5xxx-O
Tailor welded blanks: FSW & laser comparison

**Cold forming**
Room temperature

**Warm forming**
200°C @ 350°C

**Hot stamping**
400°C @ 530°C

- Solution heat treatment
- Quench
- Artificial aging

Examples of materials used:
- 5052-O
- 5754-O
- 5182-O (+ Mn)
- 6016-T4
- 6111-T4
- 7075-T6

Temperature ranges:
- Room temperature
- 200°C @ 350°C
- 400°C @ 530°C

Material grades:
- 5754-O
Tailor welded blanks: FSW & laser comparison

Hot forming issues with FSW of tailor welded blanks…

5083 SPF part, 1.5 / 2.0 mm

Aluminum B-pillar

- High travel speed:
- Lower heat input (thin sheet):

Abnormal grain growth (AGG)
Automotive trend toward dissimilar material joining (average body & closures)

- Current fusion welding processes need improvement
  - Metallurgical incompatibility (fragile intermetallics)
- Solid-state joining processes (FSW) are attractive in this regard
FSW of Al/Steel: techniques & joint performance

- Friction stir welding (Al / Steel)

  - Conventional
    - FSW pin tool enters slightly into substrate
    - Wear-resistant tool material (potential wear)

  - Assisted FSW (NRC)
    - FSW pin tool do not enter into substrate
    - Typical tool materials for Al / Al FSW

- • Passed 90° bend

Honda Friction stir welds
FSW of Al/Steel: techniques & joint performance

- Conventionnal FSW (Al / Steel)
  - Joint performance

<table>
<thead>
<tr>
<th>Aluminum sheet thickness</th>
<th>Shoulder &amp; pin diameters</th>
<th>Forge force</th>
<th>Joint resistance Load / weld length$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>mm</td>
<td>kN</td>
<td>N / mm</td>
</tr>
<tr>
<td>≈ 1.0 - 2.0 mm</td>
<td>11.0 / 4.0 mm</td>
<td>9.75</td>
<td>316.5 +/- 14.1</td>
</tr>
<tr>
<td>≈ 3.0</td>
<td>14.0 / 5.0 mm</td>
<td>12.00</td>
<td>431.2 +/- 51.8</td>
</tr>
</tbody>
</table>

$^1$Joint failure at interface

<table>
<thead>
<tr>
<th>Aluminum alloy</th>
<th>Tensile strength</th>
<th>Maximum thickness for failure in base material (11mm shoulder tool)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6016-T4</td>
<td>220 MPa</td>
<td>1.44 mm</td>
</tr>
<tr>
<td>5754-O</td>
<td>230 MPa</td>
<td>1.38 mm</td>
</tr>
<tr>
<td>5182-O</td>
<td>275 MPa</td>
<td>1.15 mm</td>
</tr>
<tr>
<td>6070-T4</td>
<td>320 MPa</td>
<td>0.99 mm</td>
</tr>
<tr>
<td>7075-T6</td>
<td>550 MPa</td>
<td>0.58 mm</td>
</tr>
</tbody>
</table>

Increased interface length yields higher joint resistance
(≈ 80% joint efficiency vs FSW Al/Al)
FSW of Al/Steel: techniques & joint performance

- Conventional FSW (Al / Steel)
  - Joint performance (fatigue)

  R = 0.1

  *Similar fatigue behaviour as Al-Al lap joints*

  Beyond standards

  Transverse loading

  Rupture through:
  - Al top sheet
  - Retreating side
FSW of Al/Steel: techniques & joint performance

- Conventional FSW (Al / Steel)
  - Environmental durability performance

  Static mechanical properties not clearly affected in durability testing

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference joint</td>
<td>1 hour</td>
</tr>
<tr>
<td>250 hours</td>
<td></td>
</tr>
<tr>
<td>500 hours</td>
<td></td>
</tr>
<tr>
<td>1000 hours</td>
<td></td>
</tr>
<tr>
<td>1000 hours (SCC)</td>
<td></td>
</tr>
</tbody>
</table>

GM9505P Cycle G (30 cycles)
- 2 hours @ -30°C
- 2 hours @ room temperature
- 2 hours @ 70°C
- 2 hours in environmental chamber
- 2 hours in salt spray
- 16 hours in high humidity

'SCC load: 22% of single lap shear strength
### Assisted FSW - NRC (Al / Steel)

#### Joint performance

<table>
<thead>
<tr>
<th>Tierce material</th>
<th>Shoulder diameter</th>
<th>Forge force</th>
<th>Joint resistance Load / weld length</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>mm</td>
<td>kN</td>
<td>N / mm</td>
</tr>
<tr>
<td>Conventional FSW</td>
<td>11.0</td>
<td>9.75</td>
<td>316.5 +/- 14.1¹</td>
</tr>
<tr>
<td>Lower-strength method</td>
<td>11.0</td>
<td>5.00</td>
<td>234.8 +/- 5.6¹</td>
</tr>
<tr>
<td>Higher-strength method</td>
<td>18.0</td>
<td>13.50</td>
<td>338.0 +/- 7.6¹</td>
</tr>
<tr>
<td></td>
<td>11.0</td>
<td>5.00</td>
<td>408.8 +/- 0.7²</td>
</tr>
</tbody>
</table>

¹Joint failure at interface
²Joint failure in base material (2.0mm thick)

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**Failure in base material**

[Image showing a welded joint with labels for Steel and Aluminum, and a graph showing load vs. weld length.]
Hybrid joining: welding processes / structural adhesives

**Pre-welding application of adhesive**

- Aluminum (Al) + Aluminum (Al)
- OR
  - Aluminum (Al) + Steel

**Post-welding application of adhesive**

- Step 1
- Step 2

**Images:**
- Step 1: Pre-welding application
- Step 2: Post-welding application
Hybrid joining: welding processes / structural adhesives

- **Al / Al hybrid joining**
  - FSW

  + 65% joint strength in hybrid joining (untreated Al) vs FSW

  Up to + 105% joint strength in hybrid joining (brushed Al) vs FSW
Hybrid joining: welding processes / structural adhesives

- Al / Al hybrid joining
  - GMAW (MIG)

  + 50% joint strength in hybrid joining vs GMAW or adhesive

  No major gain using a silane surface treatment

  Adhesive application on untreated surface gives unpredictable results

*GPS: silane surface treatment

*4043 filler
Hybrid joining: welding processes / structural adhesives

- **Al / Al hybrid joining**
  - FSW (environmental durability performance)

Still + 50% joint strength in hybrid joining in environmental durability testing

- Cataplsa degradation (Jaguar JNS 30.03.35 standard)
- UV (5 weeks; wet & dry) (ISO 11507: alternative exposure of 4 h UV at 60 °C and 4 h condensation (100% RH) at 50 °C for 5 weeks (35 days))
- Chamber 5 weeks (wet & dry conditions; replica of ISO 11507 without UV)
- UV (1 week, dry conditions) (ASTM D-904: 24 h UV for 7 days at 60 °C; in other words 168 h of UV exposure at 60 °C)
- Chamber 1 week (dry conditions; replica of ASTM D-904 without UV)
- Cyclic corrosion (ISO 14993)
### Hybrid joining: welding processes / structural adhesives

#### Al / Steel hybrid joining (FSW)

**Joint performance**

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<tr>
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<td>14.0</td>
<td>12.0</td>
<td>431.2 +/- 51.8 (^1)</td>
</tr>
<tr>
<td>Assisted FSW</td>
<td>11.0</td>
<td>5.00</td>
<td>234.8 +/- 5.6 (^1)</td>
</tr>
<tr>
<td></td>
<td>18.0</td>
<td>13.5</td>
<td>338.0 +/- 7.6 (^1)</td>
</tr>
<tr>
<td>Hybrid-conventional FSW</td>
<td>14.0</td>
<td>12.0</td>
<td>415.9 +/- 38.7 (^1)</td>
</tr>
<tr>
<td>Hybrid-assisted FSW</td>
<td>11.0</td>
<td>5.00</td>
<td>400.3 +/- 14.8 (^2)</td>
</tr>
</tbody>
</table>

\(^1\) Joint failure at interface  
\(^2\) Joint failure in base material (2.0mm thick)

 tierce material acts as a pre-treatment to adhesive bonding

Increase in fatigue strength vs conventional FSW
FSSW: techniques & joint performance

Joining processes

- Resistance spot welding
- Friction stir spot welding
- Laser welding
- Self-piercing rivets
- Clinching

Typical applications

- B-pillar: Chevrolet Corvette
- Body-in-white: Ford F-150

Typically low production cost
FSSW: techniques & joint performance

FSSW (Friction Stir Spot Welding)

FSSW

Refill FSSW

Pattern FSSW

Lower-size robot (C-frame)

Huys Industries

Kawasaki
FSSW: techniques & joint performance

- **FSSW (Friction Stir Spot Welding)**
  - Joint performance

**Pattern FSSW**
- Highest lap shear strength
- Acceptable cross-tension strength
- Same cycle time

![Bar charts showing lap shear and cross-tension strengths for different FSSW patterns and materials.](image)

- **6xxx-T4**
  - Lap shear strength: 1.0 mm / 1.0 mm
  - Cross-tension strength: 2.5 mm / 2.5 mm

![Images of FSSW welds with 6xxx-T4 material.](image)
Robotic FSW developments

- Industrialization of NRC robotic FSW technologies
  - 1st production-level robotic FSW workcell in Canada (in progress)

**Fully-integrated industrial solution**
- National Research Council Canada
- Conseil national de recherches Canada
- In-house robotic FSW process (KRL,RSI) and workcell supervisory control
- In-house hybrid force control (RSI)
- Management of FSW spindle (ProfiBus)
- Process supervision module
- Recovery modes (tool auto retract)
- Human Machine Interface

**Industrial robot configuration**
- KR500MT-2 robot arm (KRC2)
- 5 meters linear unit
- KUKA.RobotSensorInterface
- EtherNet/IP-ProfiBus

**FSW Spindle**
- Spindle torque motor
- 5000 rpm / 75 Nm
- Shear force transducers
- HSK tool interface
- Hydraulic tool changing unit

**Accuracy management**
- Automated calibration for robots working under high process loads
- Real-time corrections of tool deviations due to process loads (force > 8 kN)
- Real-time corrections of orientation errors

**Automated FSW fixture**
- Top loading of plates
- Automated positioning of Aluminium plates (pneumatic)
- Automated horizontal & vertical clamping (hydraulic)
- Integrated cooling in backing

**FSW tools - parameters**
- Design of production tools (HSK)
- Specialized tool geometry with > 1000 m life (Tungsten Carbide)
- Optimized process parameters for each range of plate thicknesses (4 tools)

RSI-based (KRC2 12ms) real-time control features:
- Hybrid position/force control module
- Control of tool plunge + transient regime
Robotic FSW developments

- Robotic friction stir welding: Control challenges

  Elastodynamic behavior of serial robots

  - FSW tool deviations (axial + transverse joint deformations, backlash, …)
  - Automation problem at tool plunge-in
  - Vibrations due to robot dynamics (rpm<1000)

  Robotization issues & seam defects

  Al 2024-T3 (2x2,3mm) Lap joint, 750rpm (robot natural frequency)

  robot oscillations during weld
Robotic FSW developments

- Technology package for accurate path generation using rail-mounted robots under load (TRL-8)

  **NRC calibration kit & method**
  > Model for axial+structural behavior
  > Solution for *improved measurement of lateral forces for COTS spindles*
  > Fully automated robot calibration in production-relevant envelope (*PCT patent pending*)
  > Fully automated parameter estimation

  **NRC 3D real-time path correction technology**
  > Real-time compensation of deviations in welding plane
  > Compensation of force-induced loss of angularity

  **Standard kinematic calibration**
  > Calibration of robot path generation errors in free motion (e.g.: KUKA Absolute Accuracy)
  > Local robot/tooling calibration

**Initial situation:**
Lateral deviations in seam plane + loss of angularity caused by heavy process loads
Robotic FSW developments

- Performance evaluation on NRC robotic FSW test-bed

Real-time compensation of lateral/angular deviations along 3D convex-concave profile — Forward path

- Process forces: $F_x = 1.2$ kN, $F_y = 1.1$ kN, $F_z = 10$ kN
- Hybrid position/force control

Estimated lateral deviations along robotic FSW trajectory:
- Studied application: Convex-concave tooling (curvature of 500 mm)
- Industrial robot: KUKA KR500NT, Process end-effector: FSL Robositr
- Average load case: $[F_x, F_y, F_z] = [+1.2, +1.1, -10.0]$ kN

$\varepsilon < \pm 0.26$ mm

FSW/FSSW travel/side angle tolerances: $\pm 1^\circ$
Robotic FSW developments

- Performance evaluation on NRC robotic FSW test-bed

**Real-time compensation of lateral/angular deviations along 3D convex-concave profile — Return path**

- Estimated lateral deviations along robotic FSW trajectory
- Studied application: Convex-concave tooling (curvature $r=500\text{mm}$)
  - Average load case: $[F_x, F_y, F_z] = [-1.2, -1.1, -10.0] \text{ kN}$

![Graph showing estimated lateral deviations](image)

- Process forces: $F_x = 1.2 \text{ kN}$, $F_y = 1.1 \text{ kN}$, $F_z = 10 \text{ kN}$
- Hybrid position/force control
Questions?

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