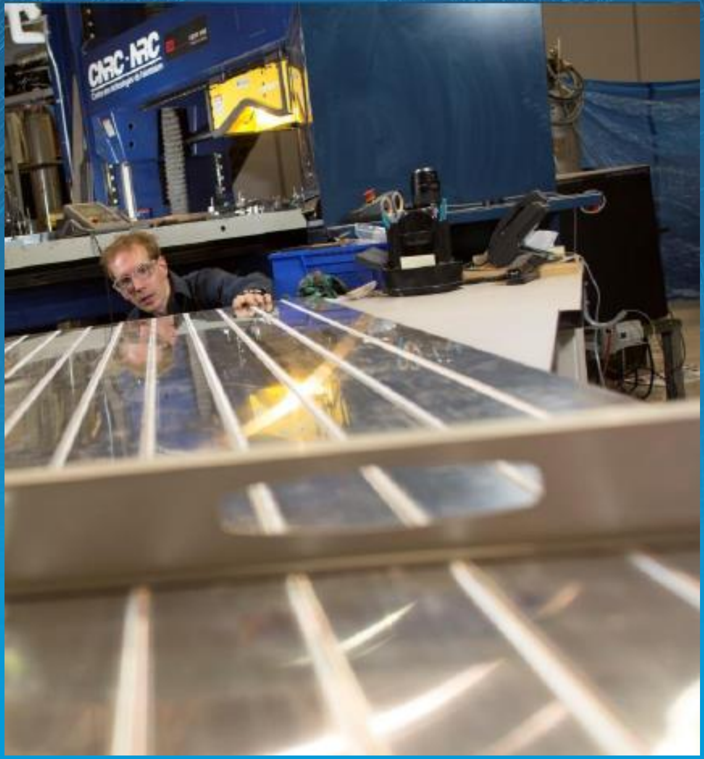
Developments in friction stir & spot welding: tailored blanks & Al/Steel joining techniques



Global Automotive Lightweight Materials 2015

François Nadeau ing., M.Sc.
NRC-Saguenay
April 14th 2015

Who's NRC ?

NRC:
- 4000 employees accross Canada

NRC (Saguenay):
- 35 employees

NRC-Saguenay (Aluminium Technology Centre)

Shaping

Extrusion

Hot/warm/cold forming

Hydroforming

Semi-solid casting (SEED)

Joining

Structural adhesives

Surface treatment

Environmental durability

Hybrid joining

Welding processes

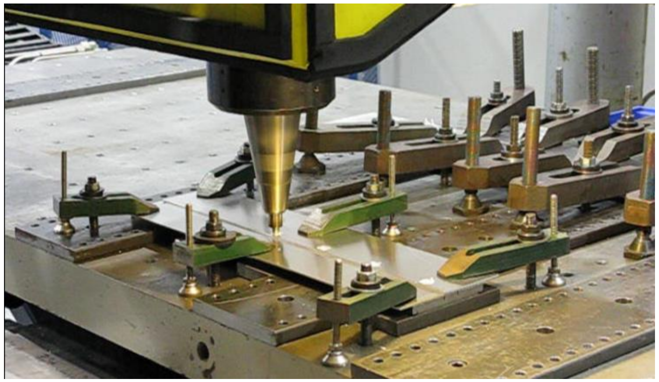
GMAW/GTAW

Laser & HLAW welding

Friction stir welding

Corrosion

Outline



Tailor welded blanks: FSW & laser comparison

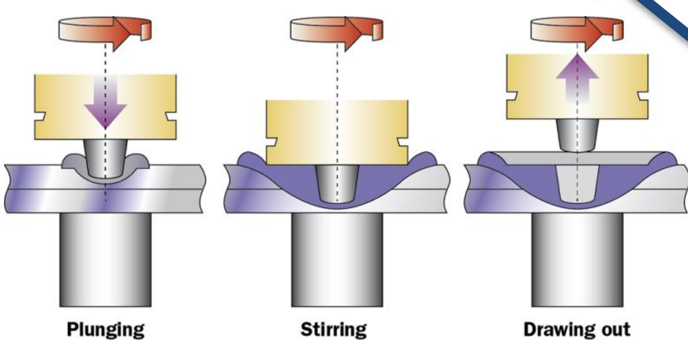
Gantry FSW systems

FSSW: techniques & joint performance

Robotic FSW/FSSW systems

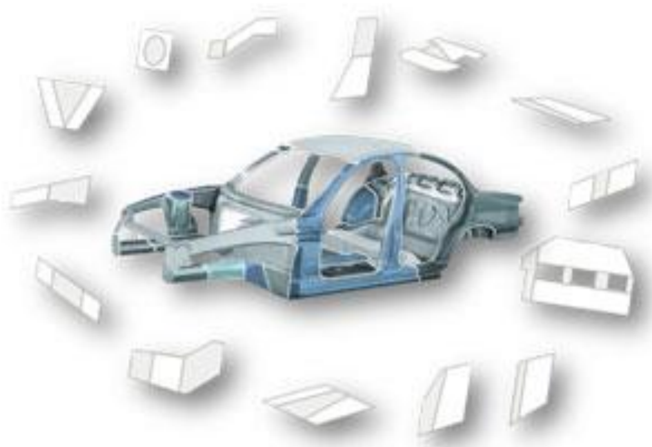
FSW Al/Steel: techniques & joint performance

Hybrid joining: welding processes + adhesives

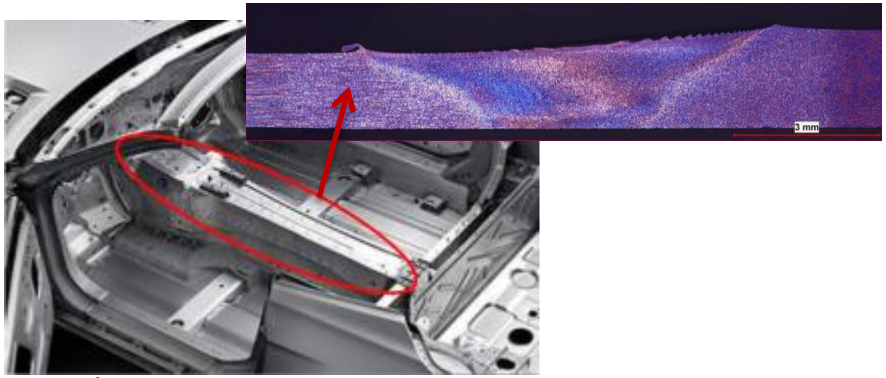


Tailor welded blanks: FSW & laser comparison

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

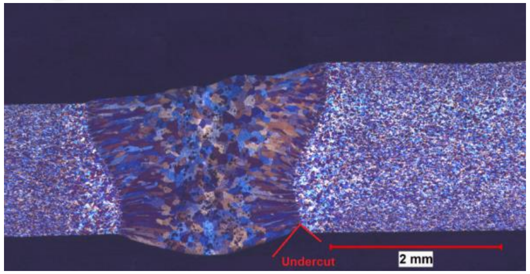


Friction stir welding



Mercedes SL

Autogenous laser welding



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

Thickness ratio	Approximate weight savings (part)
1.5 : 1	≈ 15 %
2 : 1	≈ 30 %

Tailor welded blanks: FSW & laser comparison

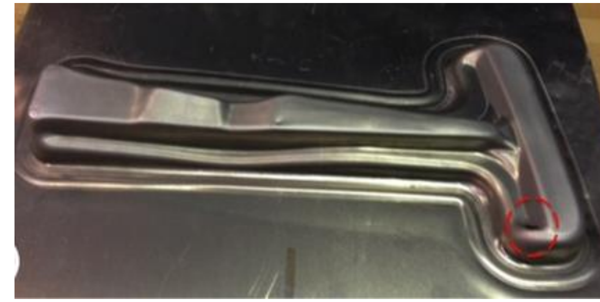
Cold forming

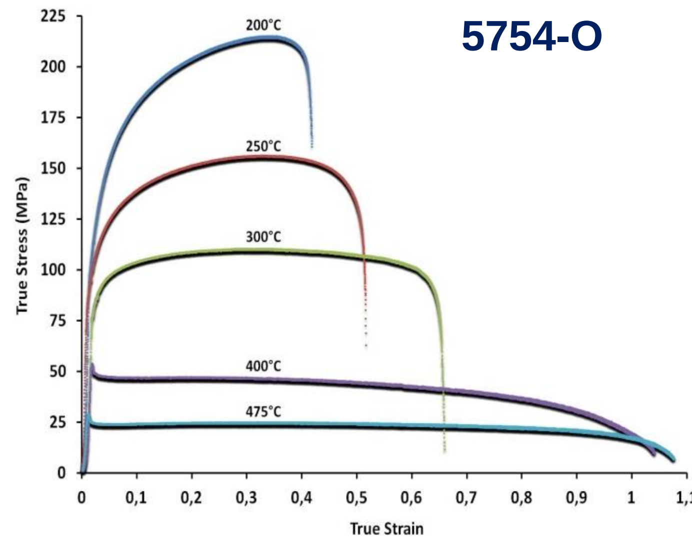
Room temperature

Warm forming

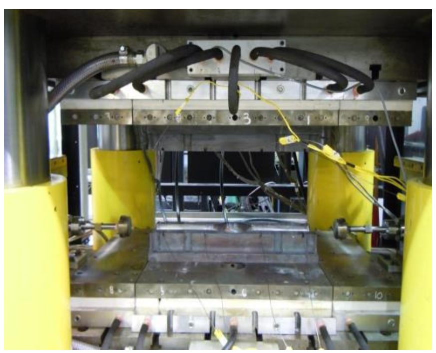
200°C @ 350°C

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





5754-O



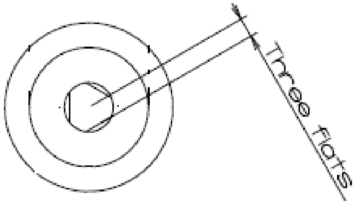
Hot stamping

400°C @ 530°C

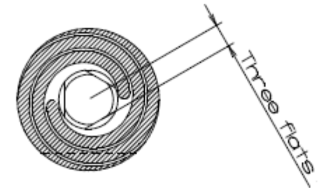
7075-T6

- Solution heat treatment
- Quench
- Artificial aging

Tailor welded blanks: FSW & laser comparison



Cup ← **FSW (shoulder design)** → Convex-scroll



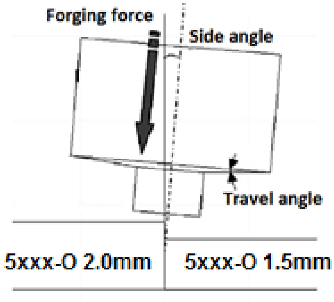
Good weldability at high travel speed: at least 3.0 m/min

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



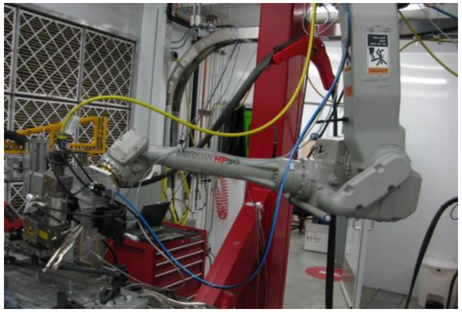
Pin tool (Φ 12.0 mm)

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

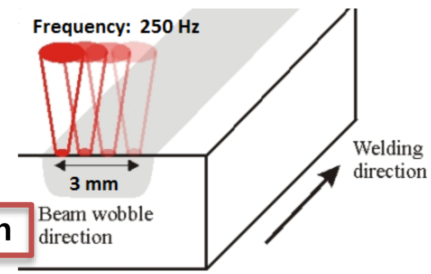
Tailor welded blanks: FSW & laser comparison

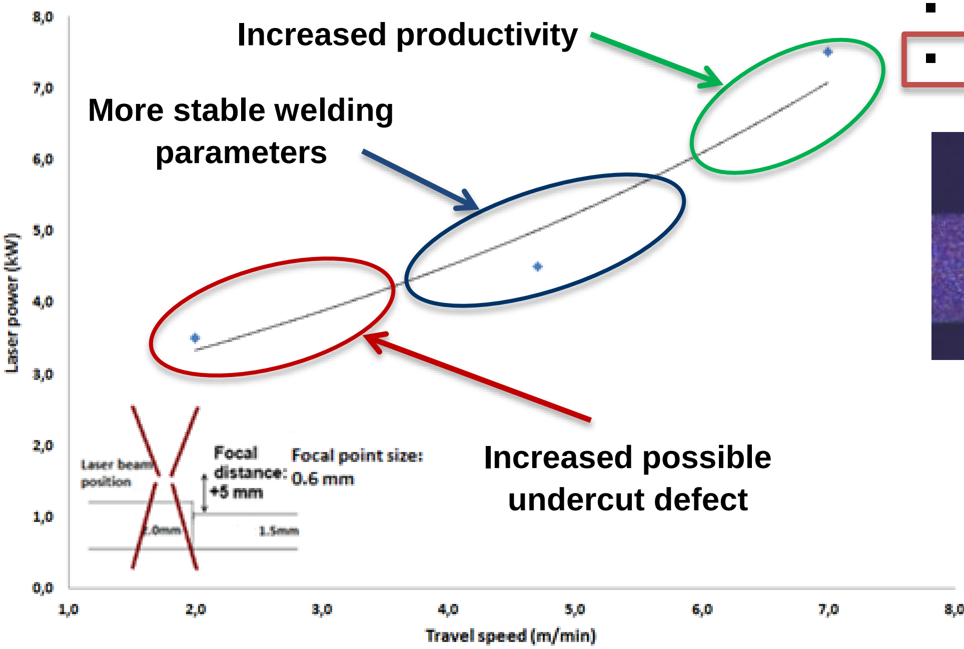


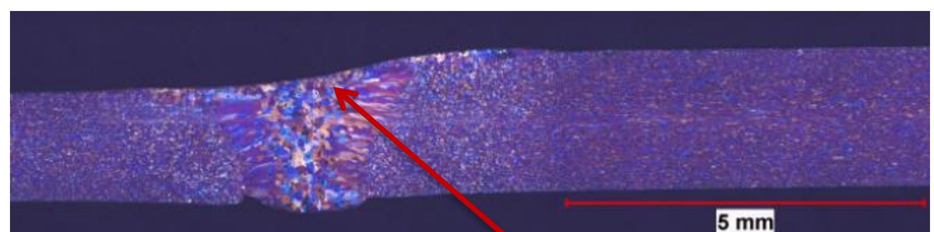
Robot (single pass)

'Remote on the fly' (double-pass)

- First pass: 7.5 kW, 7.0 m/min
- Second pass: 4.0 kW, 2.0 m/min

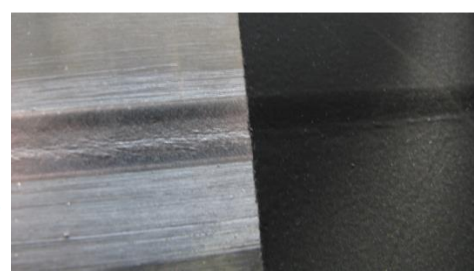




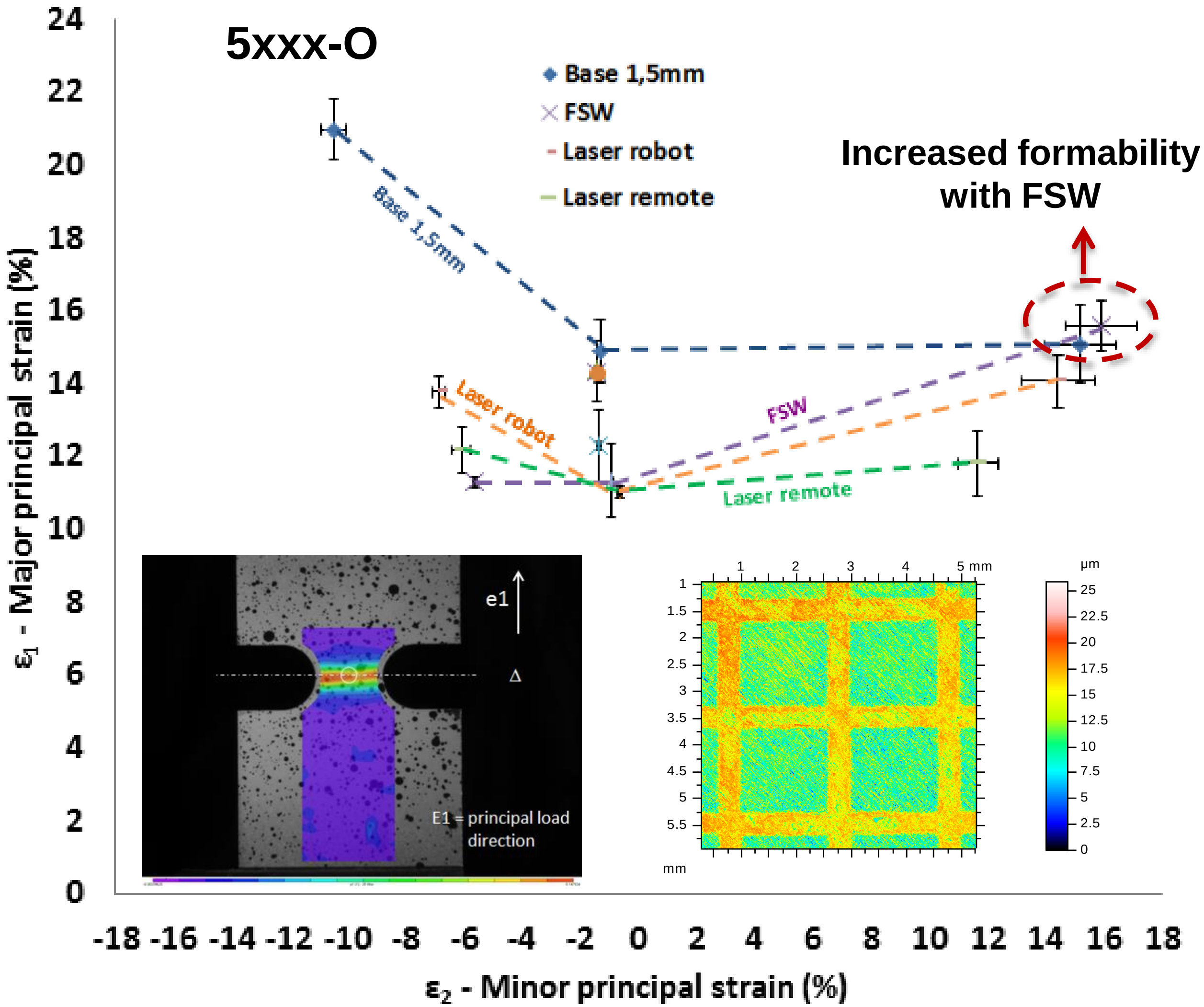


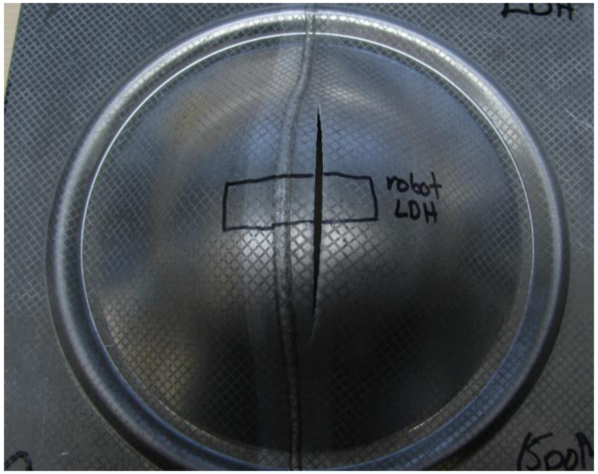
Smoother surface finish

Limitation of undercuts



Tailor welded blanks: FSW & laser comparison





FSW

Laser robot

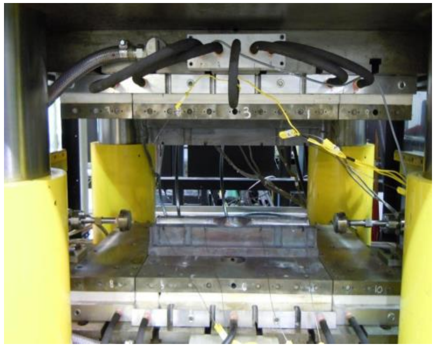
Tailor welded blanks: FSW & laser comparison

Cold forming

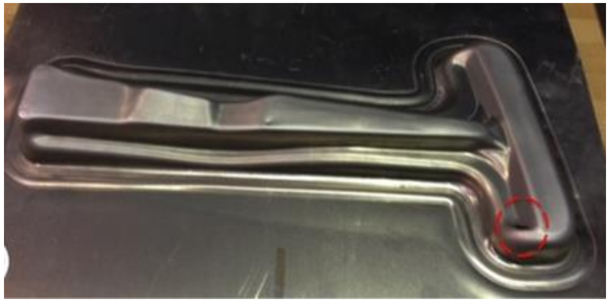
Room temperature

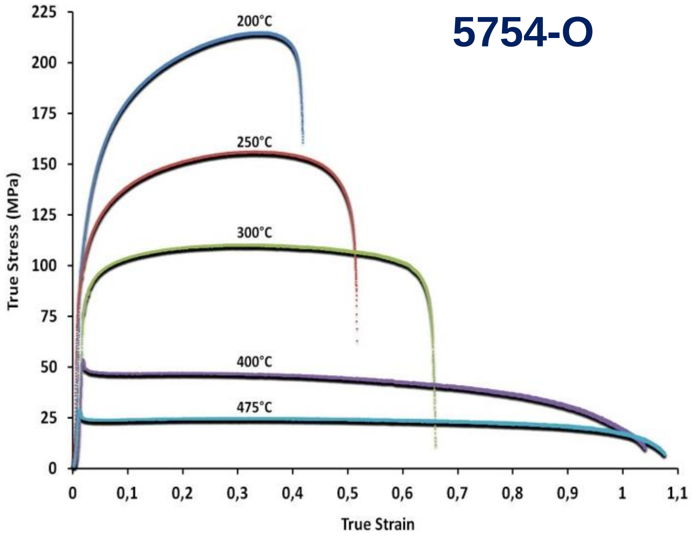
Warm forming

200°C @ 350°C



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





Hot stamping

400°C @ 530°C

7075-T6

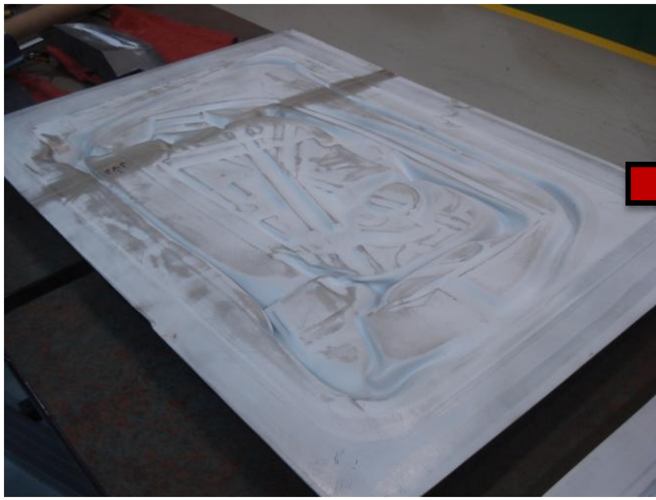
- Solution heat treatment
- Quench
- Artificial aging

Tailor welded blanks: FSW & laser comparison

Hot forming issues with FSW of tailor welded blanks…

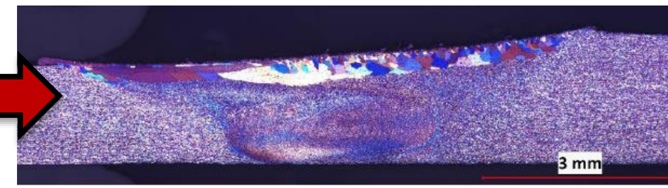
Audi

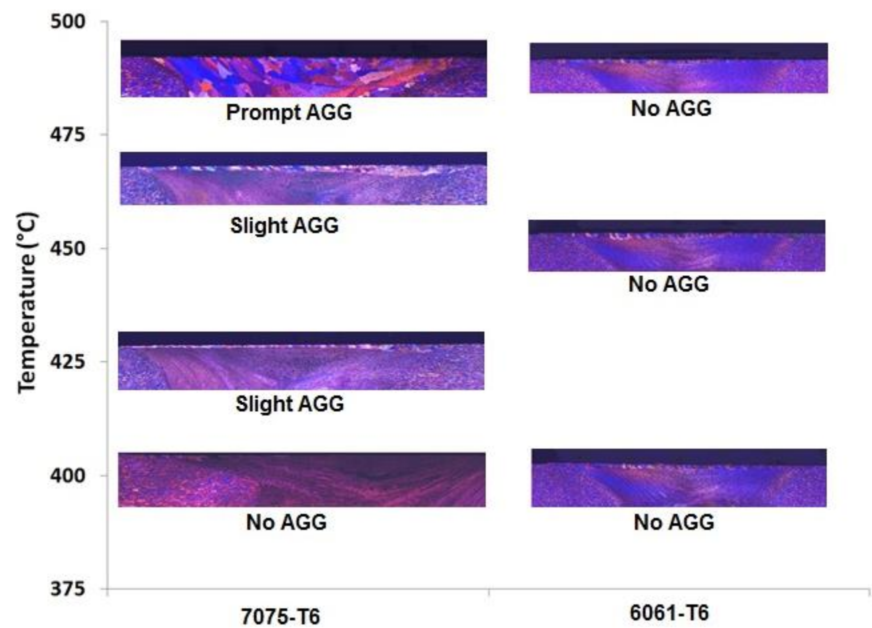
Aluminum B-pillar



5083 SPF part, 1.5 / 2.0 mm

Abnormal grain growth (AGG)

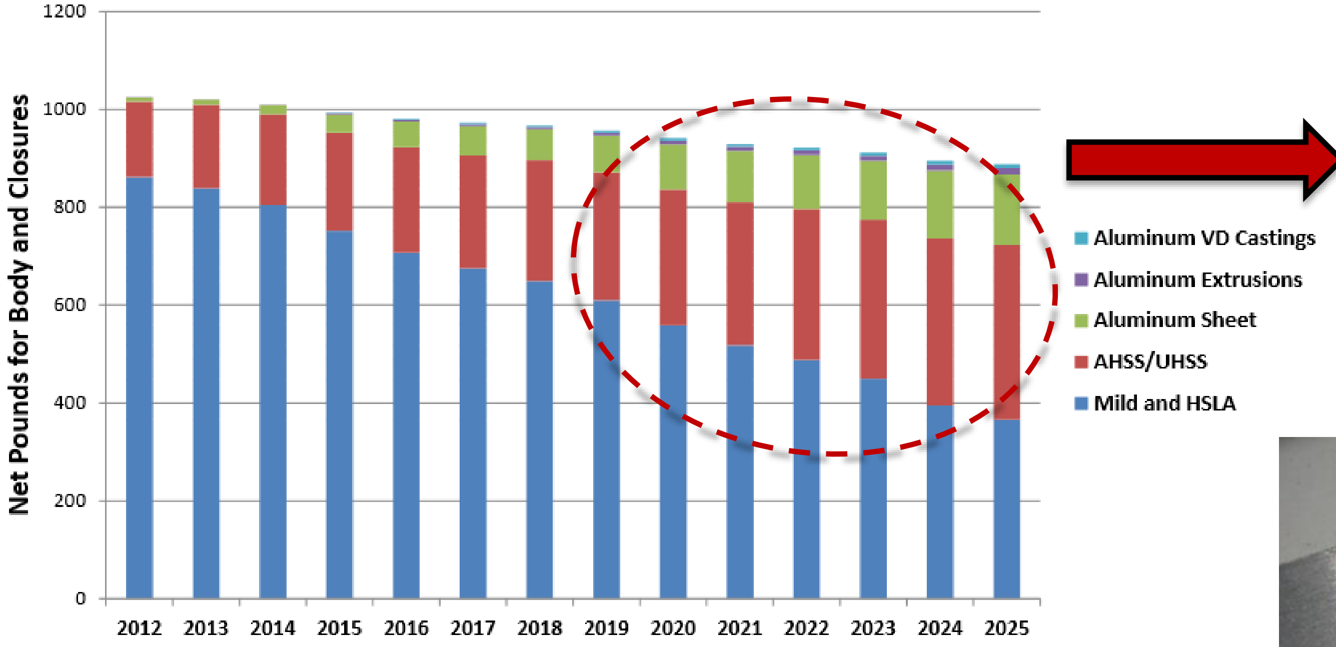




- **High travel speed:**
- **Lower heat input (thin sheet):** ⇧ **AGG**

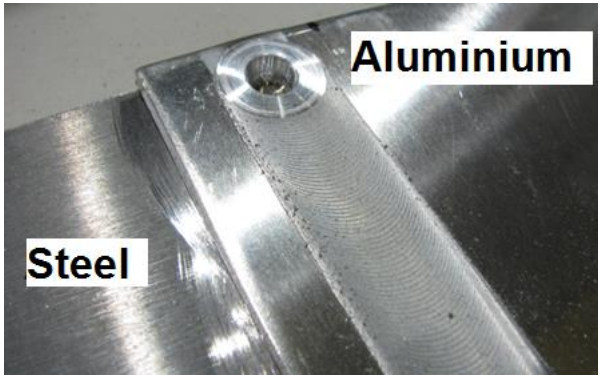
FSW of Al/Steel: techniques & joint performance

- **Automotive trend toward dissimilar material joining (average body & closures)**



Ducker worldwide (2015)

Constant growth of…
- **Aluminum**
- **AHSS/UHSS**



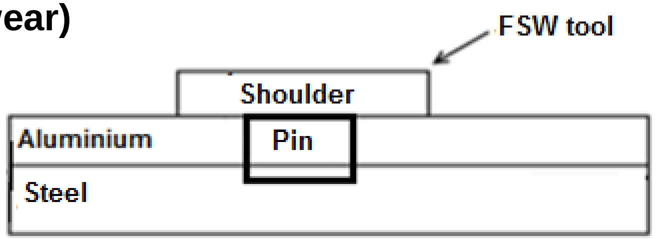
- **Current fusion welding processes need improvement**
  - **Metallurgical incompatibility (fragile intermetallics)**
- **Solid-state joining processes (FSW) are attractive in this regard**

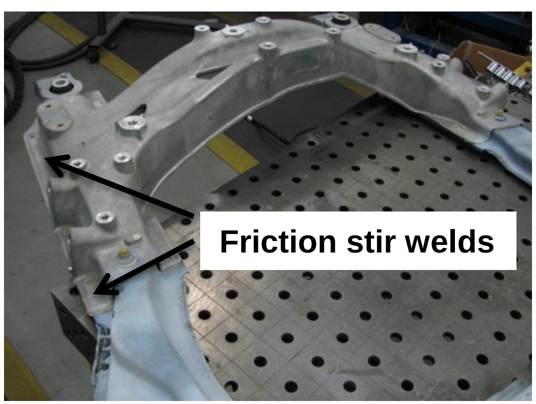
FSW of Al/Steel: techniques & joint performance

- **Friction stir welding (Al / Steel)**

Conventionnal

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

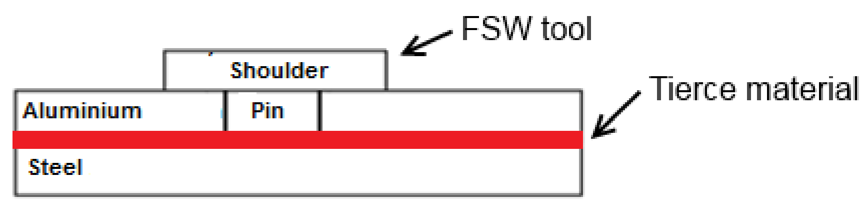




Honda

Assisted FSW (NRC)

- **FSW pin tool <u>do not enter</u> into substrate**
- **Typical tool materials for Al / Al FSW**



- **Passed 90° bend**

FSW of Al/Steel: techniques & joint performance

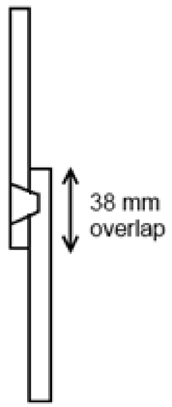
- **Conventionnal FSW (Al / Steel)**
  - **Joint performance**

Aluminum sheet thickness	Shoulder & pin diameters	Forge force	Joint resistance Load / weld length[1]
mm	mm	kN	N / mm
≈ 1.0 - 2.0	11.0 / 4.0	9.75	316.5 +/- 14.1
≈ 3.0	14.0 / 5.0	12.00	431.2 +/- 51.8

[1]Joint failure at interface

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

Single lap-shear test

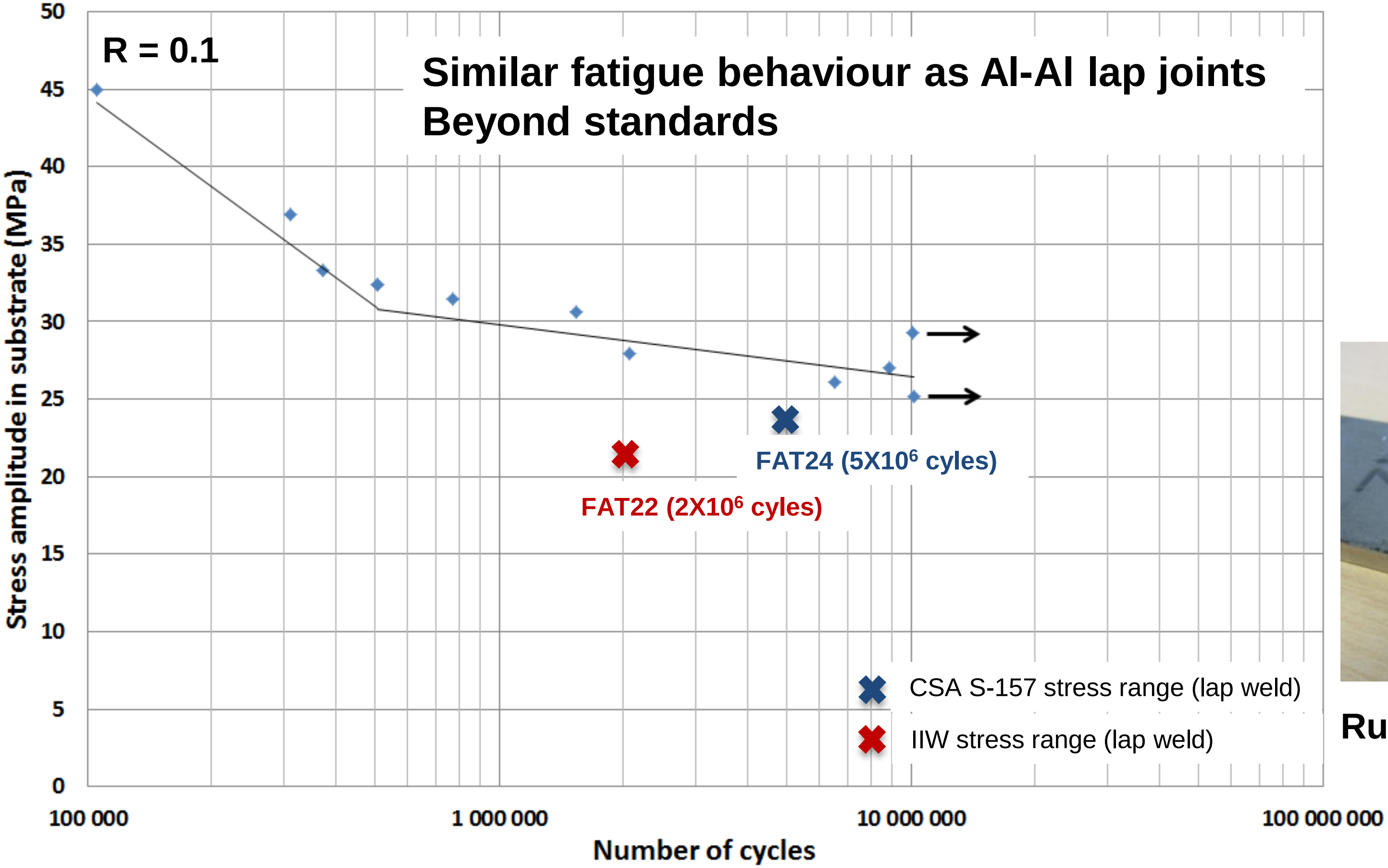


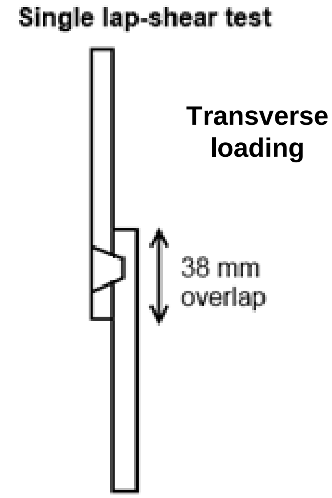
Increased interface length yields higher joint resistance

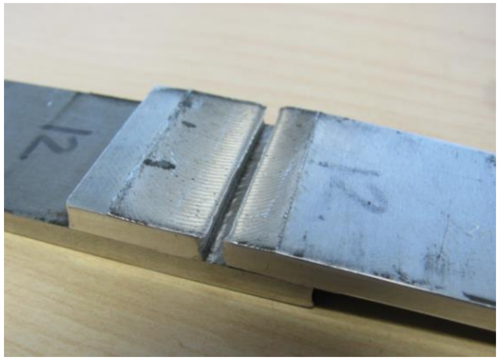
(≈ 80% joint efficiency vs FSW Al/Al)

FSW of Al/Steel: techniques & joint performance

- **Conventionnal FSW (Al / Steel)**
  - **Joint performance (fatigue)**





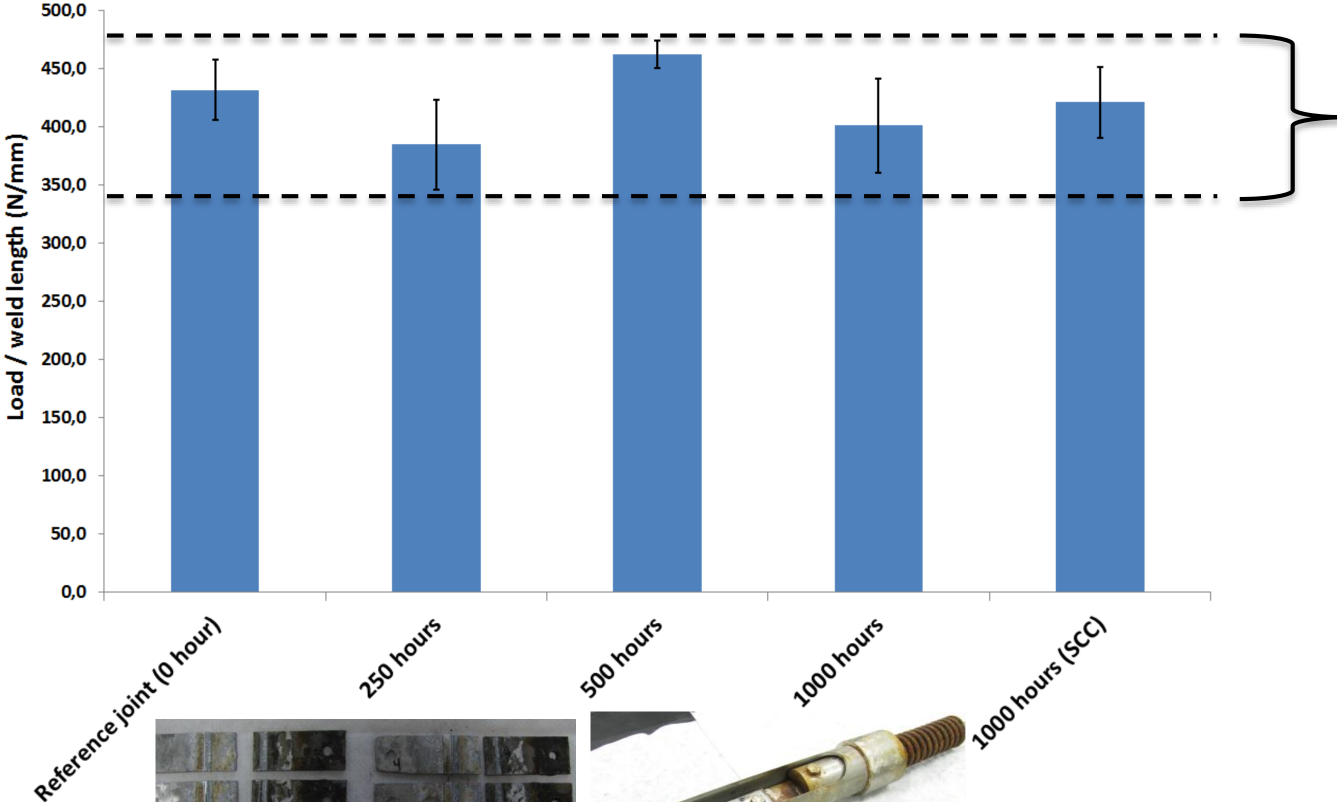


Rupture through:

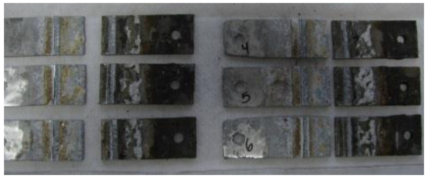
- **Al top sheet**
- **Retreating side**

FSW of Al/Steel: techniques & joint performance

- **Conventionnal FSW (Al / Steel)**
  - ➢ **Environmental durability performance**



Static mechanical properties not clearly affected in durability testing



*SCC load: 22% of single lap shear strength

GM9505P Cycle G (30 cycles)

- 2 hours @ -30ºC
- 2 hours @ room temperature
- 2 hours @ 70ºC
- 2 hours in environmental chamber
  - ➢ 2 hours in salt spray
  - ➢ 16 hours in high humidity

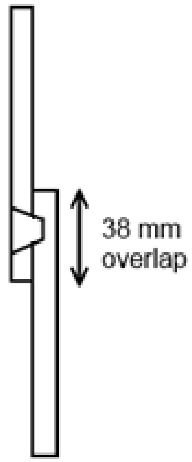
FSW of Al/Steel: techniques & joint performance

- **Assisted FSW - NRC (Al / Steel)**
  - **Joint performance**

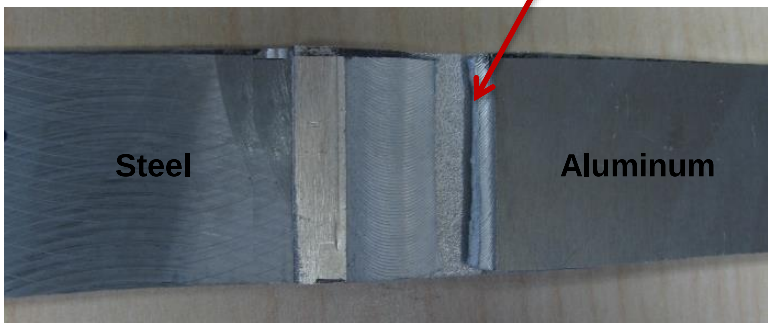
Tierce material	Shoulder diameter	Forge force	Joint resistance Load / weld length
	mm	kN	N / mm
Conventionnal FSW	11.0	9.75	316.5 +/- 14.1[1]
Lower-strength method	11.0	5.00	234.8 +/- 5.6[1]
	18.0	13.50	338.0 +/- 7.6[1]
Higher-strength method	11.0	5.00	408.8 +/- 0.7[2]

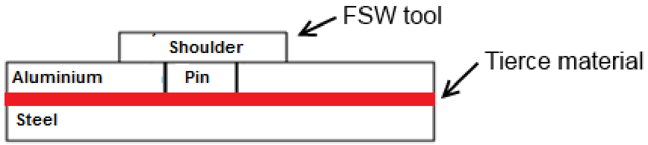
[1]Joint failure at interface
[2]Joint failure in base material (2.0mm thick)

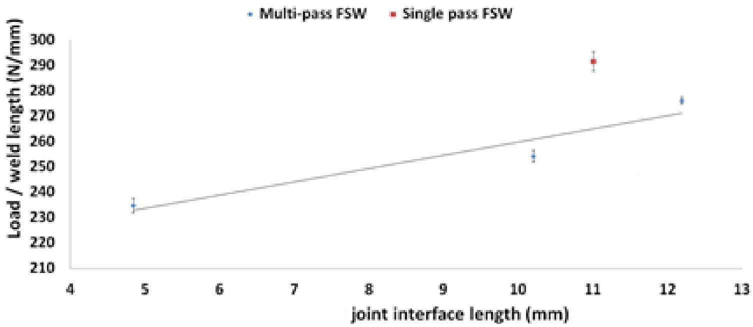
Single lap-shear test



Failure in base material



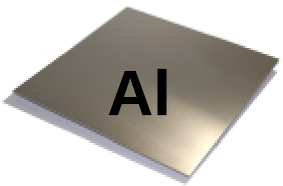




Hybrid joining:
welding processes / structural adhesives

Pre-welding application of adhesive

Post-welding application of adhesive



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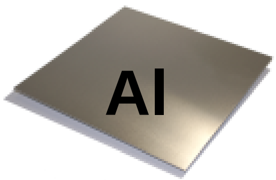
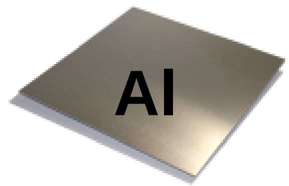


OR



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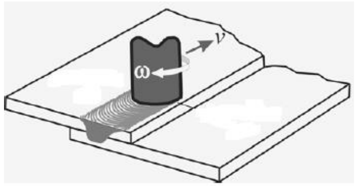
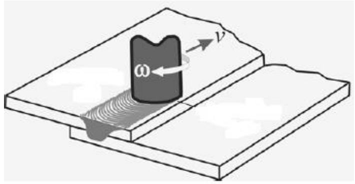
Step 1

Step 2



Step 1



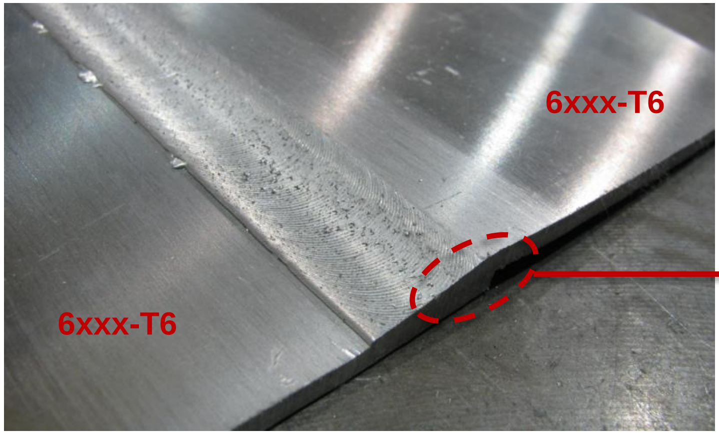
Step 2

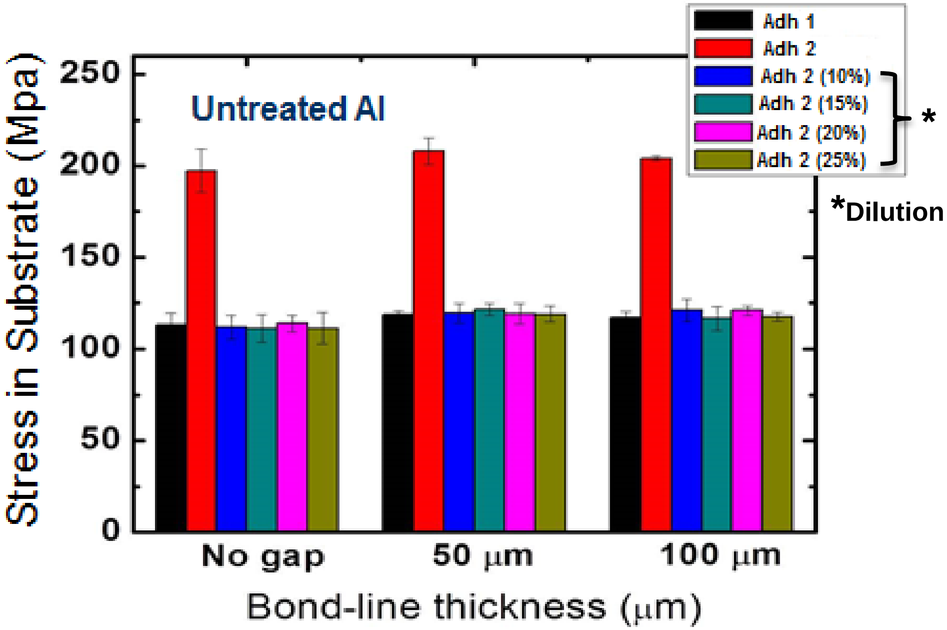
Hybrid joining: welding processes / structural adhesives

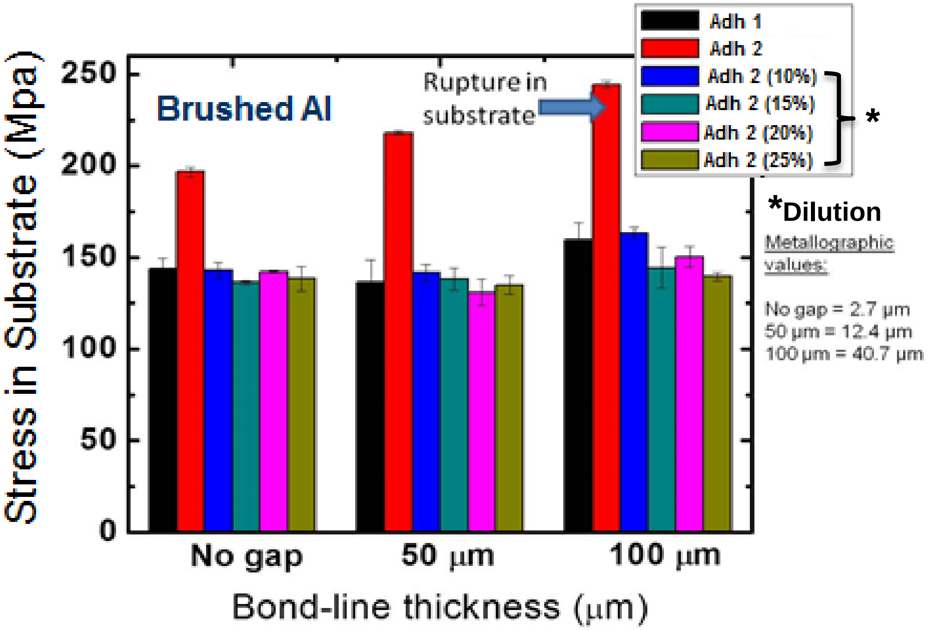
- **Al / Al hybrid joining**
  - **FSW**

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

Up to + 105% joint strength in hybrid joining (brushed Al) vs FSW

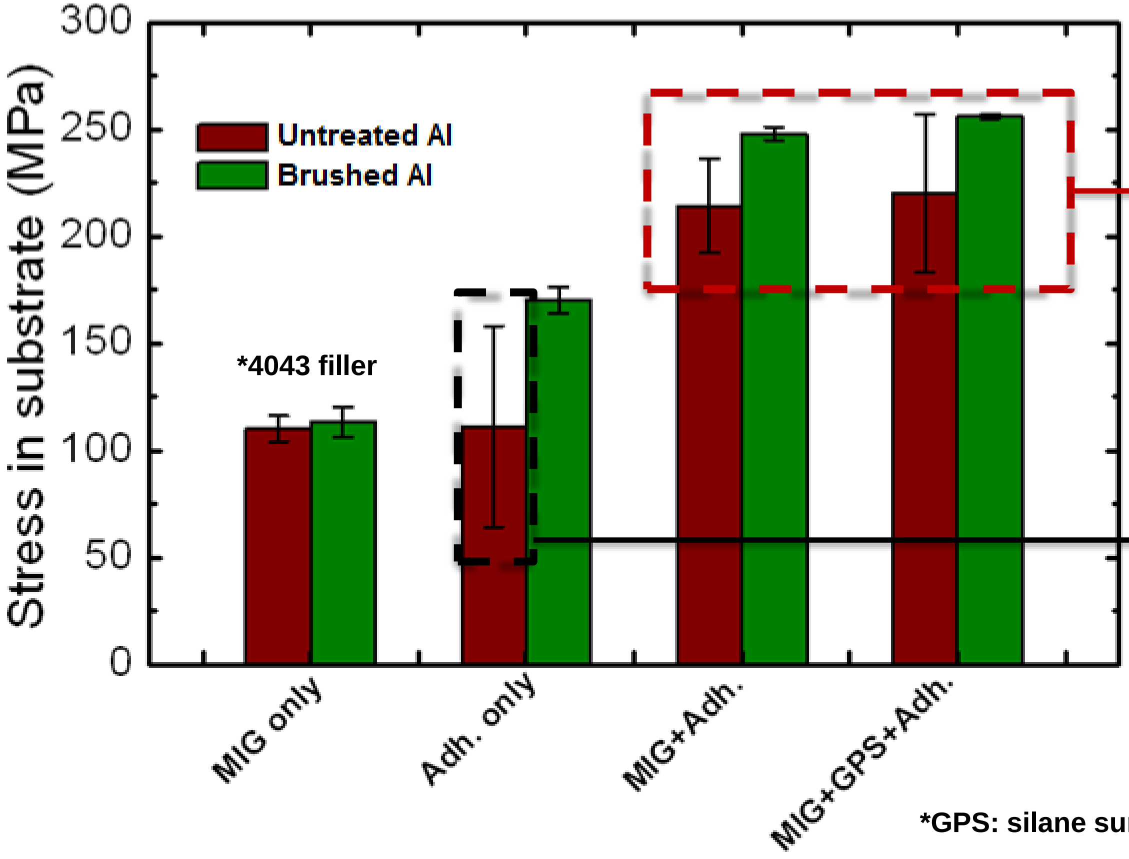


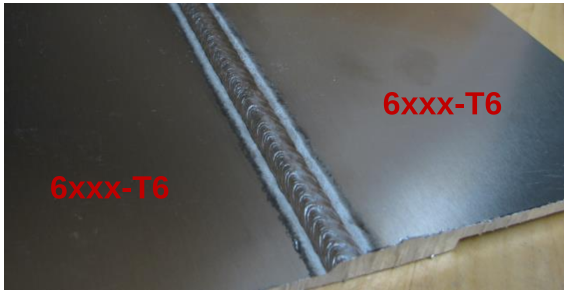




Hybrid joining:
welding processes / structural adhesives

- **Al / Al hybrid joining**
  - **GMAW (MIG)**





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

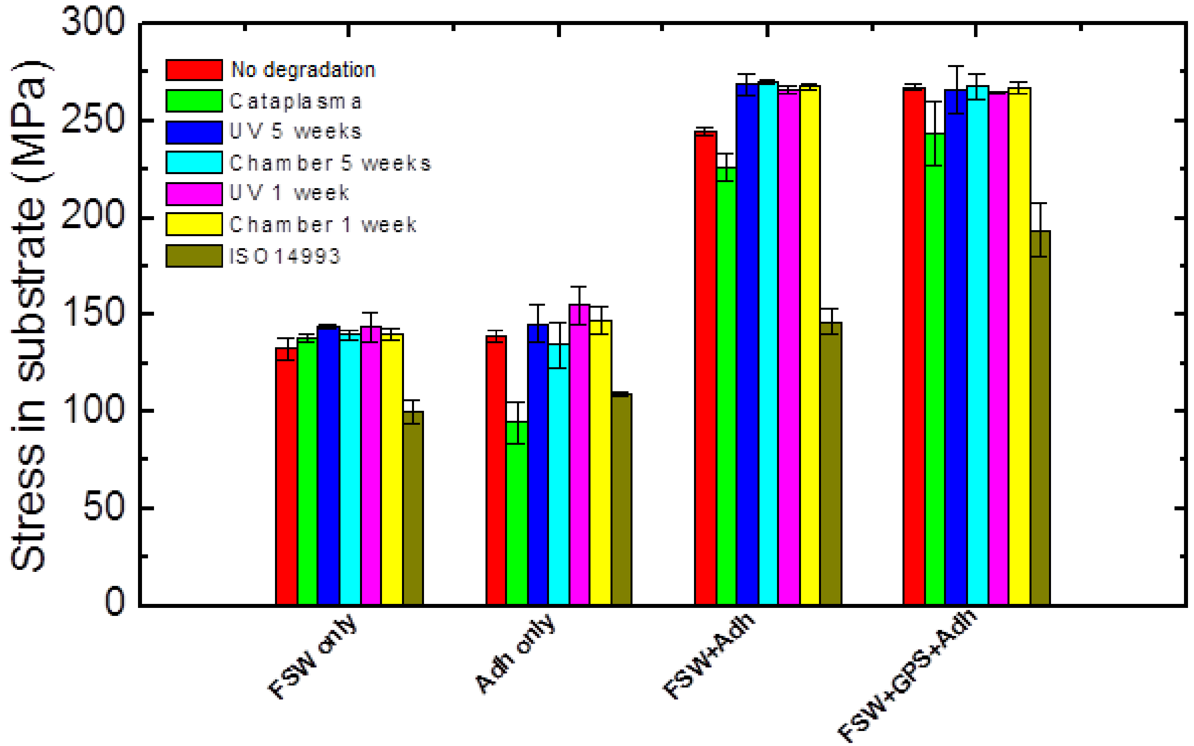
No major gain using a silane surface treatment

Adhesive application on untreated surface gives unpredictable results

***GPS: silane surface treatment**

Hybrid joining:
welding processes / structural adhesives

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



➢**Cataplsama degradation (Jaguar JNS 30.03.35 standard)**

➢ **UV (5 weeks; wet & dry) (ISO 11507: alternative exposure of 4 h UV at 60 ºC and 4 h condensation (100% RH) at 50 ºC 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 ºC; in other words 168 h of UV exposure at 60 ºC)**

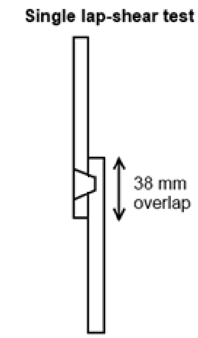
➢ **Chamber 1 week (dry conditions; replica of ASTM D-904 without UV)**

➢ **Cyclic corrosion (ISO 14993)**

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

Hybrid joining:
welding processes / structural adhesives

- **Al / Steel hybrid joining (FSW)**
  - **Joint performance**

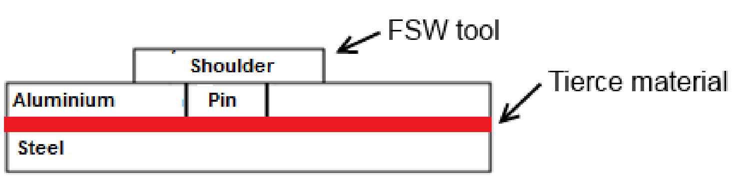


Tierce material	Shoulder diameter	Forge force	Joint resistance Load / weld length
	mm	kN	N / mm
Conventionnal FSW	14.0	12.0	431.2 +/- 51.8[1]
Assisted FSW	11.0	5.00	234.8 +/- 5.6[1]
	18.0	13.5	338.0 +/- 7.6[1]
Hybrid-conventionnal FSW	14.0	12.0	415.9 +/- 38.7[1]
Hybrid-assisted FSW	11.0	5.00	400.3 +/- 14.8[2]

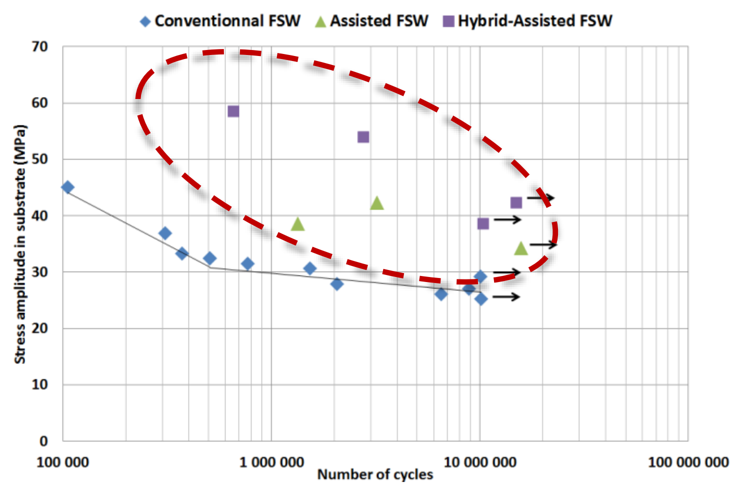
No joint strength increases using hybrid joining in conventionnal FSW

[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 conventionnal FSW



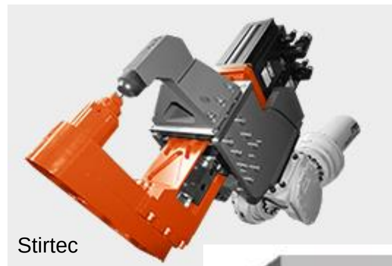
FSSW: techniques & joint performance

Joining processes

Resistance spot welding

Centerline

Friction stir spot welding

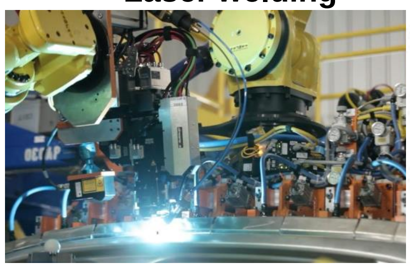


Stirtec

Self-piercing rivets

Henrob

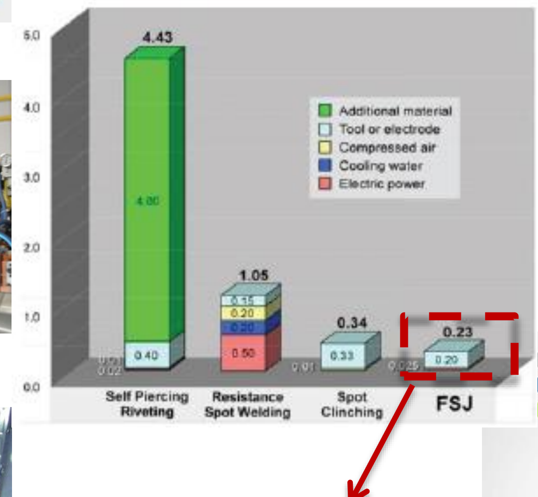
Laser welding



General Motors Co.

Clinching

Tox pressotechnik



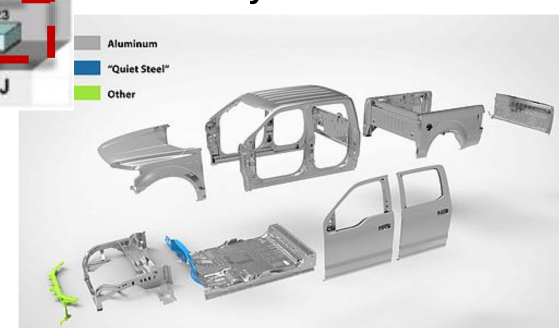
Typically low production cost

Typical applications

B-pillar

Chevrolet Corvette

Body-in-white

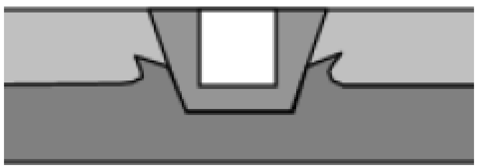


Ford F-150

FSSW: techniques & joint performance

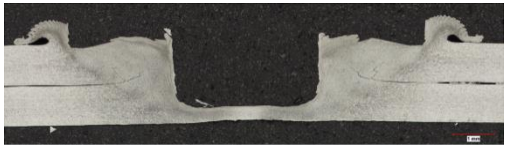
FSSW (Friction Stir Spot Welding)

FSSW



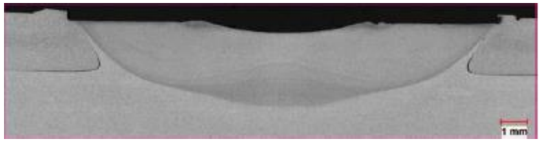
Huys Industries

Kawasaki

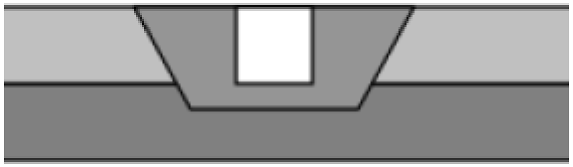


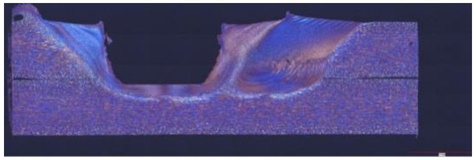
Refill FSSW

Lower-size robot (C-frame)



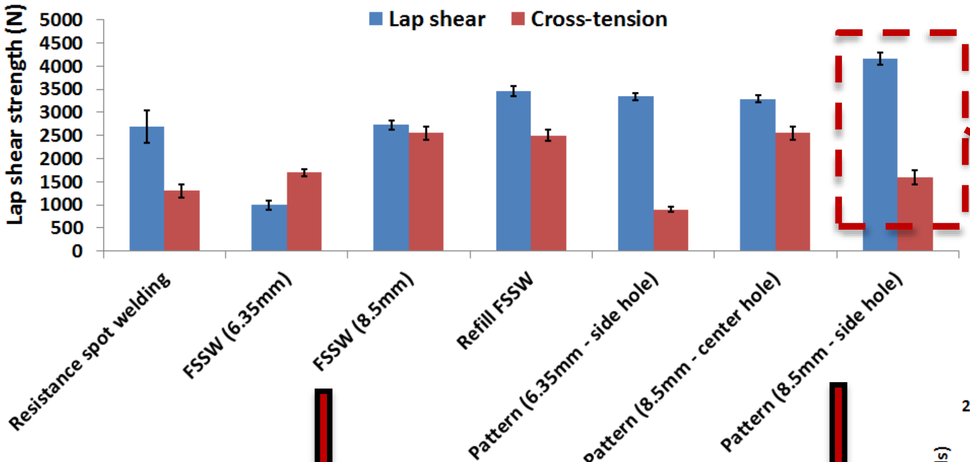
Pattern FSSW

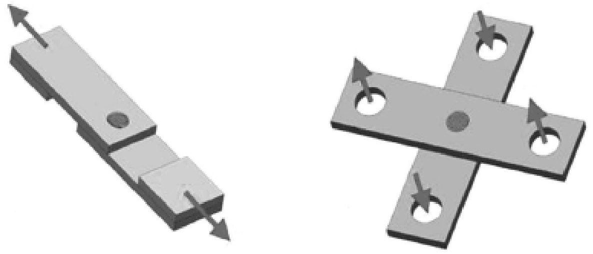




FSSW: techniques & joint performance

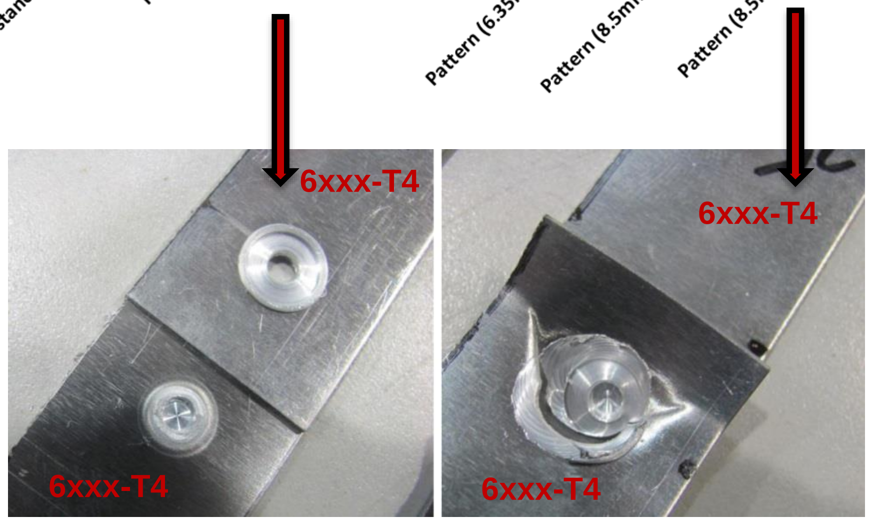
- **FSSW (Friction Stir Spot Welding)**
  - **Joint performance**

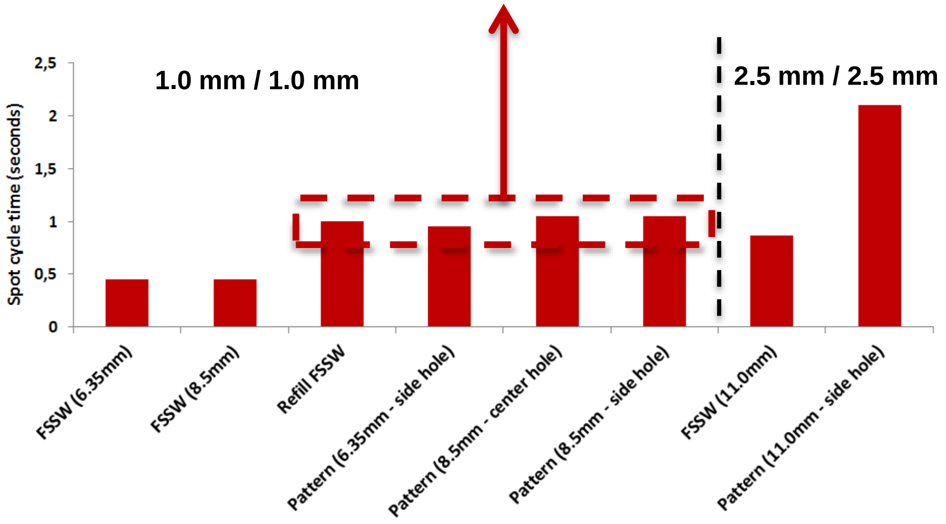




Pattern FSSW

- Highest lap shear strength
- Acceptable cross-tension strength
- Same cycle time





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

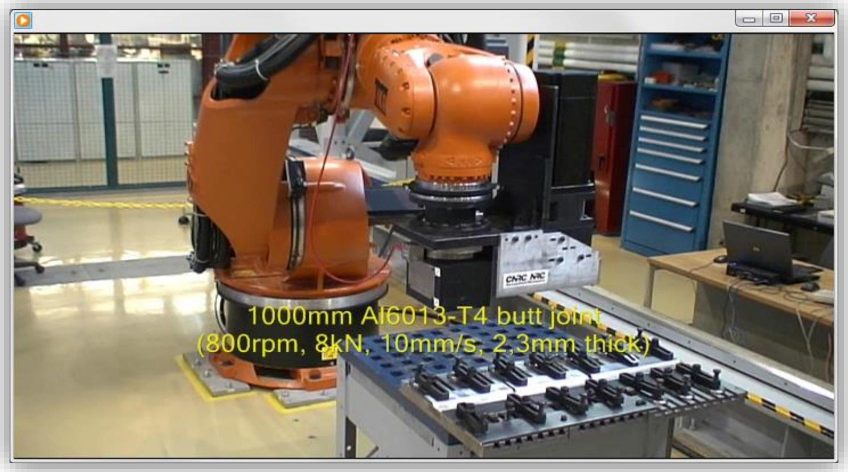
- In-house robotic FSW process (KRL,RSI) and workcell supervisory control
- In-house hybrid force control (RSI)
- Management of FSW spindle (ProfiBus)
- Process supervision module
- Recovery modes (tool auto retract)
- Human Machine Interface

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



RSI-based (KRC2 12ms) real-time control features:

- Hybrid position/force control module
- Control of tool plunge + transient regime

Accuracy management

National Research Council Canada — Conseil national de recherches Canada

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

Automated FSW fixture

National Research Council Canada — Conseil national de recherches Canada

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

FSW tools - parameters

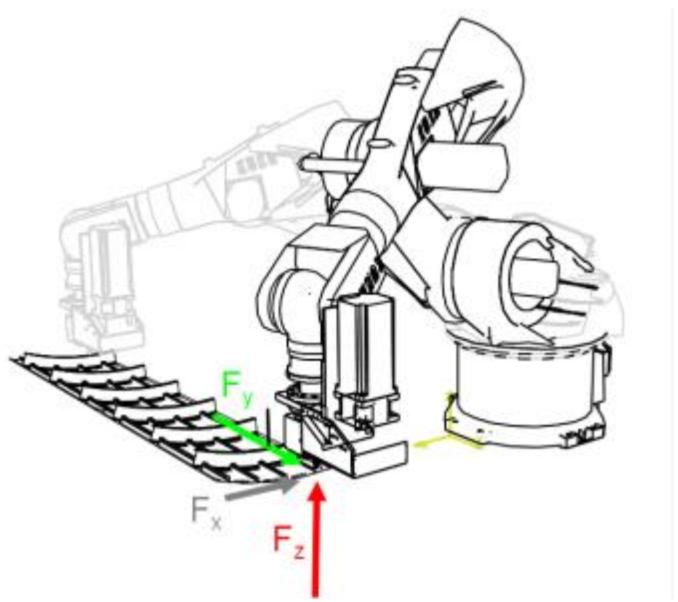
National Research Council Canada — Conseil national de recherches Canada

- 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)

Robotic FSW developments

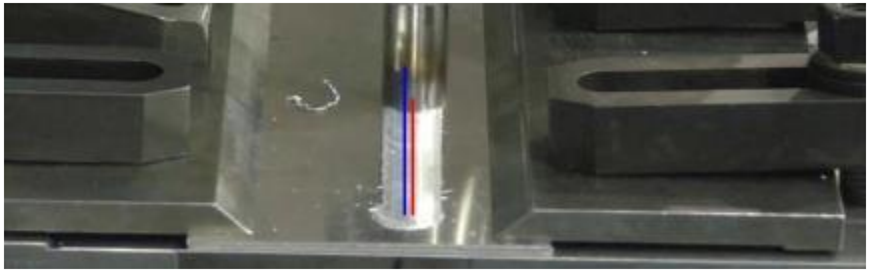
- **Robotic friction stir welding: Control challenges**

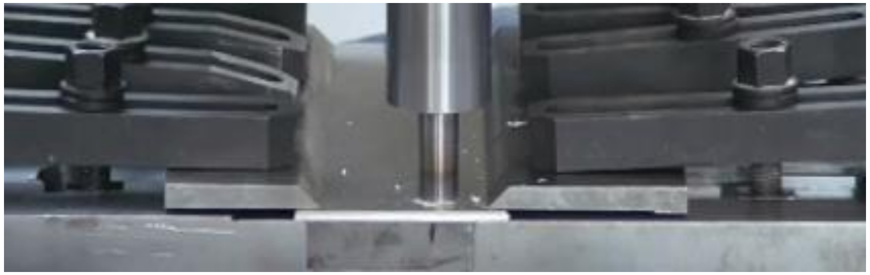
Elastodynamic behavior of serial robots



- 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

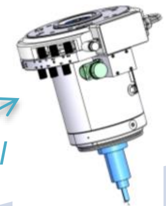




Al 2024-T3 (2x2,3mm) Lap joint, 750rpm (robot natural frequency)

Robotic FSW developments

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



accuracy performance

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

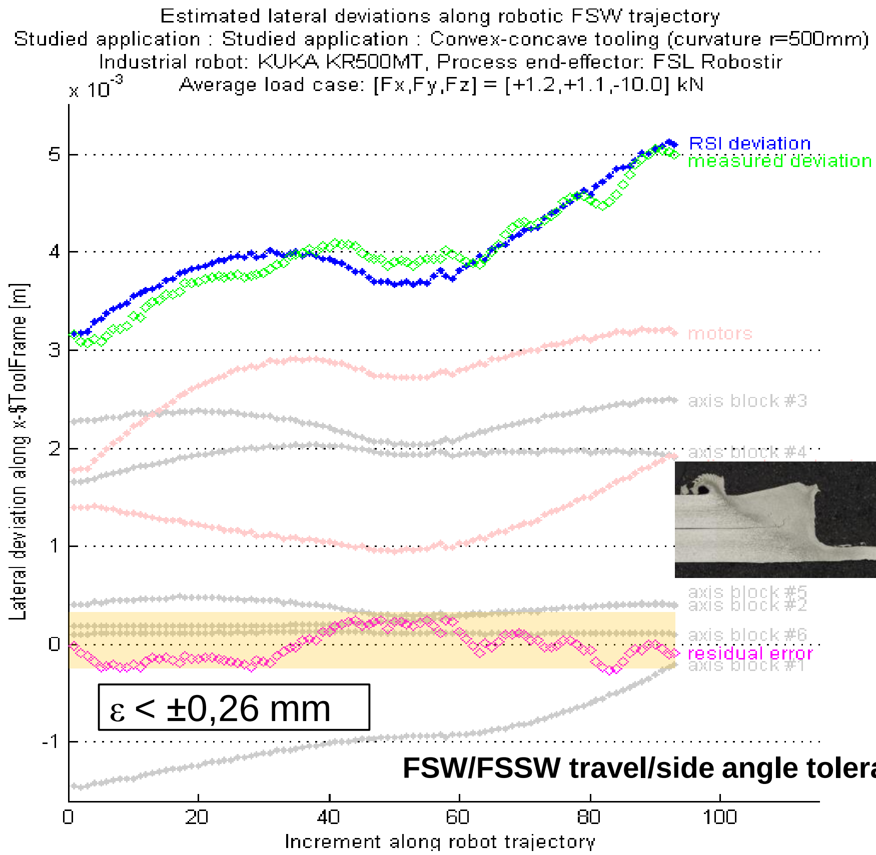
Standard kinematic calibration
> Calibration of robot path generation errors in free motion (e.g.: KUKA Absolute Accuracy)
> Local robot/tooling calibration

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



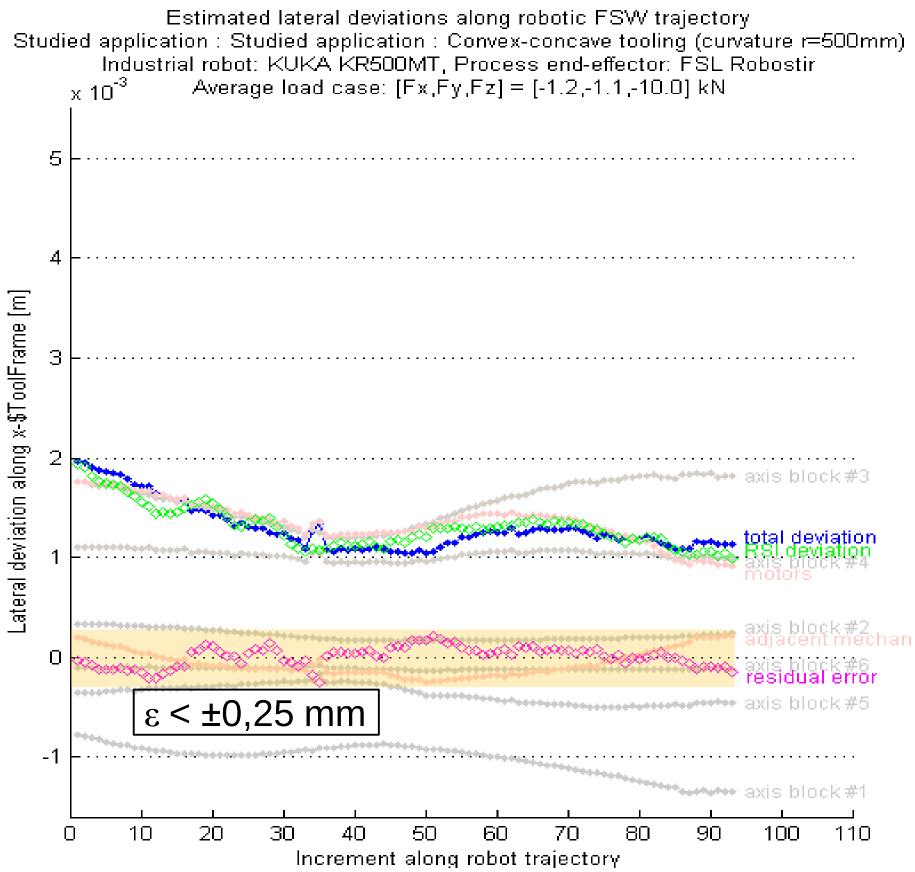
FSW/FSSW travel/side angle tolerances: +/- 1°

Process forces: Fx = 1,2 kN, Fy = 1,1 kN, Fz = 10 kN
Hybrid position/force control

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



Process forces: Fx = 1,2 kN, Fy = 1,1 kN, Fz = 10 kN
Hybrid position/force control

Questions ?

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