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Evaluating the Upset Protrusion Joining (UPJ) Method to Join Magnesium Castings to Dissimilar Metals

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Content

- Challenges of joining magnesium castings to dissimilar metals
- Benchmark joint performance results for magnesium die-castings to aluminum sheet material using a current state-of-the-art joining process
- Introduction of the UPJ joining process for joining magnesium castings to dissimilar metals
- UPJ joint performance results with comparisons to benchmark joint performance

Mass Reduction Potential (typical)

- High strength steels (5-10%)
- SMC (20-30%)
- Cast aluminum (25-35%)
- Thermoplastic polymer composites (30-40%)
- Sheet, extruded, and forged aluminum (40-50%)
- Die cast magnesium (40-60%)
- Sheet, extruded, and forged magnesium (55-70%)
- Carbon fiber prepreg composites (60-70%)

Best Practices

- Best practice is thin-wall die casting
  - Mg die casting can be very cost effective
    - Reasonable material cost
    - High level of component integration capability
      - Reduces investment and assembly costs
    - Compared to aluminum, thinner section capability with less draft
    - 2-3 times longer die life than aluminum
    - Excellent dimensional integrity
    - No need to heat treat

Best Practices

- Common examples include:
  - Instrument panel structures
    - As many as 20 stamped steel components combined into one die casting at slightly more than ½ the weight
  - Steering wheel armatures
  - Steering column mounting brackets
  - Seat structures
  - Closure inner panels
  - Transmission and transfer case housings

Why Magnesium?

- Best mass reduction potential of all metals (comparable to carbon fiber composites at much lower cost)
  - Density
    - Density - 1/4 that of steel (2/3 that of aluminum)
  - Weight for equivalent bending stiffness
    - 62% lighter than steel (23% lighter than aluminum)
  - Bending stiffness for same weight
    - 18 times stiffer than steel (2.3 times stiffer than aluminum)
    - For bending ***strength***, reductions are similar to those for ***stiffness*** depending on specific alloys being compared
  - In practice - lightest structural metal - capable of substantial (40-60%) weight reductions over steel

Best Practices Example – Viper Front of Dash

<u>**Feature Integration**</u>

Steering column attachment

HVAC opening

Brake booster attachments

Pedal attachments

Wire harness attachments

IP structure attachments

Door hinge attachments

Hood hinge attachments

“A” pillar mounting attachments

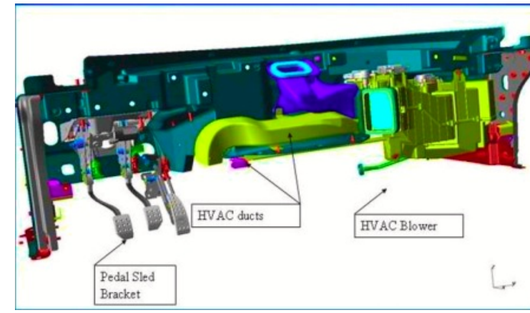
Weight Reduction – 15.4 Kg (51%)

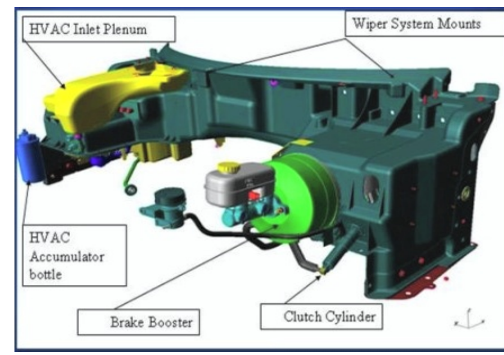
Cost Reduction – ~30%

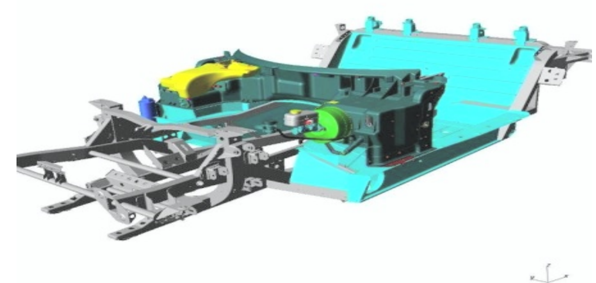
Part Integration – 51 parts replaced by 10 parts

Low volume application <5,000/yr

Viper Front of Dash







Why Not Magnesium?

- Joining Difficulties
- ***Galvanic*** corrosion
- ***Coating*** compatibility
  - Process sequence is critical

These are confounding factors that must be addressed together

- Limited infrastructure and supply base
  - Primary material production largely limited to China
- Limited knowledge base
  - Especially wrt corrosion performance

Galvanic Corrosion

Alloy		Voltage Range of Alloy vs. Reference Electrode
Magnesium	Anodic	-1.60 to -1.63
Zinc	(Least Noble)	-0.98 to -1.03
Aluminum Alloys		-0.70 to -0.90
Cast irons		-0.60 to -0.72
Steel		-0.60 to -0.70
Aluminum Bronze		-0.30 to -0.40
Copper		-0.28 to -0.36
Lead-Tin Solder (50/50)		-0.26 to -0.35
Manganese Bronze		-0.25 to -0.33
400 Series Stainless Steels		-0.20 to -0.35
90-10 Copper Nickel		-0.21 to -0.28
Lead		-0.19 to -0.25
70-30 Copper-Nickel		-0.13 to -0.22
17-4 PH Stainless Steel		-0.10 to -0.20
Silver		-0.09 to -0.14
Monel		-0.04 to -0.14
300 Series Stainless Steels		-0.00 to -0.15
Titanium and Titanium Alloys		+0.06 to -0.05
Inconel 625		+0.10 to -0.04
Platinum	Cathodic	+0.25 to +0.18
Graphite	(Most Noble)	+0.30 to +0.20

Galvanic Series in Flowing Seawater

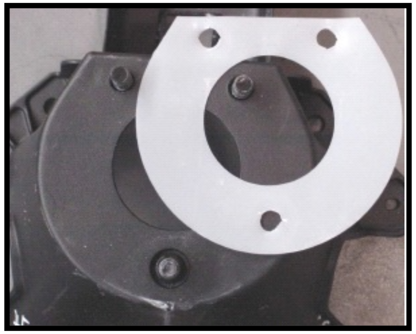
Single Material Approaches – Magnesium Intensive

2007 Jeep Wrangler Spare Tire and CHMSL Module

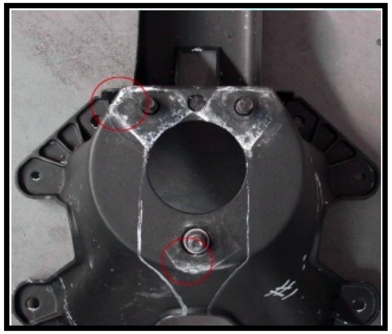
Galvanic Corrosion Example (Wheel to Carrier Interface)

- Prototype
  - Top 2 studs E-coated with tether.
  - Clearance holes in Mg casting
  - Bottom stud – double ended with Zn-Ni plating and Al washer in countersunk depression
- Production
  - Mylar sheet added to isolate Mg casting from steel wheel

Prototype with no mylar isolator after 240 Hr ASTM B117 Salt Spray exposure



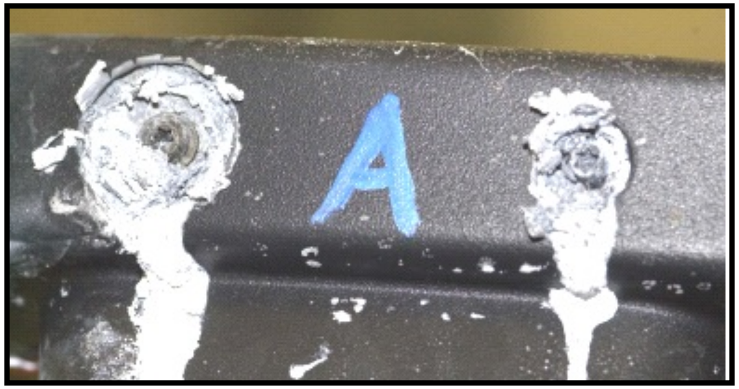
Installation of mylar isolator sheet



Production after 240 Hr ASTM B117 Salt Spray exposure and removal of mylar sheet

Galvanic Corrosion Example
(CHMSL Attaching Screws)

- Prototype
  - Screw head countersunk in depression in Mg casting
  - Zn-Ni protective plating
- Production
  - Countersink and plating same as prototype
  - Nylon washers added for isolation
- Ideal
  - Eliminate countersink
  - Use plastic screws or fasteners



Corrosion Results of Attaching Screws after 240 Hr. ASTM B117 Salt Spray Exposure

Corrosion Results of Attaching Screws with Nylon Washers after 240 Hr. ASTM B117 Salt Spray Exposure

Acknowledgement of Federal Support and Disclaimer

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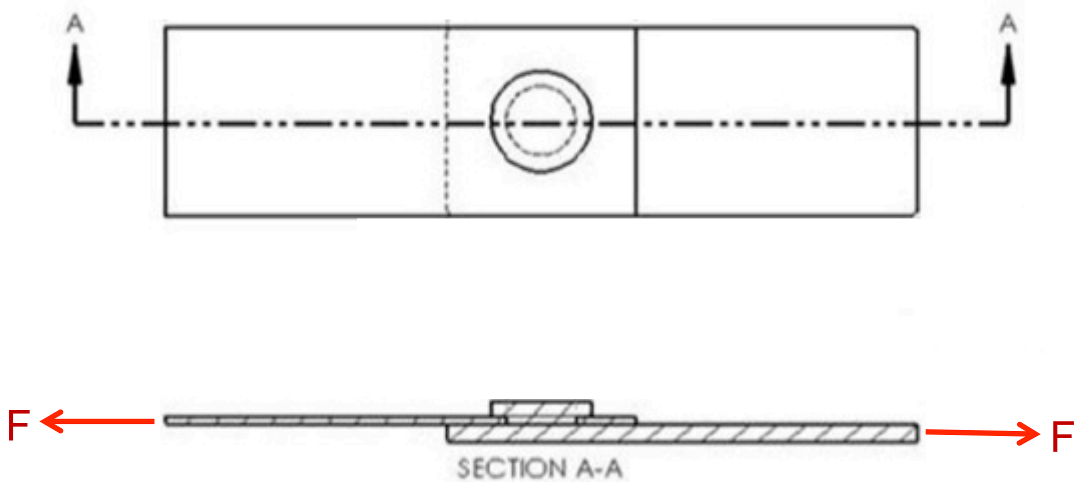
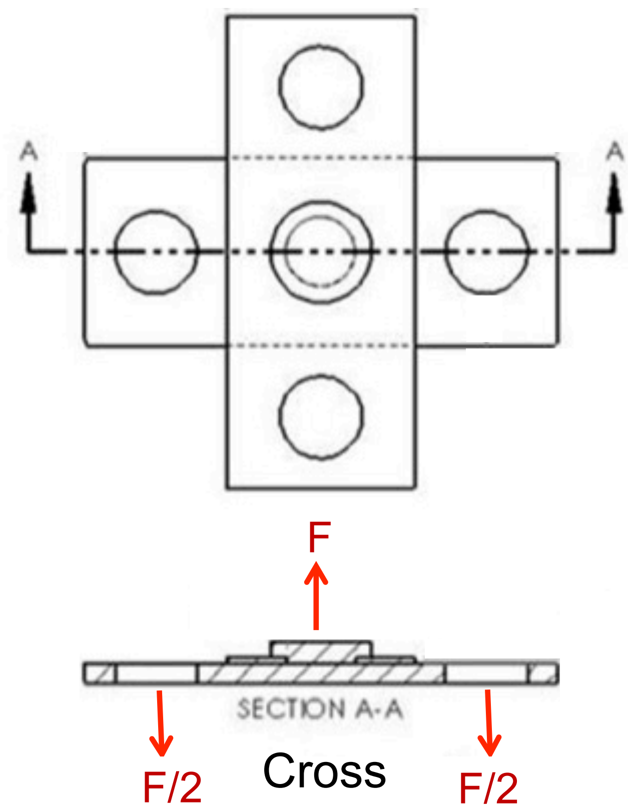
Acknowledgment: "This material is based upon work supported by the Department of Energy under Award Number(s) DE-EE0006442."

Joint Strength Test Configurations

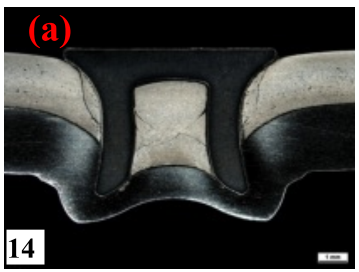


Shear Tension (ST)



Cross Tension (CT)

- Optimized Self-Pierce Riveting (SPR) joining process to produce high quality 2.0 mm Mg AM60B to 2.2 mm Al6013-T4 dissimilar metal joints by evaluating 17 different rivet and die combinations, and down-selecting four that looked most promising (best rivet engagement, least cracking, etc.).

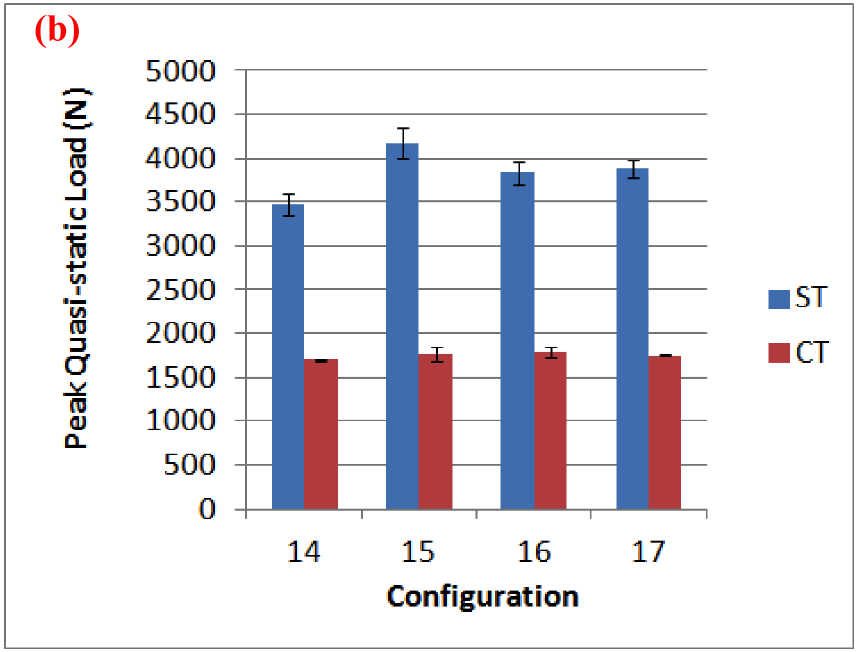


5mm x 5.5mm H4 rivet
BJ3B Die

5mm x 5.5mm H4 rivet
BD3A Die

5mm x 5.5mm H6 rivet
BD3A Die

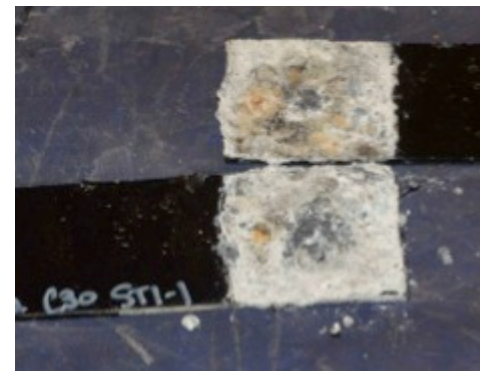
5mm x 5.5mm H6 rivet
BJ3B Die

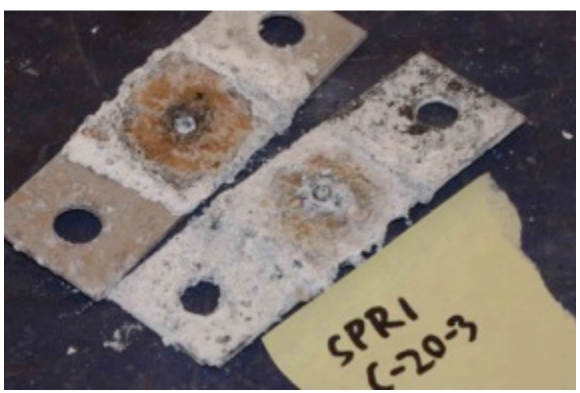


  - Configuration 17 was selected to continue development work due to least material cracking and most repeatable results.

Benchmark Joint Performance

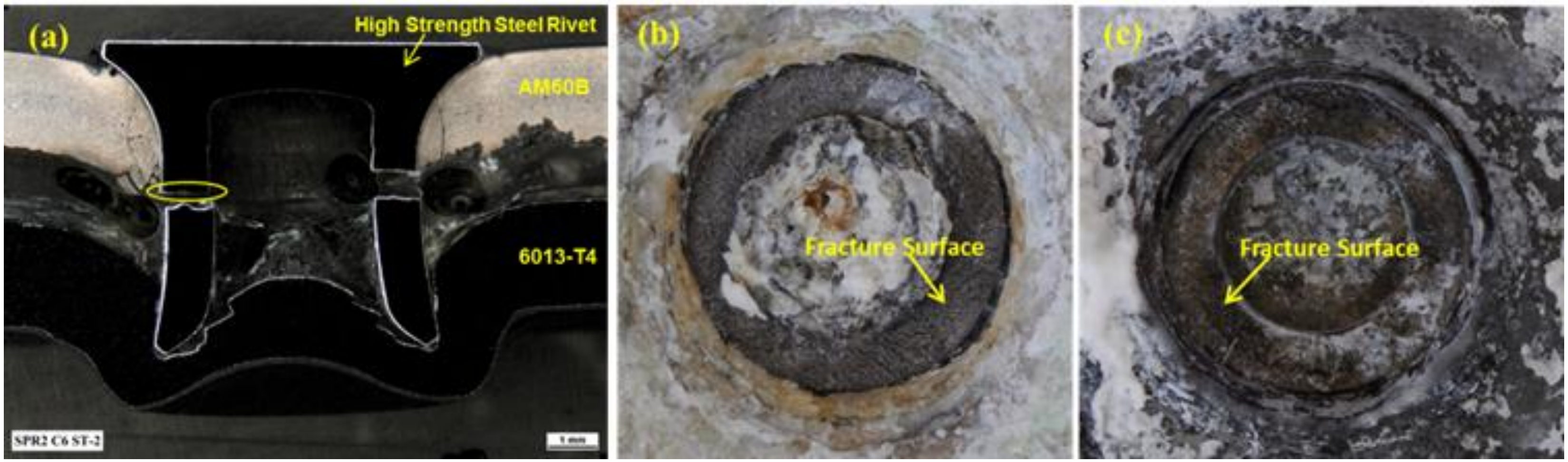
- Shear and cross tension assemblies were subjected to 12 wks of an aggressive ASTM G85-A2 accelerated corrosion procedure that caused several assemblies to separate after only 6 wks of exposure.

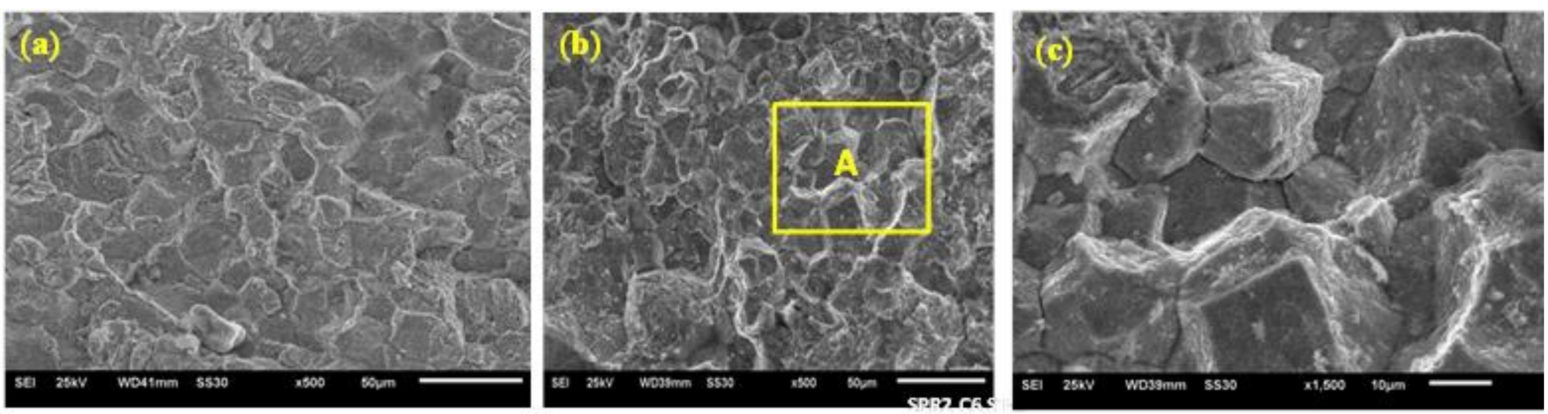




Benchmark Joint Performance

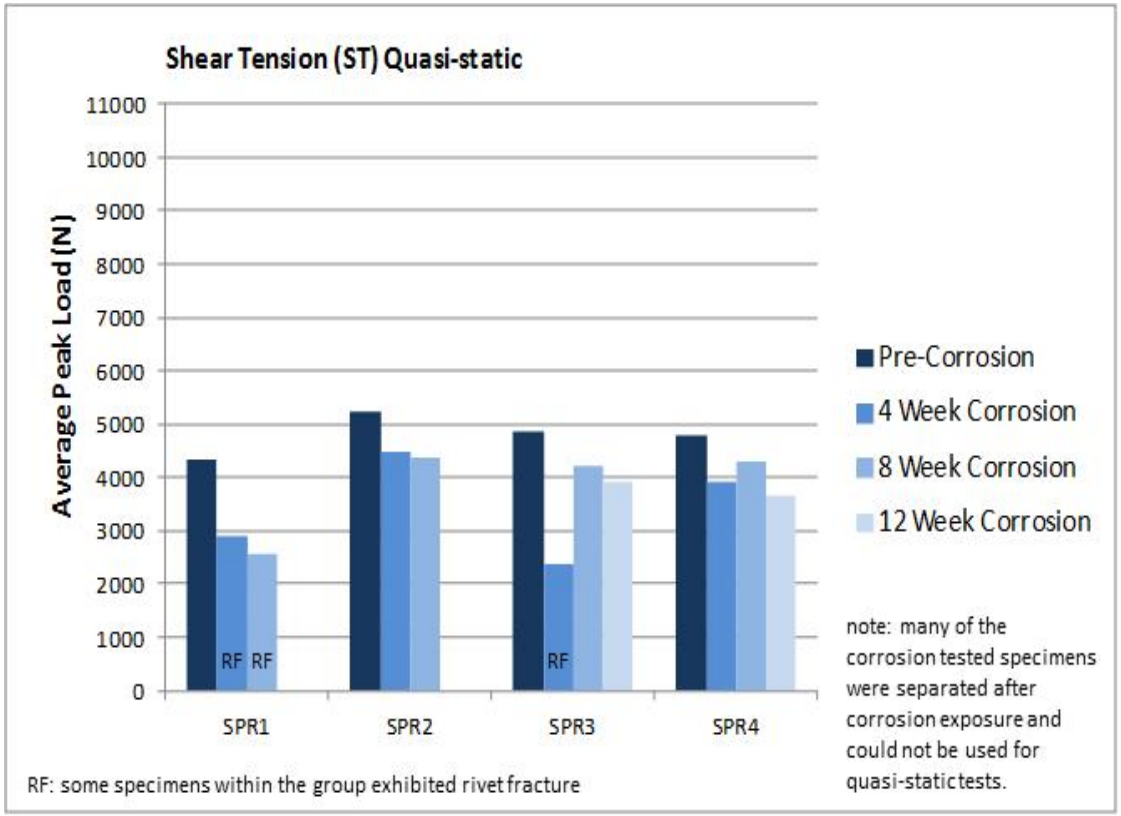
- Cause of joint separation during corrosion exposure identified as hydrogen embrittlement of the steel rivet.

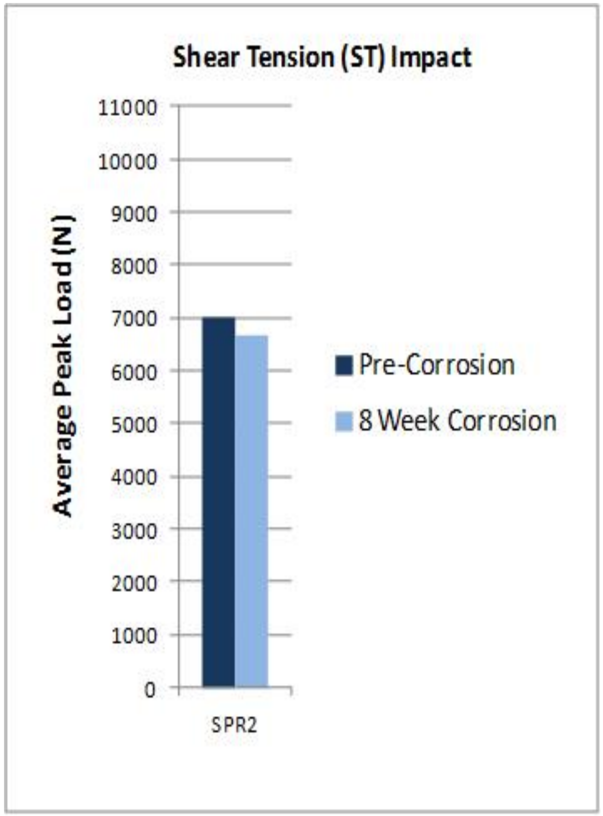




Benchmark Joint Performance

- Quasi-static and impact shear tension evaluation was conducted throughout accelerated corrosion testing.
- With the exception of the samples experiencing rivet fracture, there was little loss in joint strength as a result of corrosion exposure in this test.





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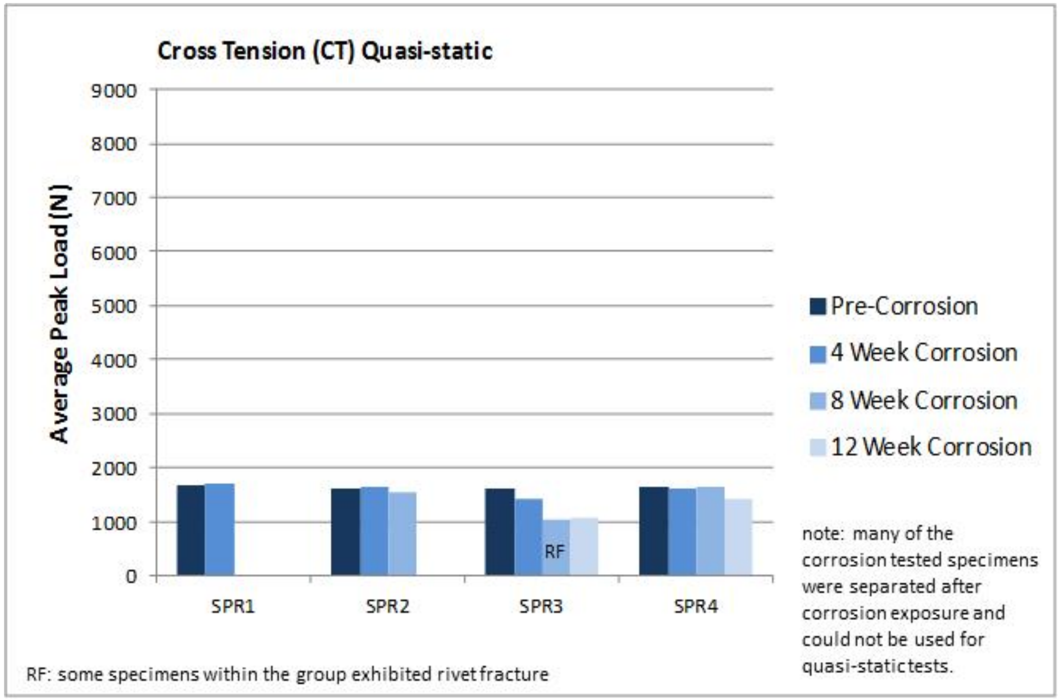
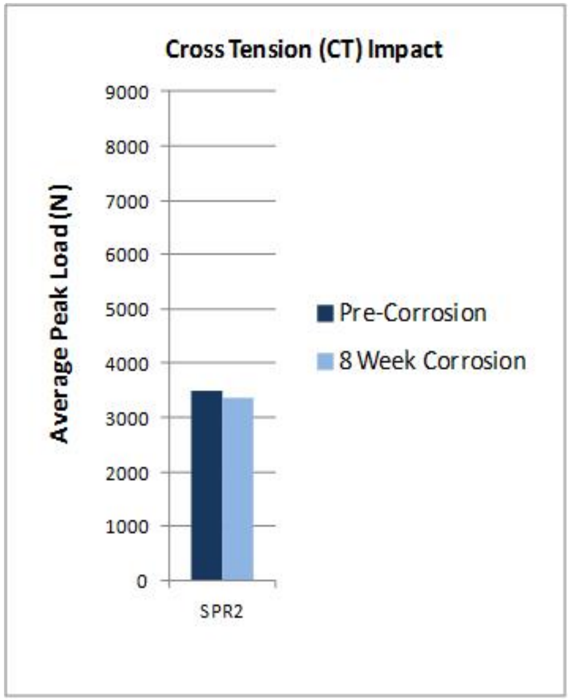
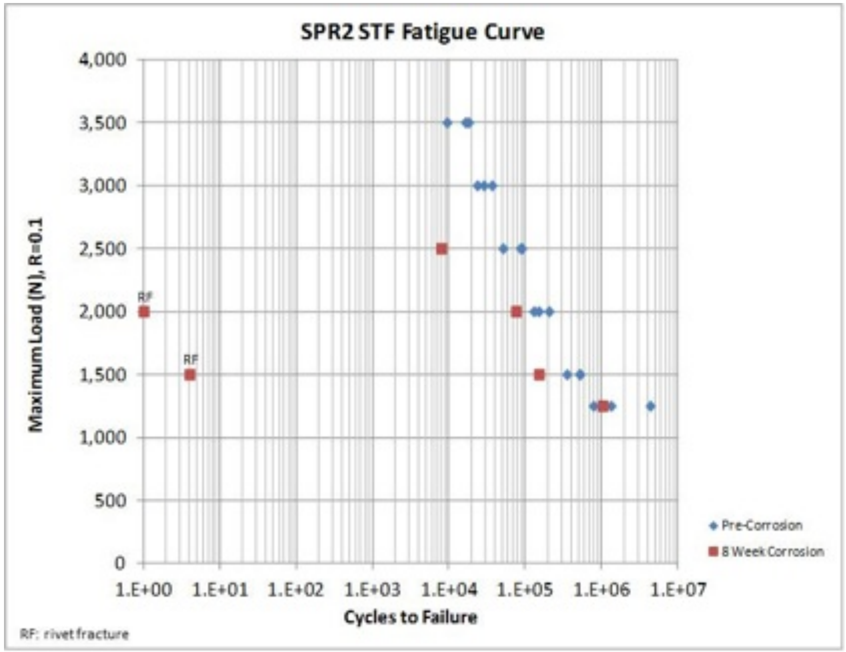
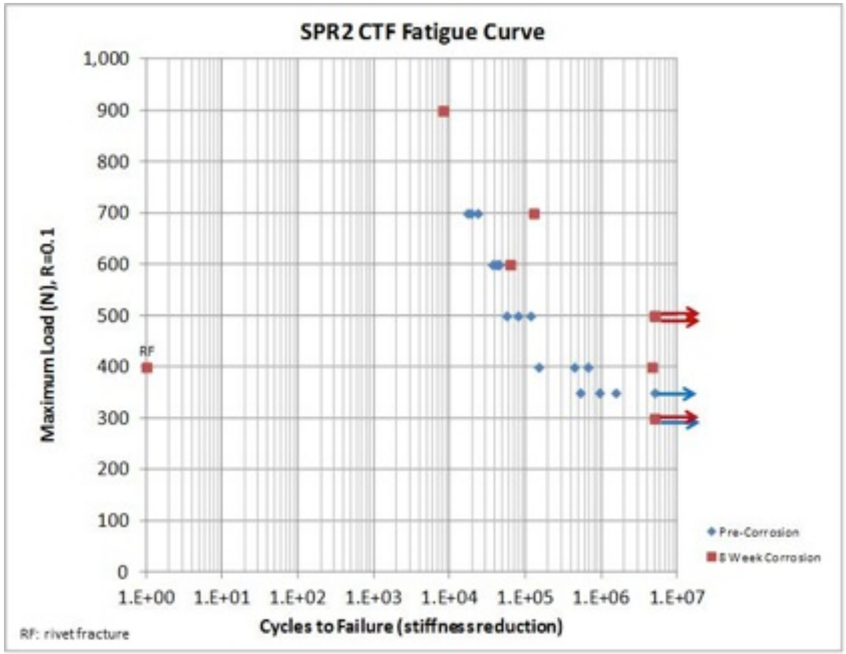




Benchmark Joint Performance

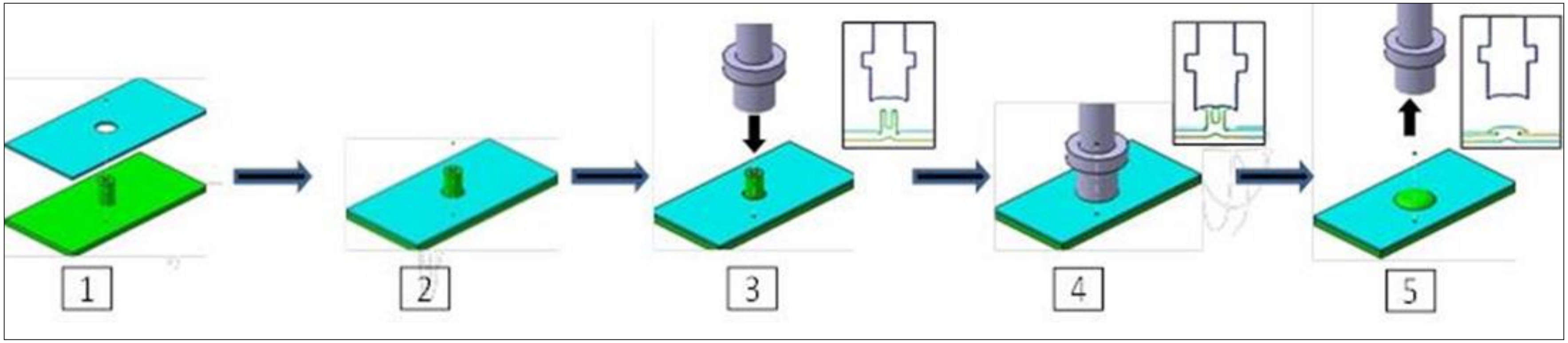
- Fatigue performance at the end of accelerated corrosion testing.





Introducing Upset Protrusion Joining (UPJ) Process

- Combines aspects of 3 different process technologies
  - Heat staking (typically used for plastics)
  - Upset forging (hence the name Upset Protrusion Joining)
  - Resistance spot welding (RSW) equipment is used to provide the heat and force required to provide the upset forging
- Conceived and developed primarily for joining castings (especially Mg) to dissimilar metal panels



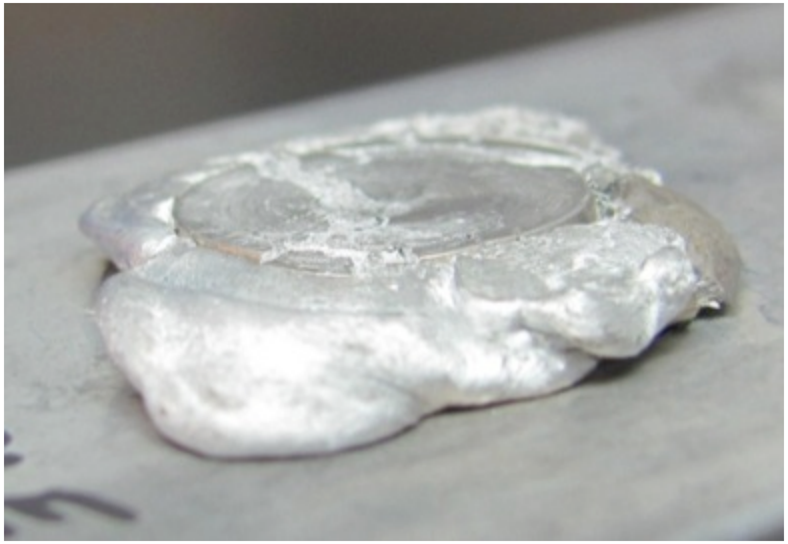
Early UPJ Conceptual Process Schematic

Upset Protrusion Joining (UPJ) Process

- Advantages
  - No intermetallic bonding required
  - Reduced risk of galvanic corrosion because of
    - Elimination of steel fastener
    - Ability to coat cathode before joining to anode
- Disadvantages
  - Limited Types of Applications
    - At least one component must be a casting
    - Attaching panel surface must be perpendicular to casting die direction at the location of the joint
  - Can be dimensionally challenging
    - The clearance holes in attaching panel must be large enough to accommodate production and assembly processes between the two components
    - The boss head must be able to expand to be large enough to completely cover the clearance hole in the attaching panel.
  - Repair process will need to be developed

Initial Trials

too much force, too little heat

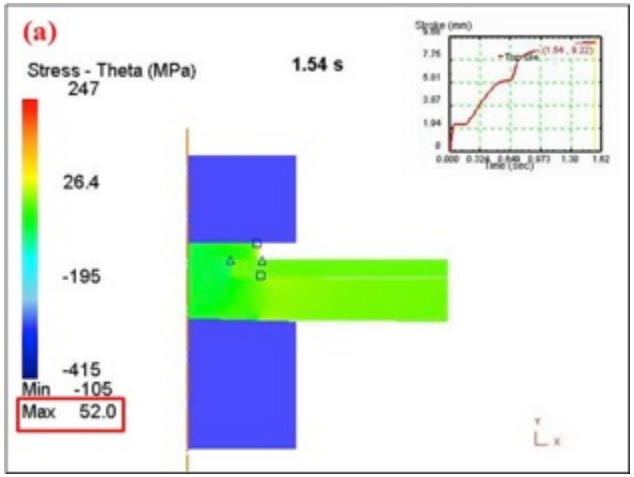


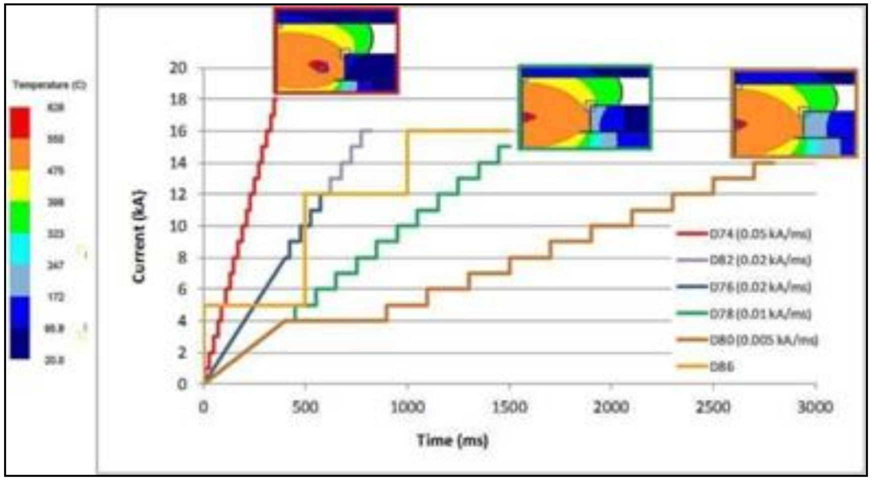
too little force, way too much heat

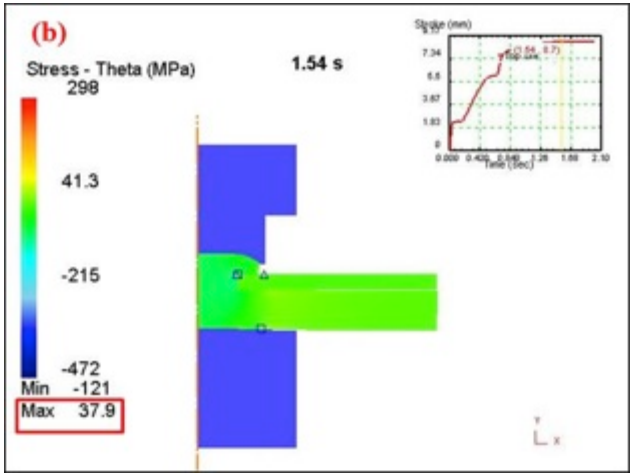
too little force, too much heat

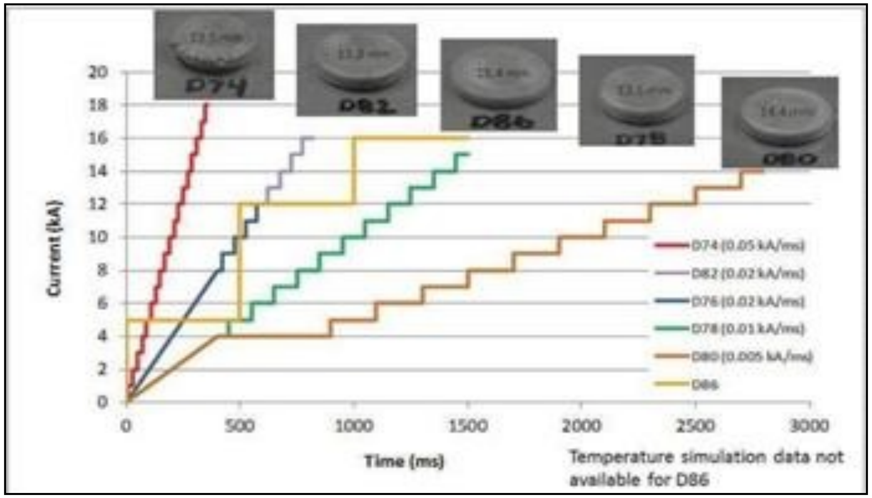
Modeling and Simulation

- Extensive process modeling and simulation development work as well as additional experimental work conducted to support production of robust, repeatable joints for 11 unique UPJ material / coating configurations.









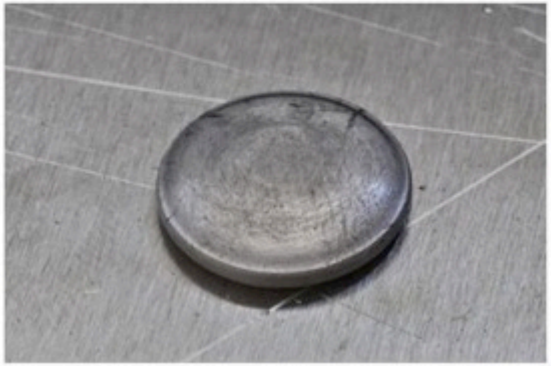
Joint Head Formation

- Eleven unique material/coating configurations have been produced to support mechanical and corrosion performance evaluations. Six examples are shown below:

UPJ8-1
2.0 mm (Armorgalv) DP590
(Bare) AM60

UPJ8-4
2.2 mm (Pre-treated) Al 6013-T4
(Pre-treated) AM60
Powdercoated Assembly

UPJ8-6
2.2 mm (Powdercoated) Al 6013-T4
(Pre-treated) AM60
Powdercoated Assembly

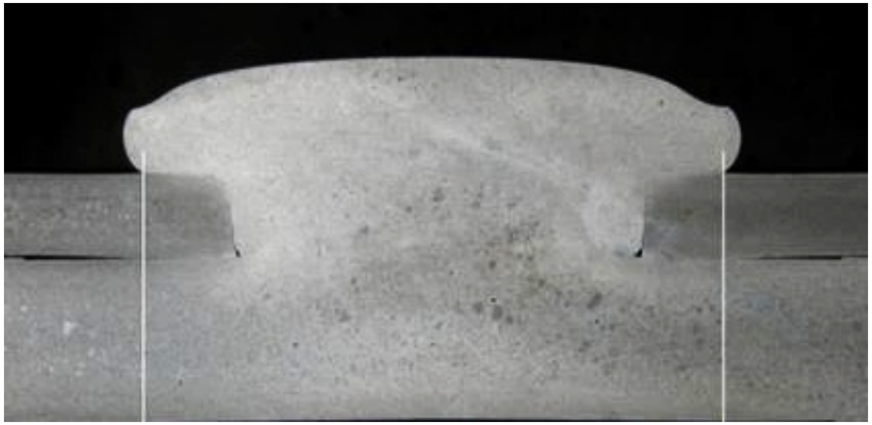


UPJ8-2
2.2 mm (Bare) Al 6013-T4
(Bare) AM60

UPJ8-5
2.2 mm (Powdercoated) Al 6013-T4
(Pre-treated) AM60

UPJ8-7
2.0 mm (Bare) AM60
(Bare) AM60

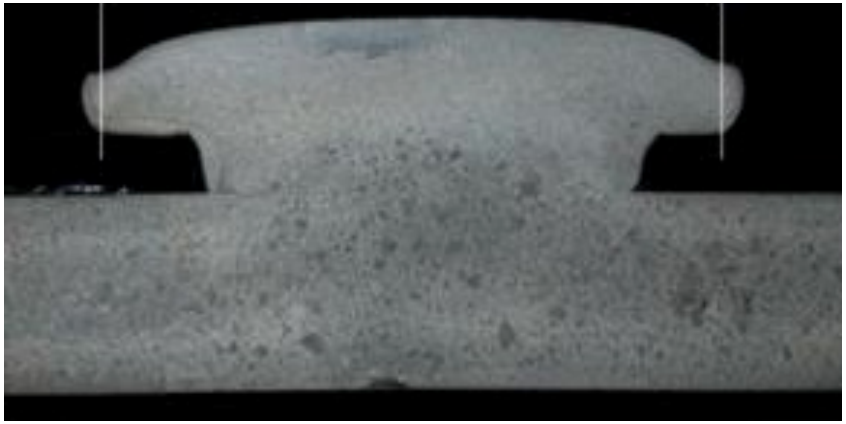
Sample UPJ Cross Sections



Magnesium Upper Sheet (2 mm thick)

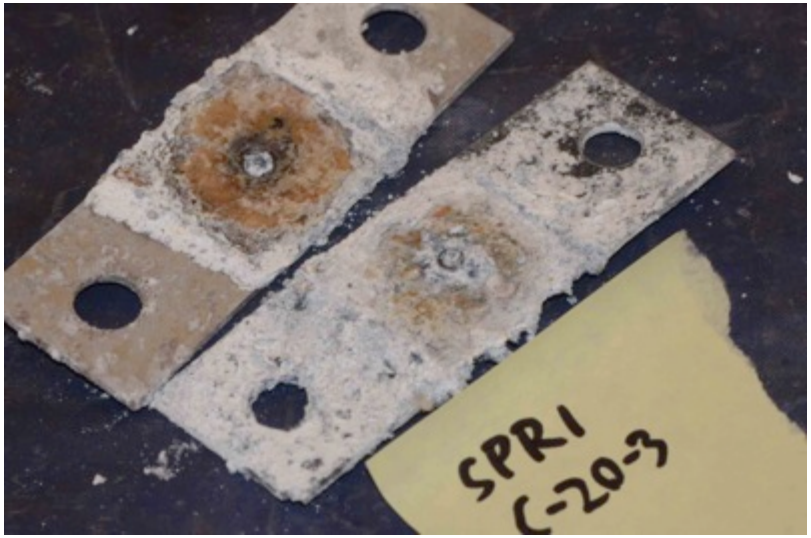
Steel Upper Sheet (2 mm thick)

Aluminum Al6013 Upper Sheet
(2.2 mm thick)

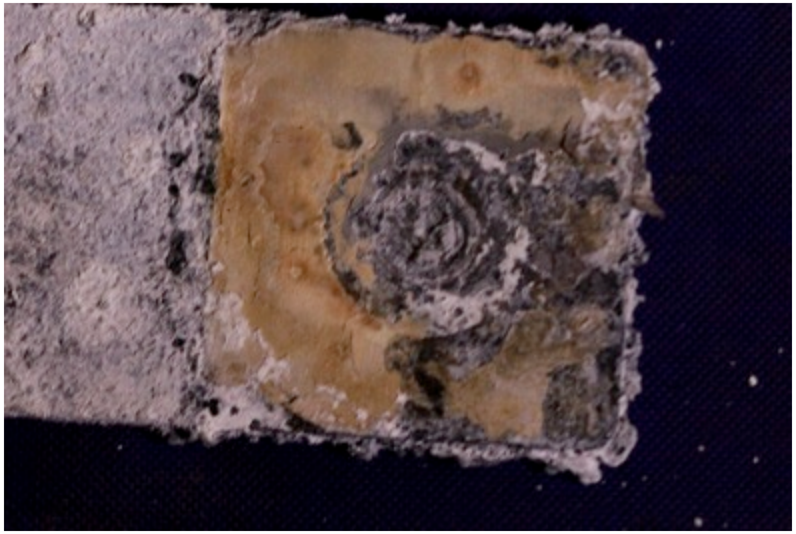


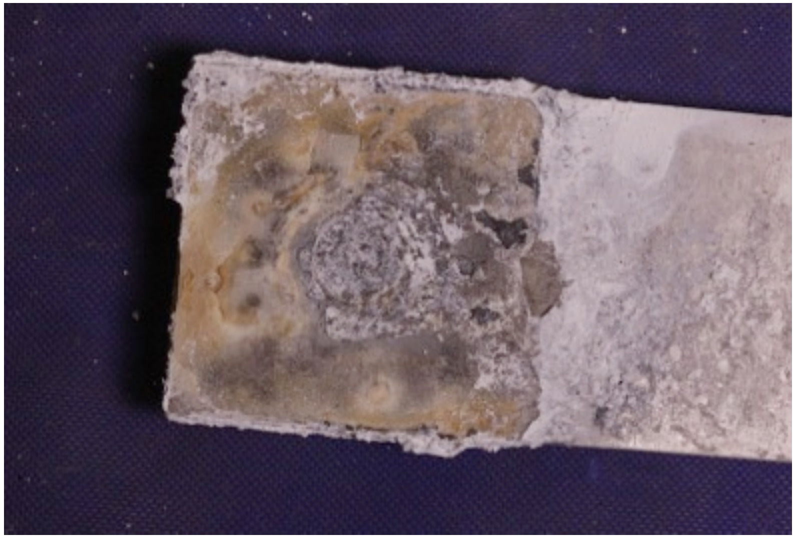
Aluminum Al6016 Upper Sheet
(1 mm thick)

Corrosion Performance Comparison @ 6 wks
Bare Mg AM60B / Bare Al6013



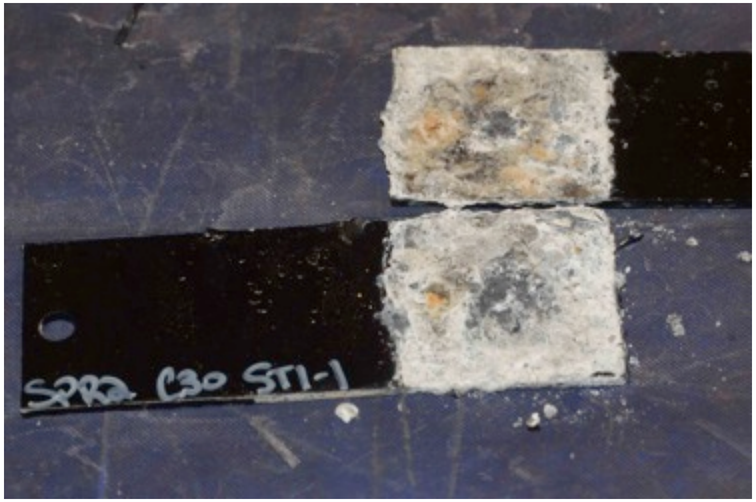
SPR ST and CT Samples (4 samples separated)

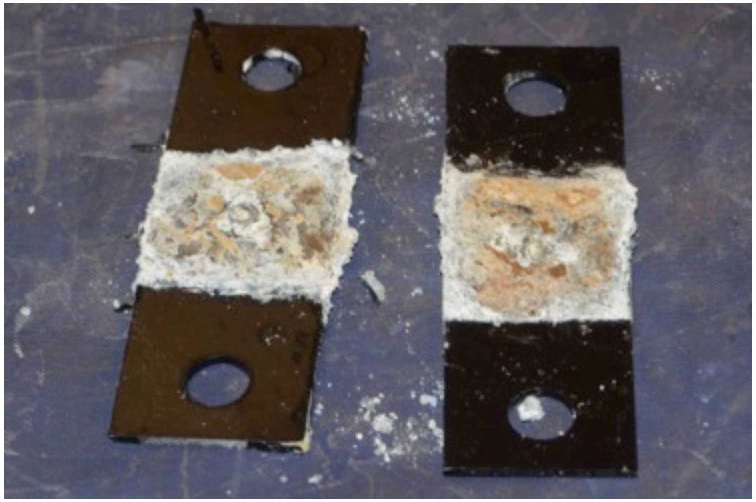




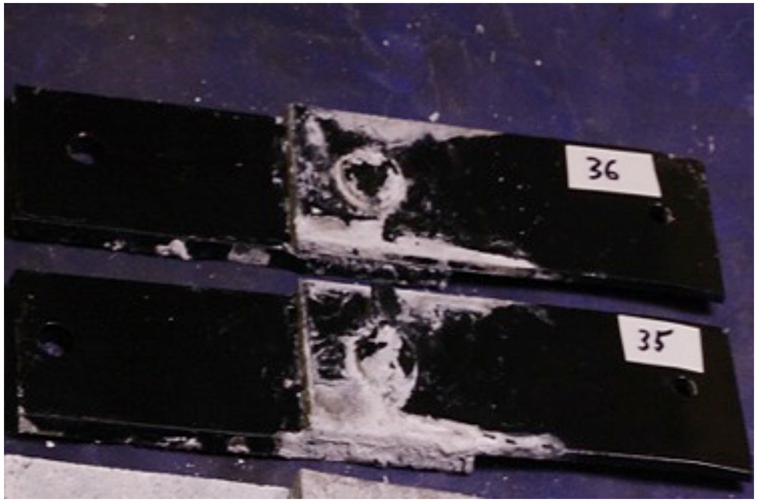
UPJ ST Sample Mg and Al (1 sample separated)

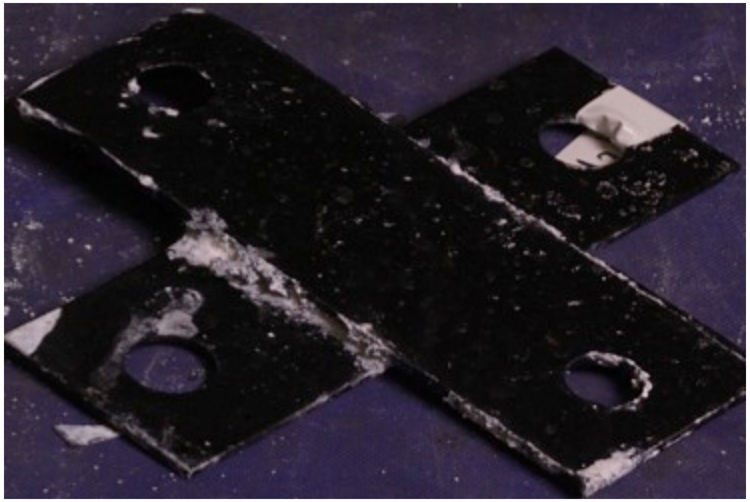
Corrosion Performance Comparison @ 6 wks
Pretreated Mg AM60B / Pretreated Al6013 / Coated Assy





SPR ST and CT Samples (7 samples separated)





UPJ ST and CT Samples (no separations)

Quasi-Static Shear Tension Comparison

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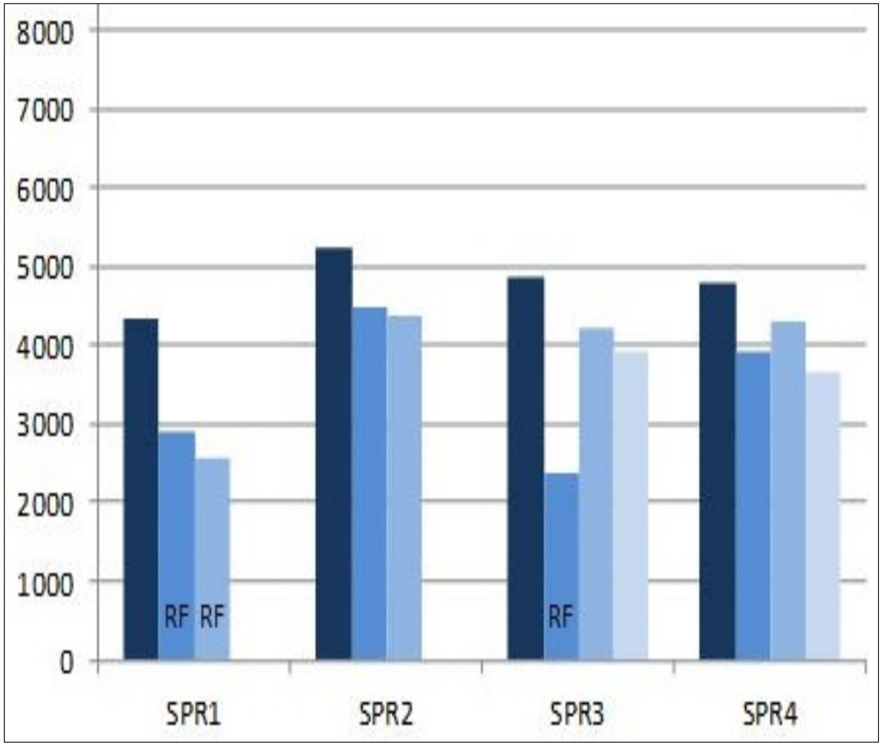
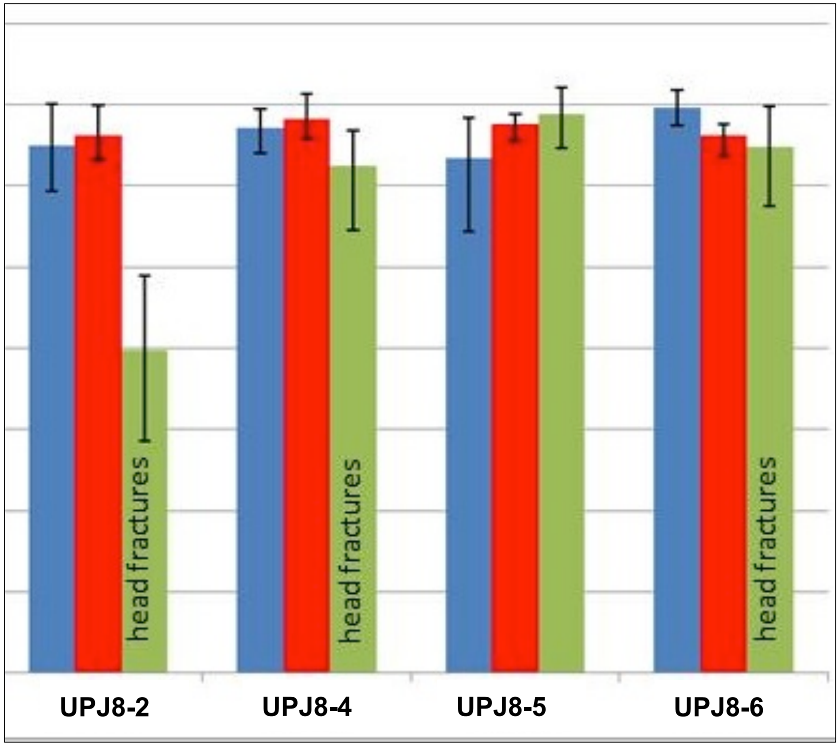




Quasi-Static Shear Tension Test Results of SPR (left) and UPJ (right) Joints Before and After Accelerated Corrosion Exposure to ASTM G85-A2

SPR1, UPJ8-2 = Bare Al6013 to bare AM60B

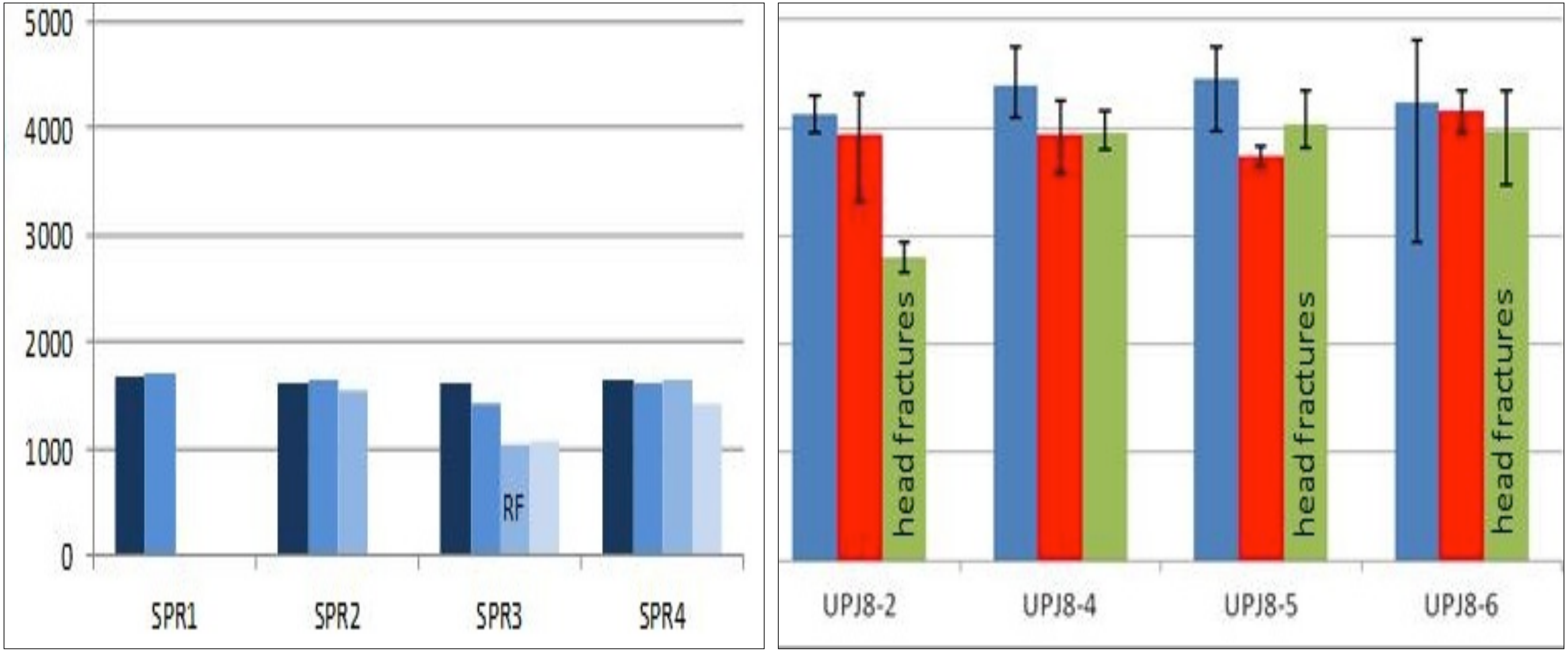
SPR2, UPJ8-4 = Pretreated Al6013 to pretreated AM60B, with powdercoating after assembly

SPR3, UPJ8-5 = Powdercoated Al6013 to pretreated AM60B, with no coating after assembly

SPR4, UPJ8-6 = Powdercoated Al6013 to pretreated AM60B, with powdercoating after assembly

*** - RF = Rivet Fracture**

Quasi-Static Cross Tension Comparison



Quasi-Static Cross Tension Test Results of SPR (left) and UPJ (right) Joints Before and After Accelerated Corrosion Exposure to ASTM G85-A2

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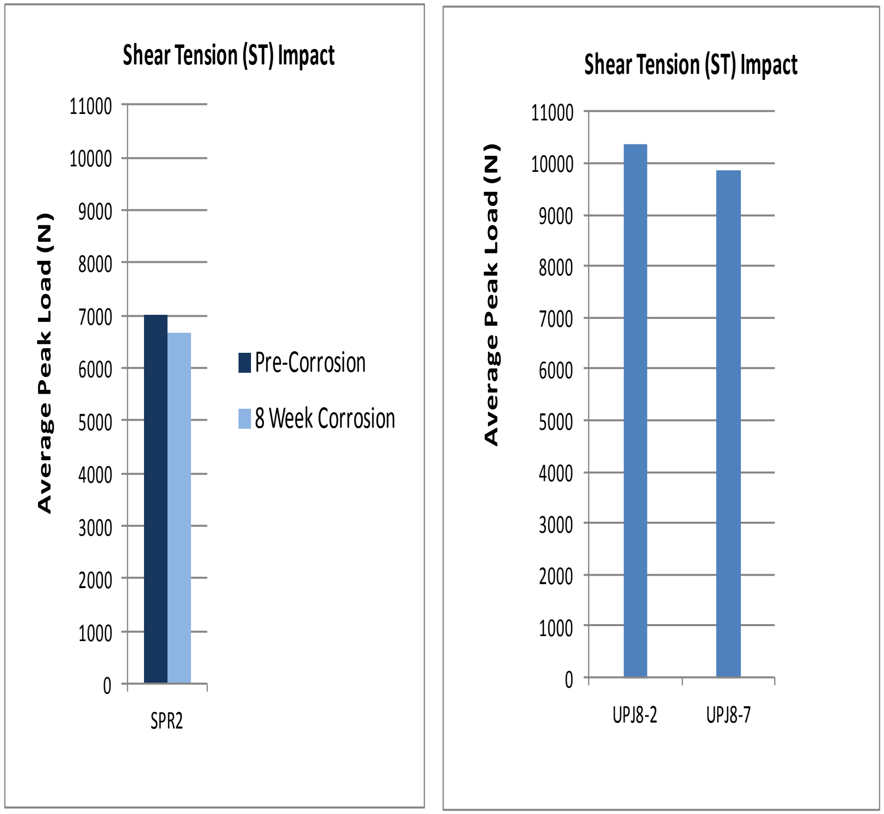
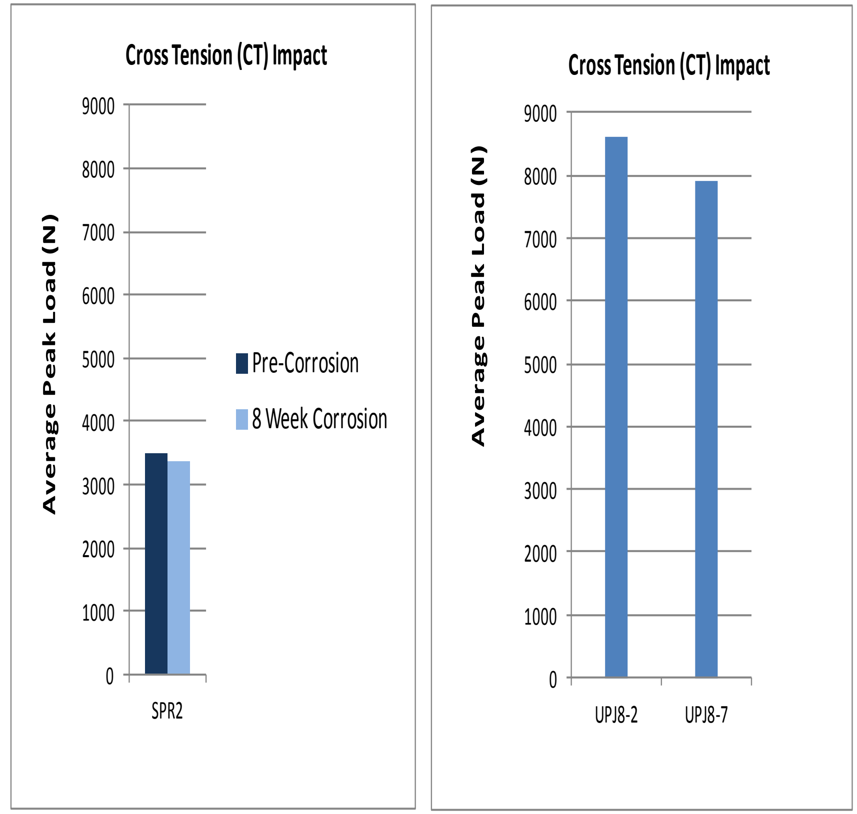
Impact Performance Comparison



Impact Shear Tension Test Results of SPR (left) and UPJ (right)



Impact Cross Tension Test Results of SPR (left) and UPJ (right)

*** - UPJ post corrosion impact testing has not been conducted yet.**

Shear Tension Fatigue Comparison

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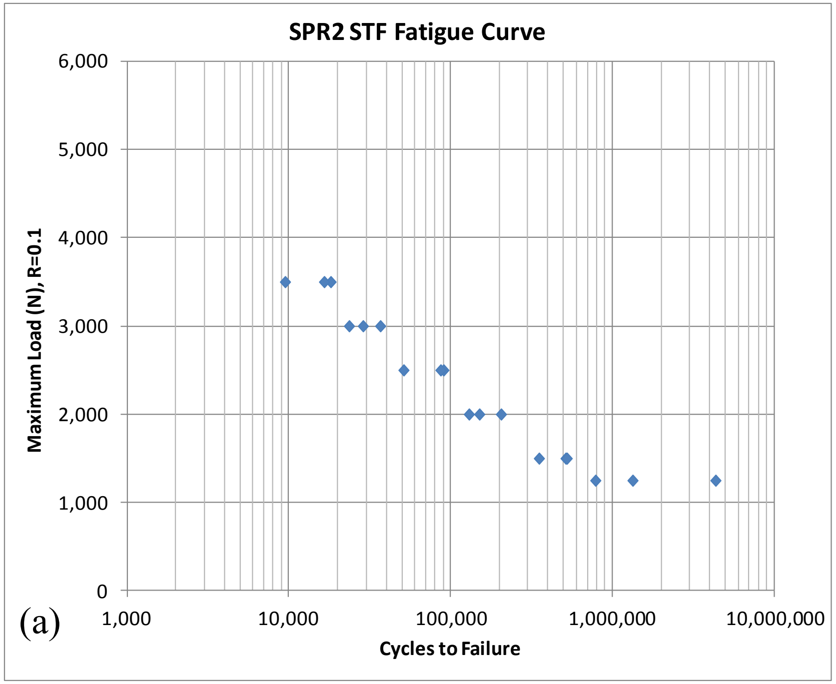
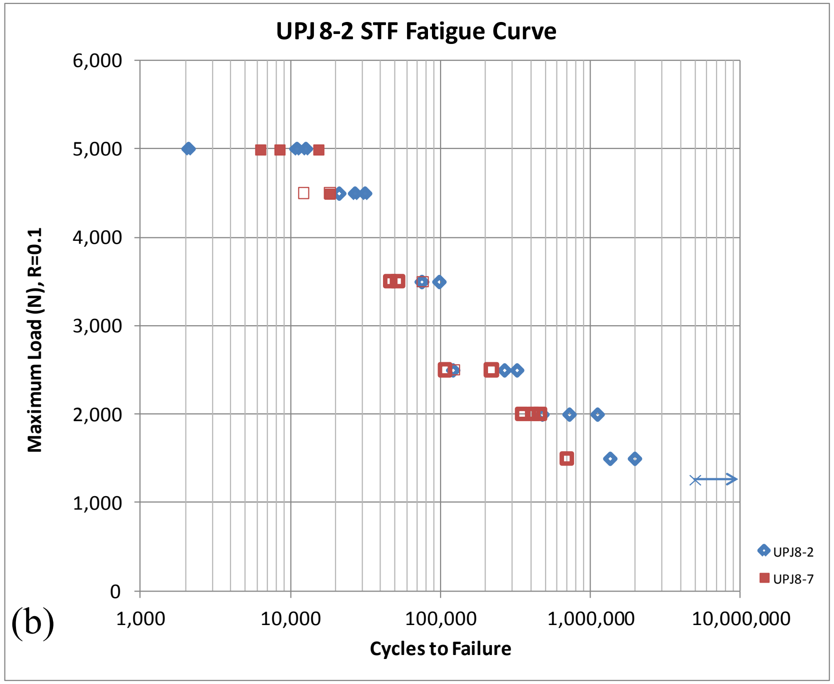
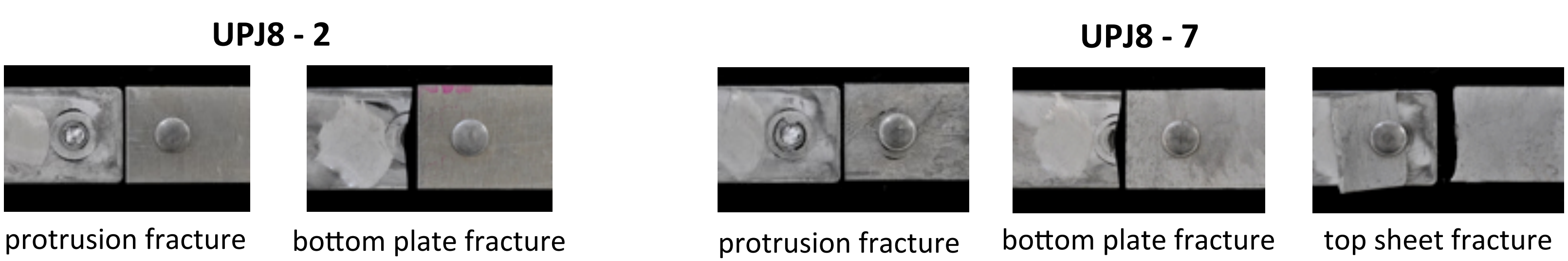


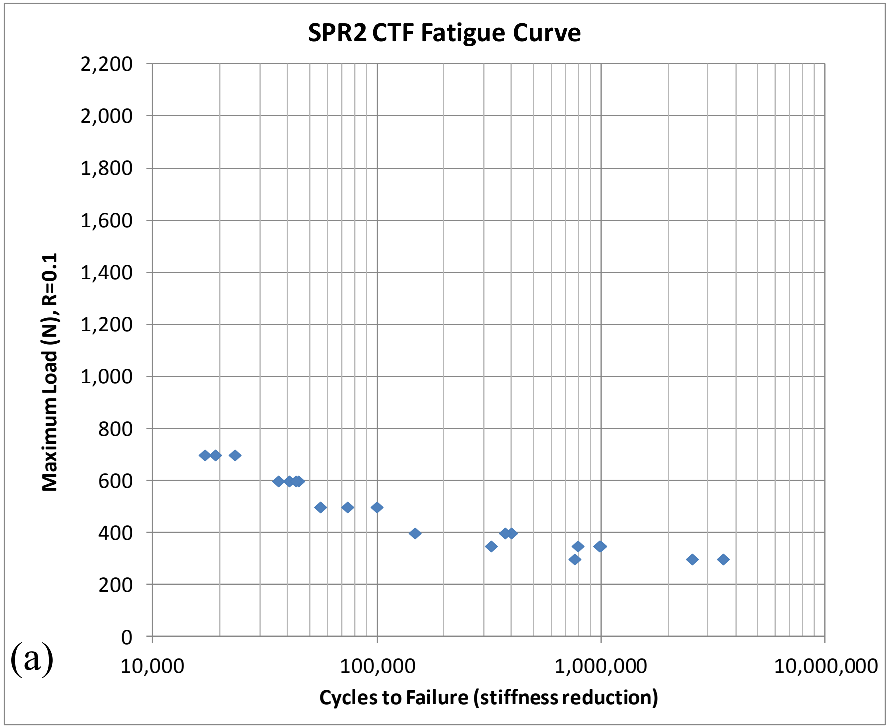


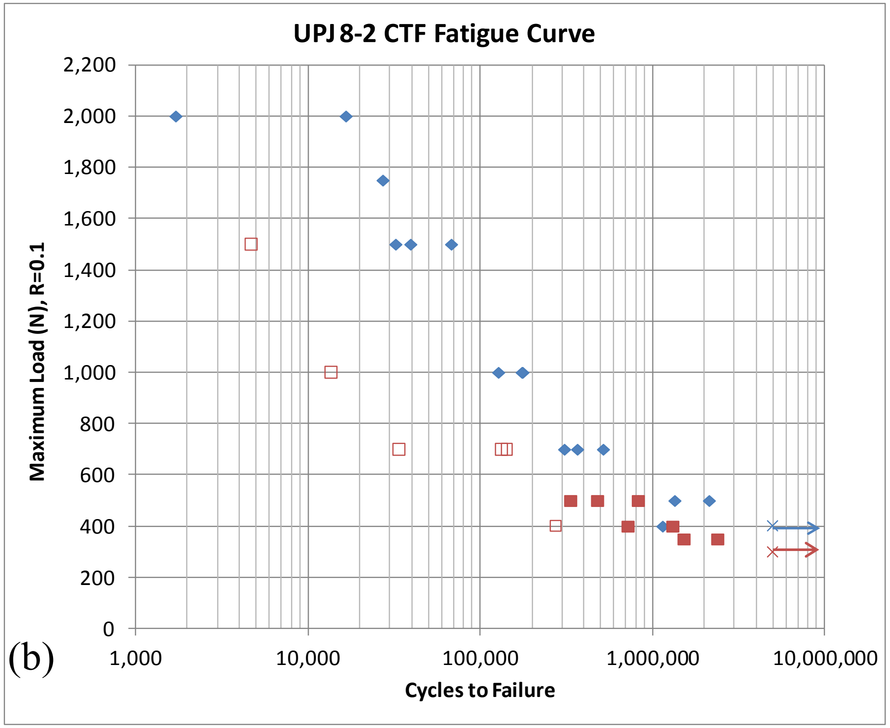
Comparisons of SPR (left) and UPJ (right) Shear Tension Fatigue Performance



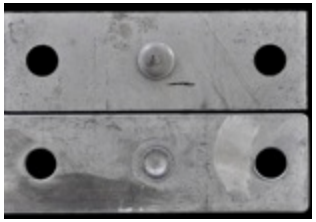
UPJ Shear Tension Fatigue Fracture Modes

Cross Tension Fatigue Comparison





Comparisons of SPR (left) and UPJ (right) Cross Tension Fatigue Performance (above) and Associated Failure Modes (below)



protrusion fracture ■

top sheet fracture □

Summary

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- Magnesium has outstanding potential as a lightweight structural material alternative, especially when used with the die-casting process to integrate components and features.
  - However, significant challenges to increased use of magnesium include joining, galvanic corrosion, and coatings performance.
- A new process known as upset protrusion joining (UPJ) has been developed by FCA US and its partners to reduce some of the joining challenges associated with joining Mg die-castings to similar and dissimilar metals.
- The UPJ process has been evaluated against a current light metal joining benchmark (SPR) for joining AM60B magnesium alloy test coupons to Al6013 aluminum sheet test coupons.
  - It should be noted that while SPR is currently used on a large number of current production Al to Al applications, it is not currently used for joining Al to Mg.
  - Evaluations included quasi-static, fatigue, impact, and corrosion performance comparisons.

Summary

- SPR joints displayed consistent joint strength in quasi-static, fatigue, and impact. However, several joints separated when subjected to an aggressive ASTM G85-A2 accelerated corrosion procedure.
  - Separation resulted from hydrogen embrittlement of the steel rivet.
- UPJ demonstrated significantly improved quasi-static and impact performance over SPR, especially in cross tension performance.
- UPJ demonstrated improved low cycle fatigue performance over SPR and similar high cycle fatigue performance.
- Corrosion performance evaluation of SPR and UPJ joints exposed to ASTM G85-A2 allows for the following conclusions:
  - For ***bare*** Mg AM60B to ***bare*** Al6013 joints, both SPR and UPJ joints can separate in only 6 wks, though fewer separations are observed for UPJ.
  - For ***pretreated*** Mg AM60B to ***pretreated*** Al6013 joints, a substantial number of SPR joints have separated by 6-wks while none of the UPJ joints have separated even after 8 wks.
  - For ***pretreated*** Mg AM60B to ***coated*** Al6013 joints, neither SPR or UPJ showed any joint separations or substantial joint performance degradation even after 12 wks.

Collaboration Partners

FCA US would like to acknowledge the following partners for their invaluable assistance in this program

- U.S. Department of Energy and U.S. Department of Defense
  - Provided substantial funding support to help this program be successful.
- AET Integration, Inc. – Industry Primary subcontractor to FCA US
  - Provided weld process development, machining services, joint evaluations, and metallurgical services throughout the project as well as overseeing additional subcontractors, joining SPR coupons, overseeing process modeling simulation efforts, and providing testing and evaluation services for all testing except corrosion.
- Automotive Partnership Canada (APC)
  - Provided substantial funding support to McMaster University and Canmet Materials to provide thermo-mechanical material characterization of magnesium alloys.
- McMaster University – University collaboration
  - Worked with Canmet to develop magnesium alloy thermo-mechanical compression data and constitutive equations to support process modeling efforts.
- Canmet Materials (CMAT) – Canadian federal laboratory collaboration
  - Provided use of their Gleeble® test machines and technical assistance to McMaster University researchers in order to obtain thermo-mechanical evaluation and characterization data from cylindrical compression test coupons.