Project ID: PM004_grant_2014

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Novel Manufacturing Technologies for High Power Induction and Permanent Magnet Electric Motors

(Agreement ID 23726)

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GENERAL MOTORS RESEARCH AND DEVELOPMENT

2014 DOE HYDROGEN PROGRAM AND VEHICLE TECHNOLOGIES PROGRAM ANNUAL MERIT REVIEW AND PEER EVALUATION MEETING

JUNE 19, 2014

WASHINGTON, DC

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Start: FY2011
- Project end date: Sept 2014
- Percent complete: 60%

Budget

- Total project funding
  - DOE - $1,225k
  - GM - $1,306k (in-kind)
  - 50/50 Cost Share with GM through in-kind contribution
- DOE Funding for FY11: $200k
- DOE Funding for FY12: $295k
- DOE Funding for FY13: $300k
- DOE Funding for FY14: $360k

Barriers

In support of the Advanced Power Electronics and Electrical Motors (APEEM) R&D activity

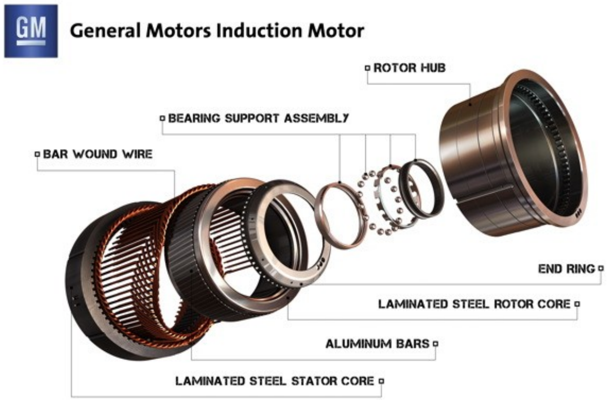
- Need Decreased Cost through lower cost manufacturing processes – bring electronic propulsion systems costs below $8/kW
- Need Decreased Weight – bring specific power to 1.3 kW/kg by 2015
- Need Increased Durability – through better thermal fatigue performance and higher strength joining process
- Need Increased Efficiency – bring power density to 5 kW/L by 2015

Partners

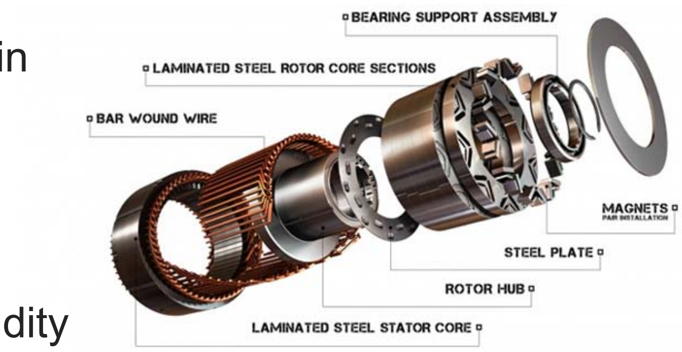
- CRADA with General Motors Research
- Project lead: PNNL

Relevance
Background - Opportunities

- Induction motors have several advantages over permanent magnet motors for traction drives
  - Can be higher efficiency than a PM motor over the entire drive cycle (especially at low speed / high torque, and at high speed)
  - Lower cost
  - No “critical” materials (no high temperature permanent magnets)



- However, induction motors can show large I^2R losses in the stator winding and in the rotor conductor.
- Because of this, the highest efficiency variants use copper in the windings and rotor, rather than aluminum, because of copper’s 60% higher conductivity.
- Copper induction machines can also have size and weight advantages over aluminum because they can have higher power densities, better heat removal and an increase in rigidity and strength

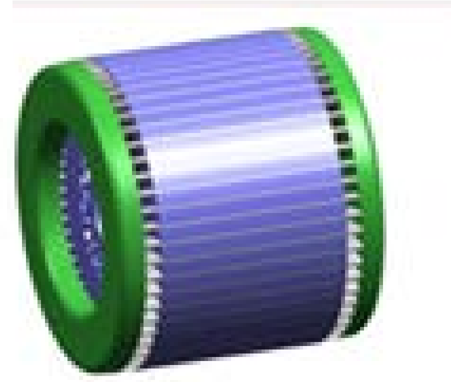


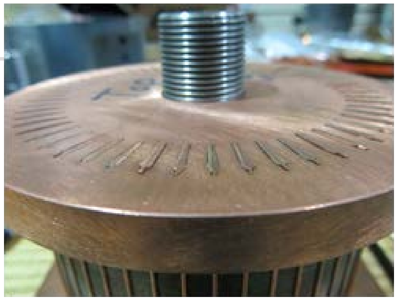
The challenge comes in manufacturing. Aluminum is easily die cast, copper is not as easy

Relevance
Background - Opportunities

Manufacturing Challenges for Copper Rotors

- How is it done today?
  - Brazed rotors – Disadvantages:
    - The braze alloy has lower conductivity than the pure copper – this reduced efficiency
    - The braze alloy can be expensive (15% Silver)
    - The braze process is “semi” manual and production variability occurs that can affect either efficiency (lack of good electrical connection) or strength (poor or incomplete braze joints)
  - Die Cast Rotors – Disadvantages:
    - The casting process (liquid copper) is very high temperature and copper is highly reactive with conventional low-cost die materials. (expensive!)
    - High temperature can affect the coated laminates below the end caps, shorting them and reducing efficiency



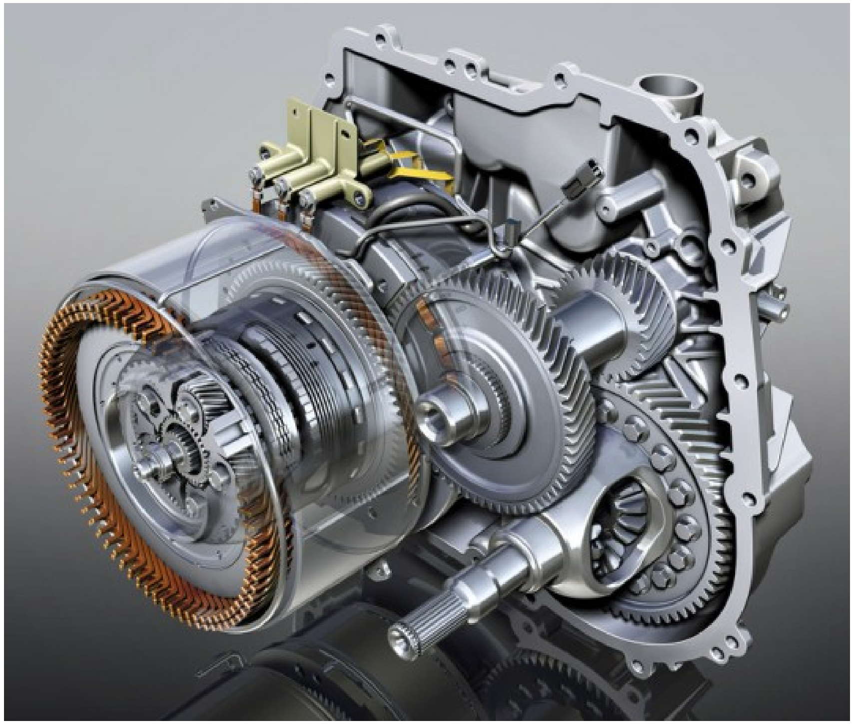


The objective of this project is to develop a low cost method to join the bars to the end caps using a solid state welding process – Friction Stir Welding

Relevance

Project Objective

- To develop and deploy high-power induction rotors and stators that are:
  - lighter weight
  - higher performance
  - are a lower cost to manufacture than current rotor/stator assemblies
- Achieve these objectives through the application of novel solid state joining and fabrication technologies
- Demonstrate that these objectives can be achieved by fabricating full sized rotors and stators for testing in current GM electric motor platforms.



Approach and Strategy for Deployment

- Develop the fundamental understanding needed to successfully apply solid state joining techniques for the manufacture of electric motor components
- Specifically develop the joining process, tooling and statistical confidence around the process to be able to transfer the technology to the industrial partners
- Produce prototype parts that can be evaluated and tested by the industry collaborators to demonstrate efficiency or cost benefits

This project will be divided into two primary task areas:

- Task 1 Develop the solid state joining process to join copper end caps to copper shorting bars on a high power induction rotor.
- Task 2 Develop the process to allow dissimilar material joining, primarily copper to aluminum to improve component performance and weight savings.

Approach and Strategy for Deployment
Task Breakdown

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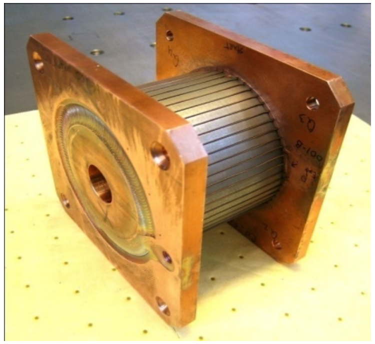
- Task 1 - Friction Stir Welding (FSW) of Copper alloys.
  - The project will develop a fundamental understanding of solid-state joints between copper materials for:
    - low thermal input
    - low distortion of adjacent parts
    - produce joints with a high degree of structural integrity
    - produce joints with high thermal and electrical continuity.



  - Task 1 will develop the FSW process parameters, as well as evaluate proper tool materials and techniques to produce defect-free FSWs in copper alloys
  - The fundamental information gained will be used to develop techniques to manufacture prototype copper rotor and stator assemblies
  - Components will be fabricated, then evaluated and tested by industry collaborators to demonstrate efficiency benefits and commercial applications.

Approach and Strategy for Deployment
Task Breakdown

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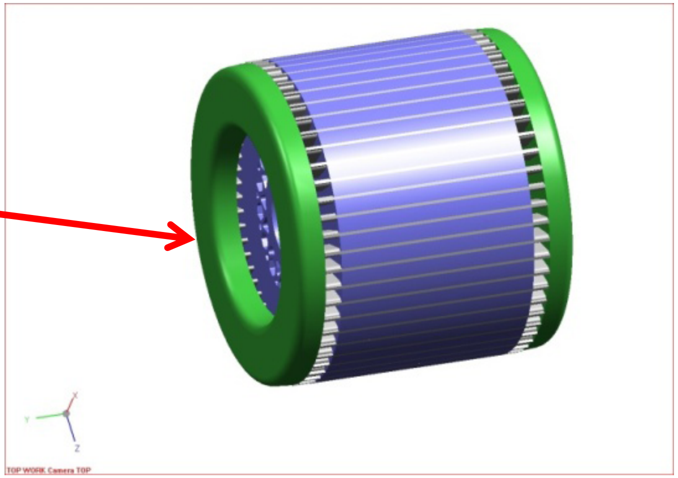
- Task 2 - Friction Stir Welding (FSW) of Dissimilar Copper to Aluminum Joints.
  - The approach will follow the same subtask structure as the Task 1 Cu/Cu joining development.
  - The fundamental information gained will be used to develop techniques to manufacture copper /aluminum hybrid assemblies.
  - Components will be evaluated and tested by industry collaborators to demonstrate efficiency benefits and commercial applications.

Significant weight savings could occur if end caps could be aluminum as long as tradeoff can be made with the lower conductivity



Also there may be other applications in the motor that could benefit from a Cu – Al dissimilar metal joint

Technical Accomplishments and Progress

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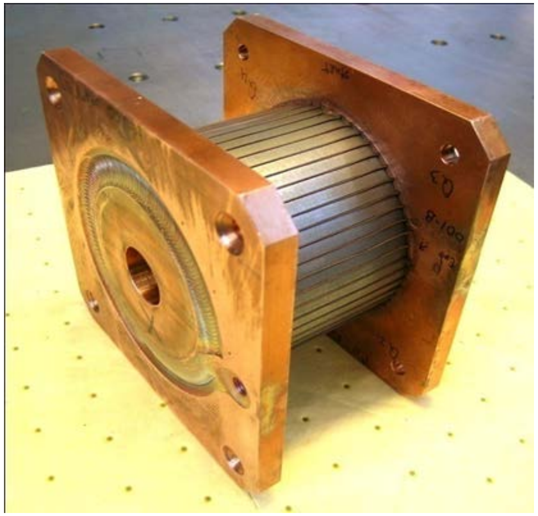
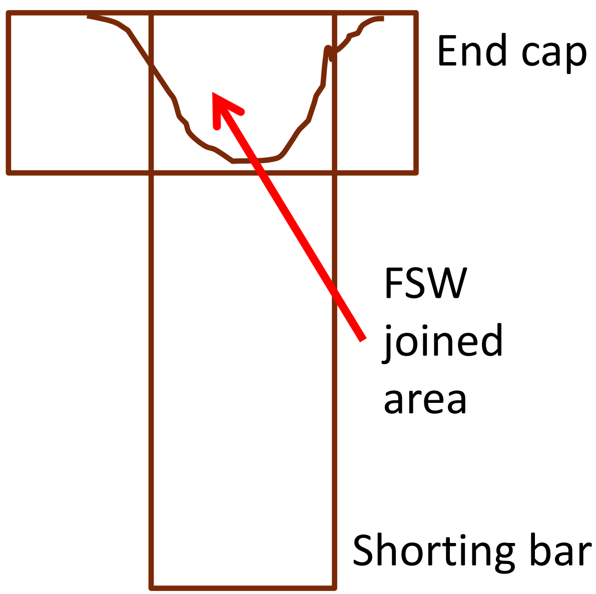
- The joining application investigated is the joint between the copper end caps and the “shorting bars” that traverse the rotor longitudinally.
- Primary challenges and discoveries made during 2013/2014 :
  - The joint design for the highest electrical cross section at the minimum weight penalty dictates specific tool design and materials
  - Joining process parameters strongly affect joint integrity / defect content
  - Control of distortion and over-heating is needed during welding - Adaptive control of the weld power and tool temperature was developed
  - Strategy for minimizing end cap diameter and distortion was investigated (cooled fixtures and the stationary shoulder tool)
  - Strategy for closing the FSW “exit hole” was investigated

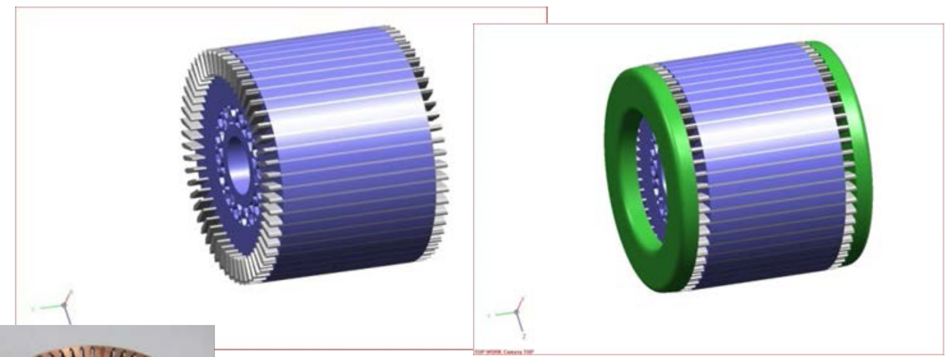


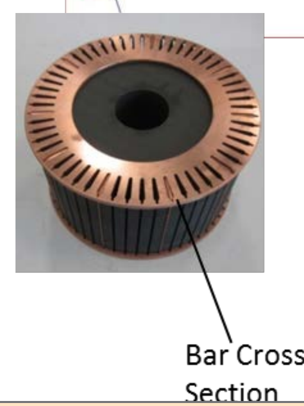
Rotor fabricated by Friction Stir Welding

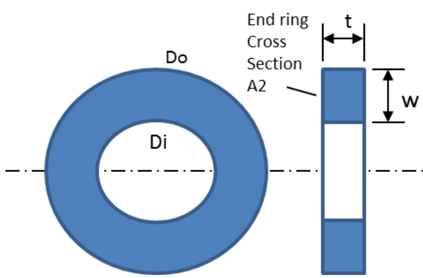
Technical Accomplishments and Progress

- Joint design for the highest electrical cross section at the minimum weight penalty









- It is desired to have the minimum end cap thickness for weight savings.

- The end cap thickness is dictated by motor efficiency FEA calculations, assuming 100% electrical cross section with the shorting bar. The FSW joined area is less than this 100% overlap, so to optimize weight you need to optimize joint / tool design to get the maximum width joint with the appropriate depth

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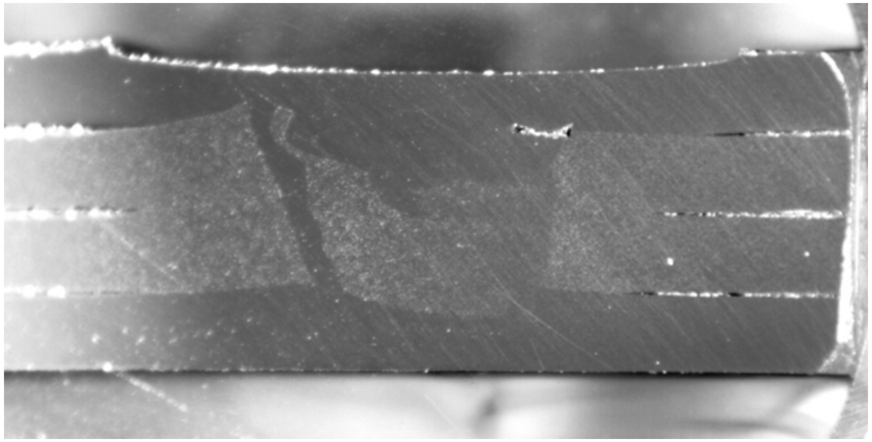
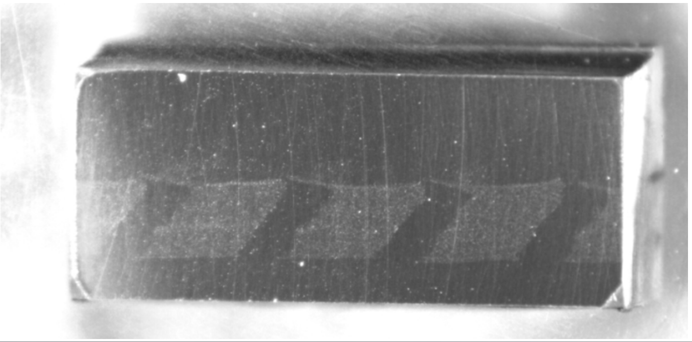
- The weld process and power requirements for specific tools and fixture conditions were defined during 2013.
- Defect free welds can now be produced that show good metallurgical bonding across shorting bars and end cap laminate gaps



Small defect at the top end-cap copper laminate not in the electrical path. Otherwise defect free joint.



Longitudinal section showing defect free joints between shorting bars and end caps

Technical Accomplishments and Progress
Control of distortion and heating during welding

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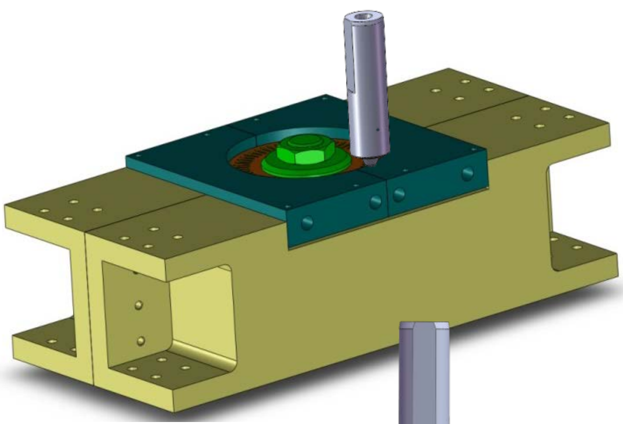
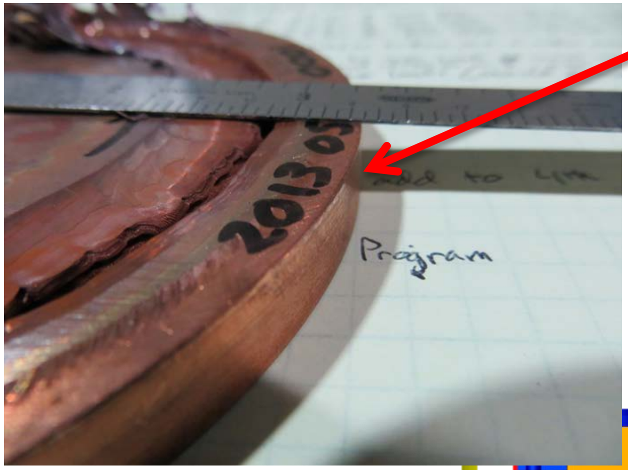
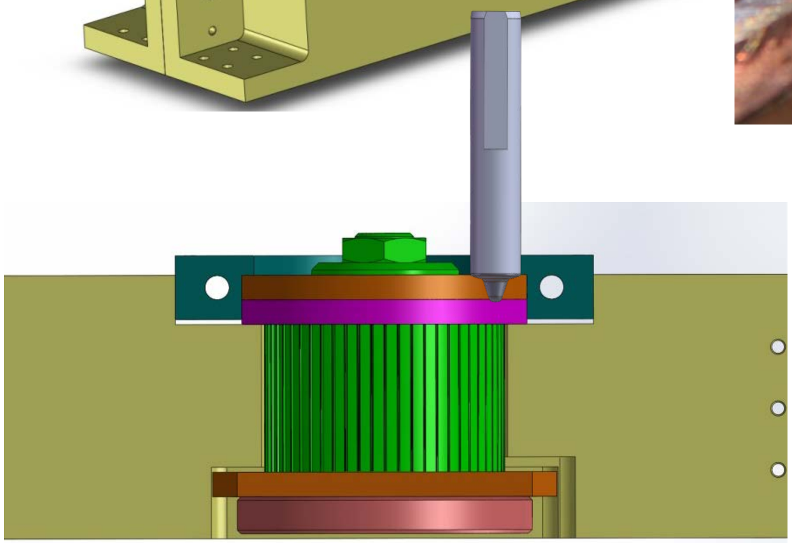
Two types of actively cooled fixtures were designed and built to address control of temperature boundary conditions, and control of distortion

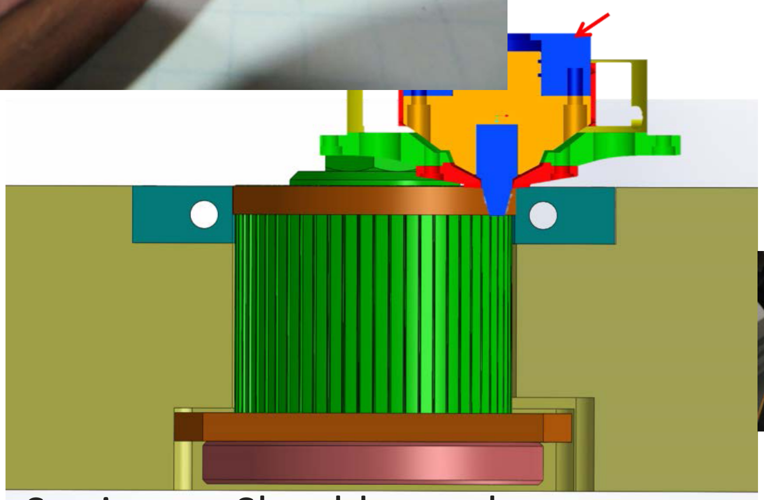




- Cooled fixture allowed for good edge retention of end cap
- Less to machine away in production



Conventional Tool



Stationary Shoulder tool
(Completed but not yet tested. Stationary should may allow welding at the shorting bar diameter – no machining)

Technical Accomplishments and Progress
Control of distortion and heating during welding

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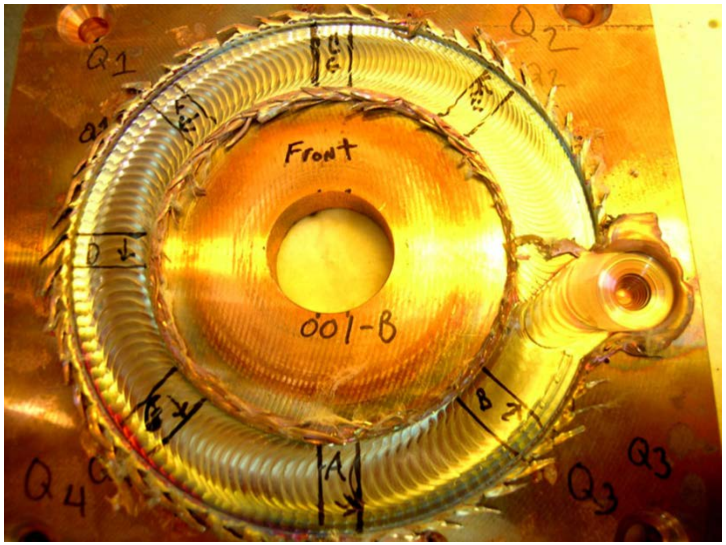
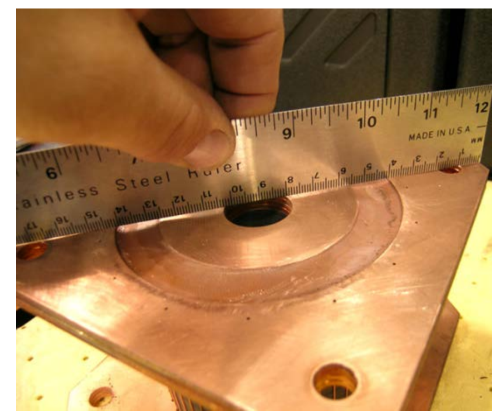
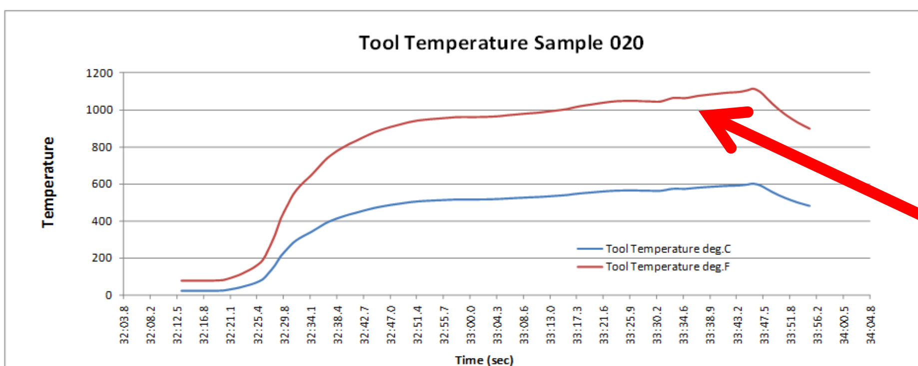
- Another challenge discovered in the rotor fabrication trials is excess heat build up during welding



Weld conditions too hot produce excess flash (which produces volumetric defects called wormholes) and distortion





Also, because this is a circular weld, the tool moves into previous heat field as it comes around part.

Technical Accomplishments and Progress

Power and Temperature Control Algorithms

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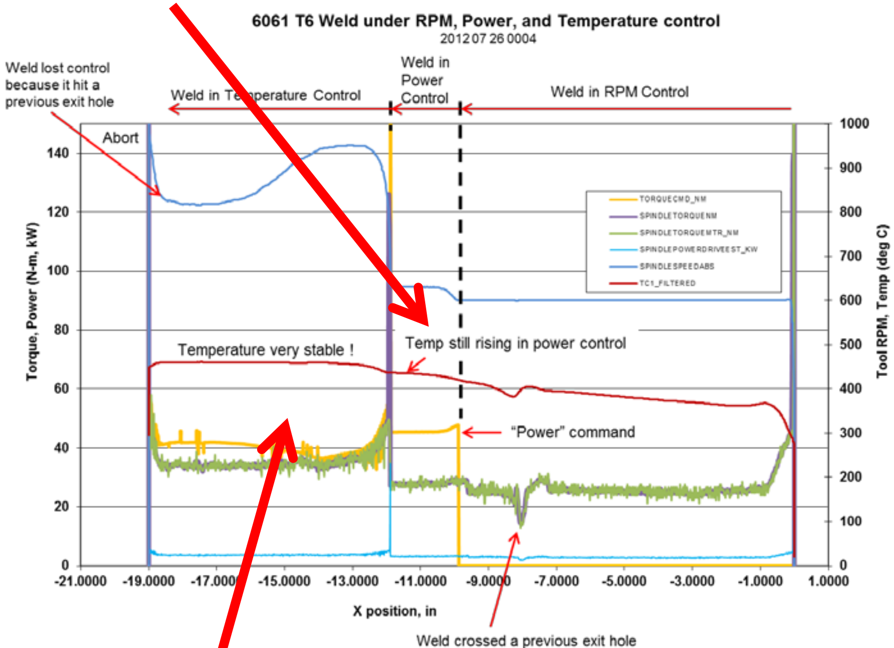
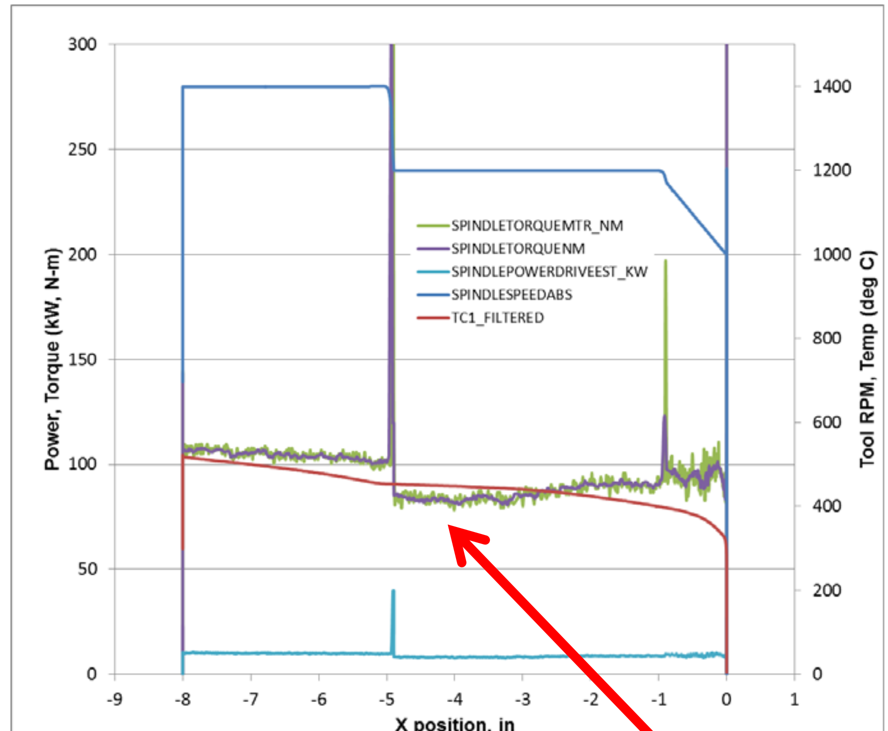
- Controller algorithms implemented on our FSW machine during 2013
- System controls torque to maintain a commanded power and tool temperature
- This results in a steady temperature in the weld and results in a consistent microstructure

Power control



Temperature control



Copper welds in spindle control. These runs are used to set the requested power and determine PID settings for the controller

Power control resulted in stable copper weld temperatures below 500C

Technical Accomplishments and Progress
Dealing with the Exit Hole

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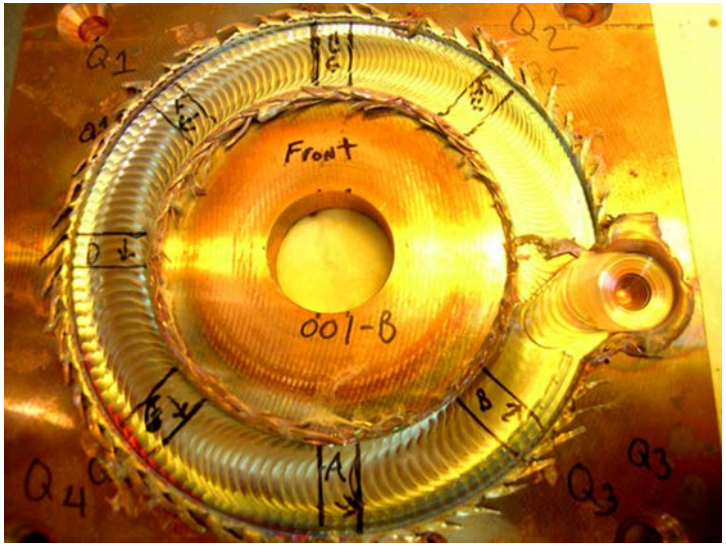
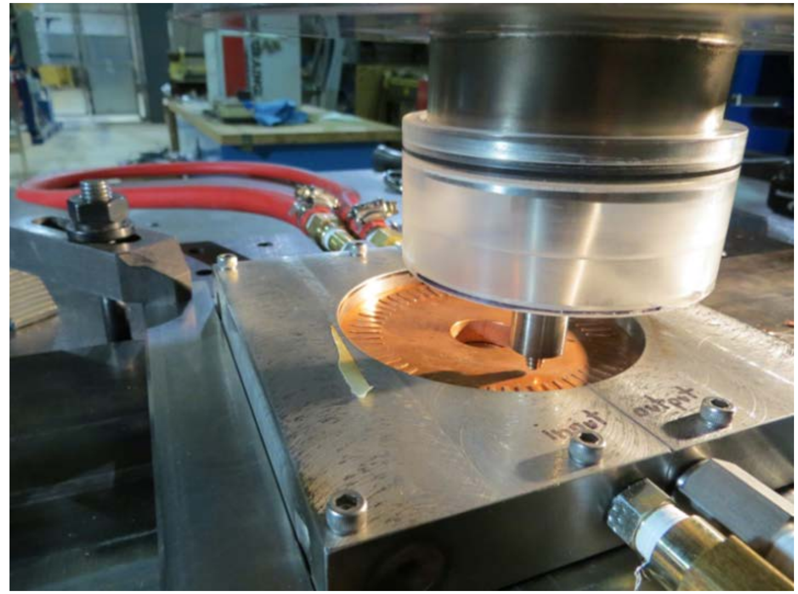


Run Off tab



- Disadvantages of turning out to a runoff tab:
  - If tab is part of end cap, then excess material needs to be machined off - waste
  - If not part of end cap (ie tab insert) then faying surface defect pulled into end cap on retreating side of weld
  - Cooled fixture difficult to design to accommodated tab

<u>Two Solutions:</u>

1. Exit ramps (out of plane)
2. Plug welds with taper plug

Technical Accomplishments and Progress

Dealing with the Exit Hole – Ramp out of Plane

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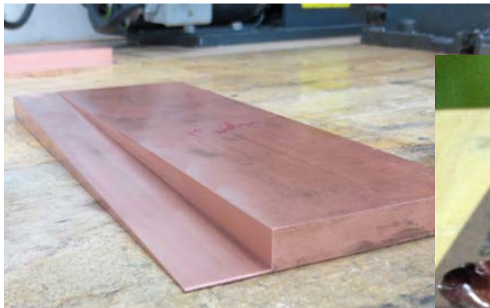
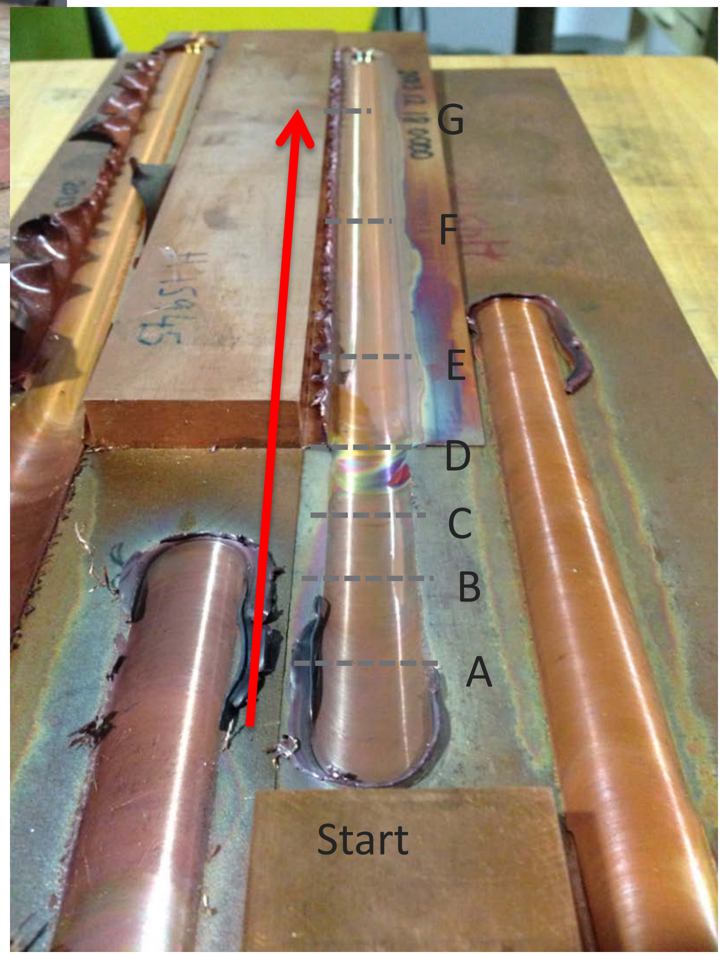
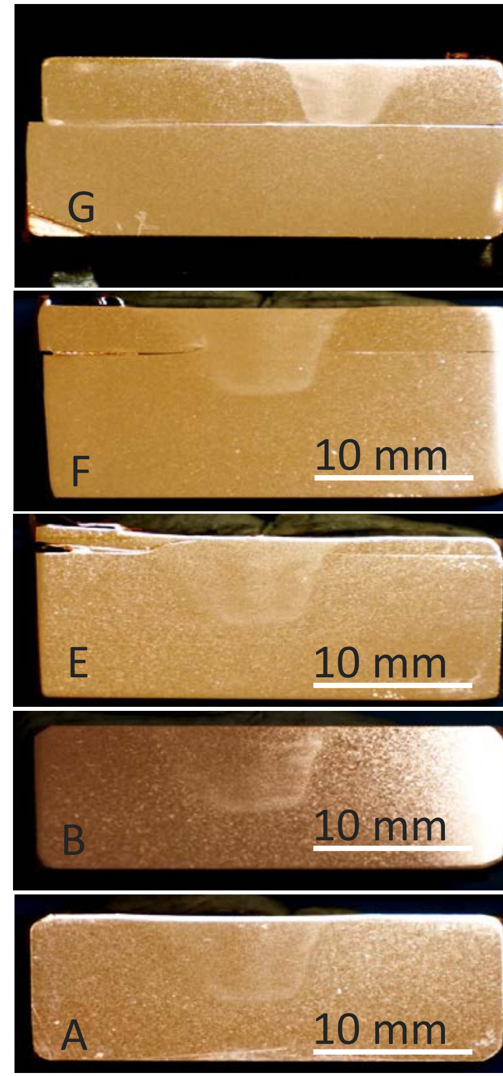




- Weld started in base plate and rode up the ramp
- No volumetric defects
- Horizontal surface between base and wedge on cross sections E and F don't dive inside the material.



Technical Accomplishments and Progress

Dealing with the Exit Hole – Ramp out of Plane

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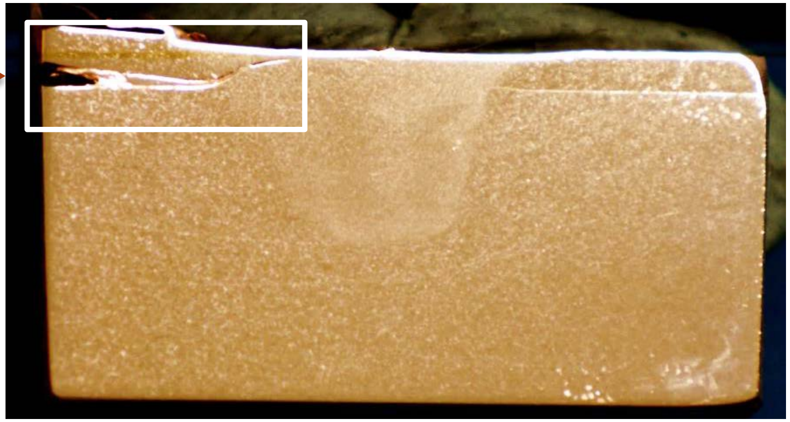
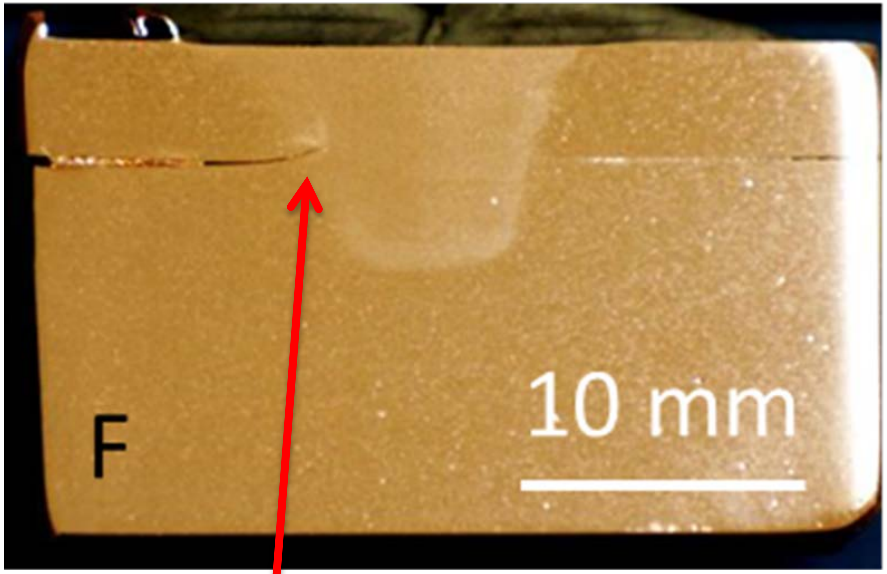
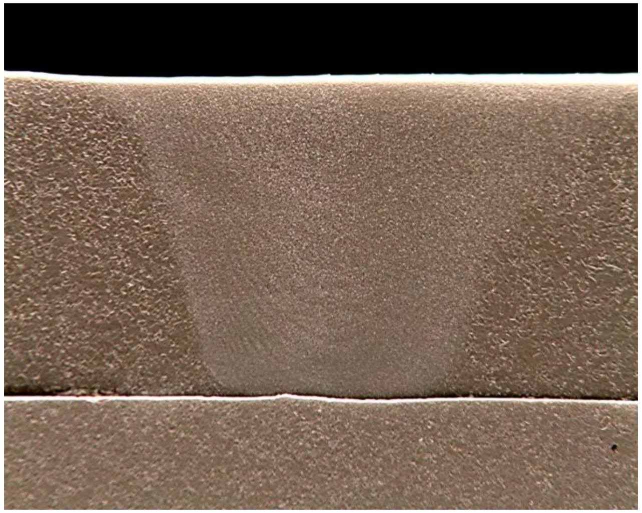
- This photo shows how the defect generated at the interface between the wedge and the plate goes upward, and does not dive inside the material. It would be removed during the final machining operation.





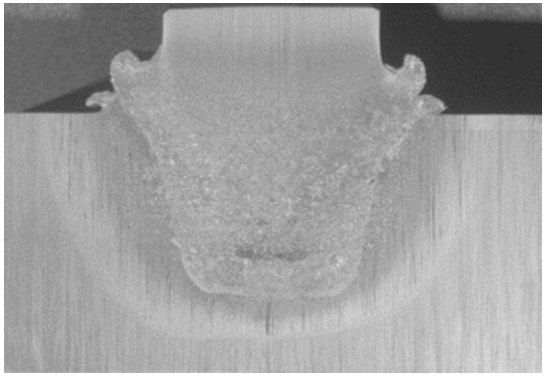
Surface defect still points upward, out of plane, into material that will be machined off.

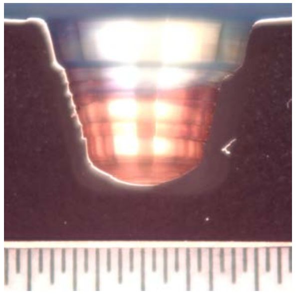


Also no surface defect at tool exit on wedge

Friction taper stud welding

- The technique involves rotating a consumable tool concentrically in a hole while applying a downwards load, to continuously generate a localized plasticized layer.
- The plasticized material develops at a rate faster than the axial feed rate of the consumable tool, and hence the frictional rubbing surface rises up along the length of the tool, creating a dynamically recrystallized interface layer which forms the dense plug.
- There is literature reporting the technique applied to steels, aluminum, magnesium.





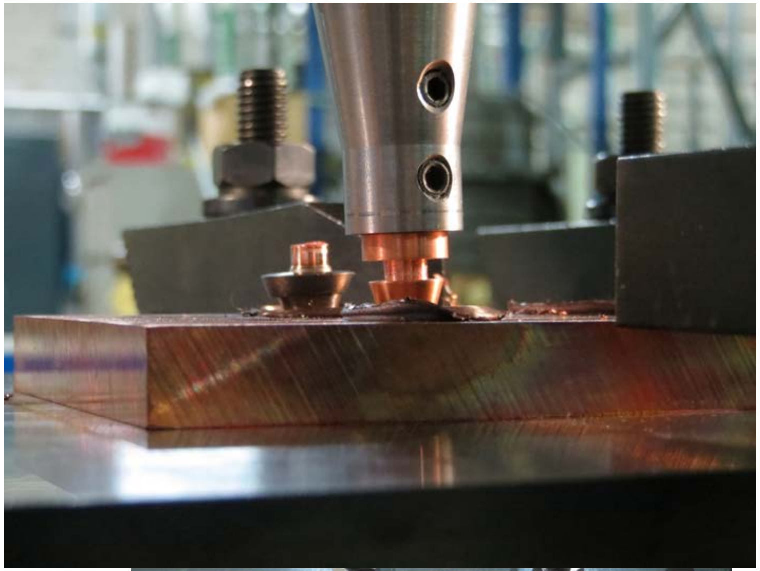
Our tool exit hole

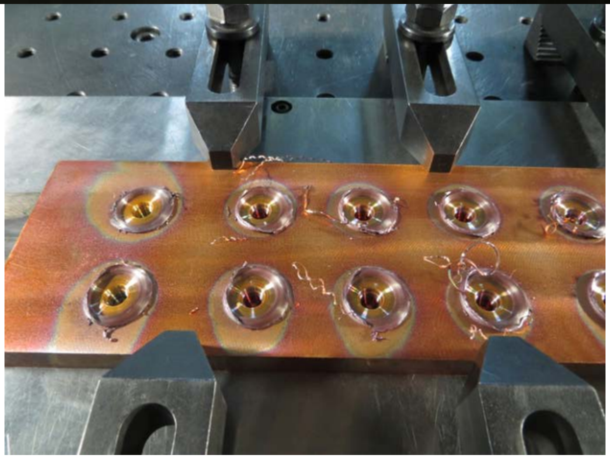
The friction plug needs to be designed so that it has a taper slightly smaller than the hole, and a bottom diameter slightly smaller than the pin bottom

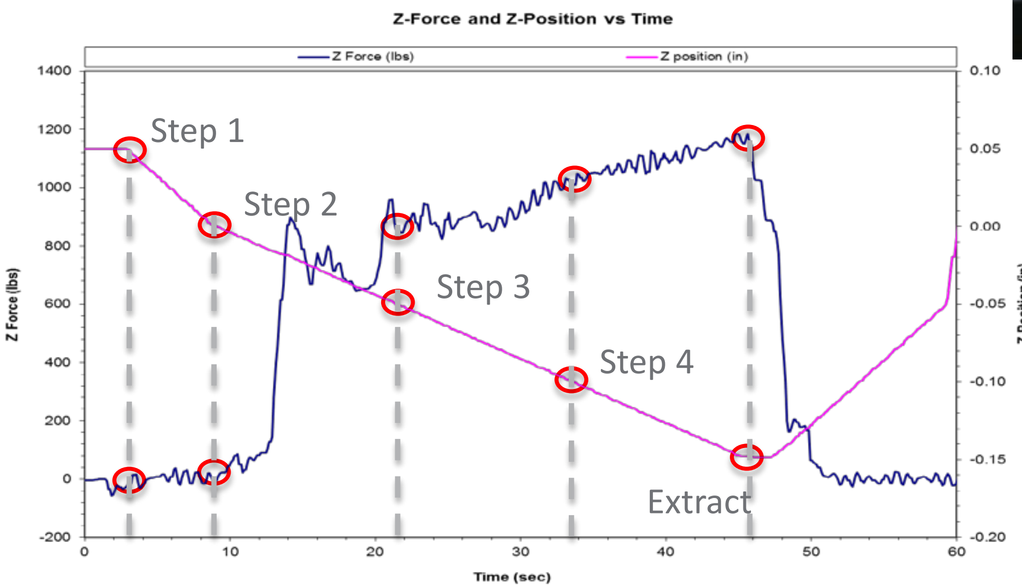
Technical Accomplishments and Progress

Dealing with the Exit Hole – Plug welding

- Trials are just beginning to outline the process parameters needed to make full dense plug welds
- Partial success, but still dealing with voids on the bottom







Milestones and Gates

- 2013 Milestone: Characterize the microstructure and mechanical properties of Cu/Cu joints. Gate is established on minimum mechanical performance threshold established by the project team. – Completed
  - First go/no go gate has been achieved with the mechanical testing of a friction-stir welded rotor at GM. Test was completed on a friction-stir welded rotor using a10,000 revolutions per minute (RPM) run-up test. - Gate passed. No other mechanical performance test is anticipated because of the mixed mode loading condition of a squirrel cage configuration. Microstructure shows defect free metallurgical bonding of the end cap to shorting bar.

- 2013 Milestone: Develop, fabricate, and test actively cooled welding fixture to allow for FSW of copper and aluminum rotor parts – Completed

- 2013 Milestone: Demonstrate a robust weld process on copper/aluminum dissimilar material welds and verify that mechanical properties pass metrics established by the project team.
  - Behind Schedule. The project partners have decided to put more emphasis on the all-copper rotor first. We will return to the copper-aluminum joints after working out the temperature control and exit hole issues.

- 2014 Milestone 2nd Quarter (March 31) (SMART goal) Demonstrate the software to produce a temperature controlled weld in Copper that can hold weld temperature to within +/- 5 degrees C during the welding of a 4 inch diameter copper rotor endplate. Start-up transient and exit ramp can be outside the 5 degree window, but the 5 degree window must be maintained during the steady-state, circular welding operation.
  - On track – Have demonstrated software on linear welds , not yet on circular welds

Responses to Previous Year Reviewers' Comments

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- "The reviewer reported the assumption was that it (*the contact between the end cap and shorting bar)* must be fully electrically conductive, although the weld zone does not completely fuse the contact area." RESPONSE: We have greatly improved the process this year through more process parameter development and now have a bond between the copper end cap and copper shorting bar that is fully metallurgical.
- "The reviewer asked if there was a potential for motor efficiency loss over time with a contact fit between dissimilar metals, and if this was a concern" RESPONSE: Yes. The bond between copper and aluminum will be important to study. If the two are intimately in contact there is a question whether or not intermetallics or oxides will give the interface a low level of long term performance in conductivity or fatigue. Cu – Al joints however are common in the power distribution business, usually made by rotary or linear friction welding. These joints in conductor terminals are not subject to the same degree of loading a squirrel cage might see, so mechanical testing is very important
- "The reviewer's primary overall concern was that the presentation showed very few actual results from the project and the results that were shown were primarily non-quantitative" RESPONSE: We have endeavored to include more data in this presentation. However, weld process development is somewhat qualitative by nature. The iterative studies of tool design and materials eventually yielded defect free welds as shown in this presentation. The cooled tool holder produced end caps with less distortion, and as far as mechanical property tests are concerned, the radial and bending loads encountered by the complex joint between a shorting bar and a end cap really does not have a simple mechanical test analog. This is why we went straight to the run up test. We cannot share the details of the test because of CRADA issues but it is a very practical screening test that has a pass/fail quality. When we do the dissimilar development, we will be using standard tensile tests because we are interested in interface strength and fatigue performance, so more data will be coming.

Future Work in 2014

- 2014 Milestone 3rd Quarter (June 30) Demonstrate a welding strategy that eliminates the exit hole left by the tool pin in the copper end plate. The leading candidate is the ramp or wedge extract concept. Test the viability of this concept through experimental weld trials.

- 2014 Milestone 4th Quarter (Sept 30) (SMART goal) Complete construction of a stationary shouldered tool assembly, and demonstrate that defect free welds can be made within 4 mm of the weld fixture wall, minimizing material wastage and part deformation.

Collaboration and Coordination with Other Institutions

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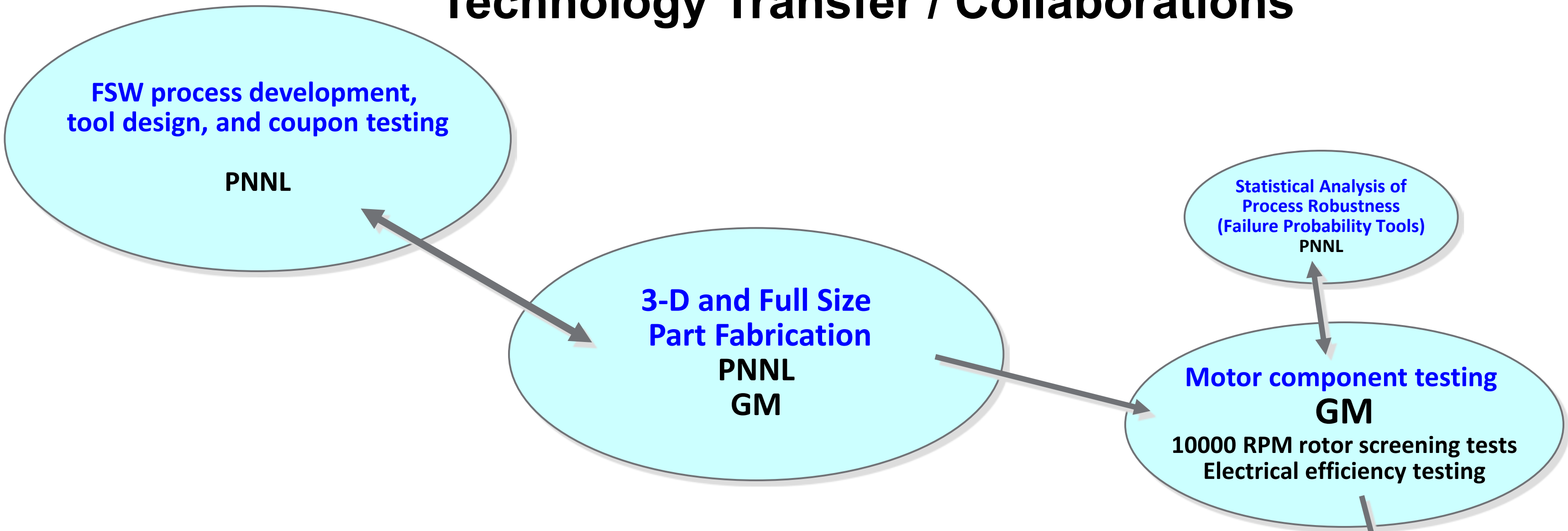
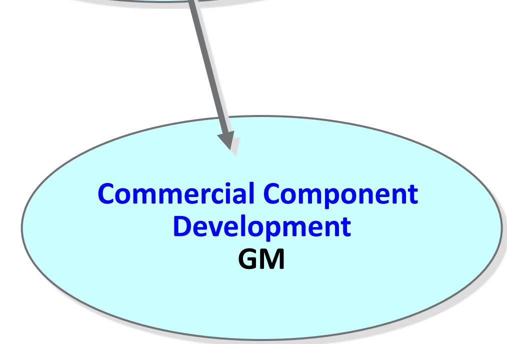
Technology Transfer / Collaborations





- Performance data and manufacturing technology will be transferred to industry through the mechanism of a Cooperative Research and Development Agreement (CRADA) with General Motors (GM), ensuring a clear path to commercialization.

Summary

- This project will use new solid-state joining and processing technologies to achieve both increased performance and a lower manufacturing cost.
- The project will develop the fundamental understanding of solid-state joints between copper materials and between copper-aluminum dissimilar joints so that they can be accomplished with:
  - low thermal input,
  - low distortion of adjacent parts,
  - a high degree of structural integrity,
  - a high degree of thermal and electrical continuity.
- Joined or processed components will be evaluated and tested by the industry collaborators to demonstrate efficiency benefits
- The manufacturing methods developed will lead to motors that will display
  - lighter weight
  - higher performance
  - a relatively lower cost to manufacture