Project ID: PM004_grant_2015

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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

2015 DOE VEHICLE TECHNOLOGIES PROGRAM
ANNUAL MERIT REVIEW AND PEER EVALUATION MEETING
JUNE 10, 2015
WASHINGTON, DC

Overview

Timeline

- Start: FY2011
- Project end date: Sept 2015
- Percent complete: 85%

Budget

- Total project funding
  - DOE - $1,505k
  - GM - $1,306k (in-kind)
  - 54/46 Cost Share with GM through in-kind contribution
- DOE Funding for FY13: $300k
- DOE Funding for FY14: $360k
- DOE Funding for FY15: $300k

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 and Development
- Project lead: PNNL

Relevance
Background - Opportunities

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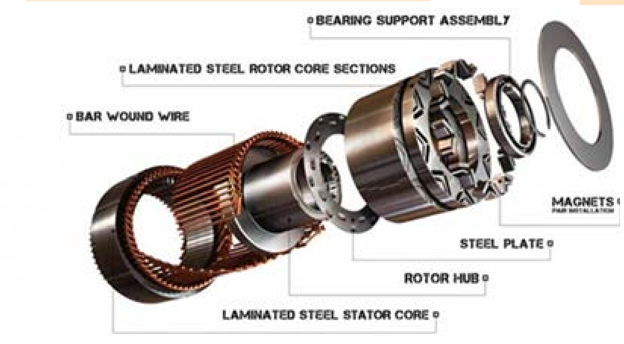
Two primary traction drive motor classes:

Permanent Magnet Motors	Induction Motors



- Induction motors have several advantages over permanent magnet motors for traction drives in EVs
  - Can be higher efficiency than a PM motor when the whole drive cycle is considered (going from low speed / high torque to high speed operation) but usually less efficient at a given RPM
  - Can be lower cost
  - No expensive permanent magnets that use “critical” materials (no heavy REE)
- 2011 ORNL study assessing electric motor technologies identified non-permanent magnet motors as having the greatest opportunity to impact motor cost reduction

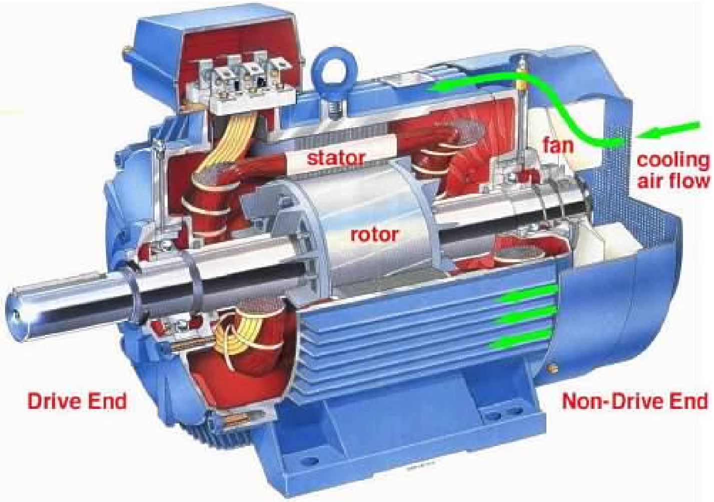
Advanced Power Electronics and Electrical Motors R&D Area

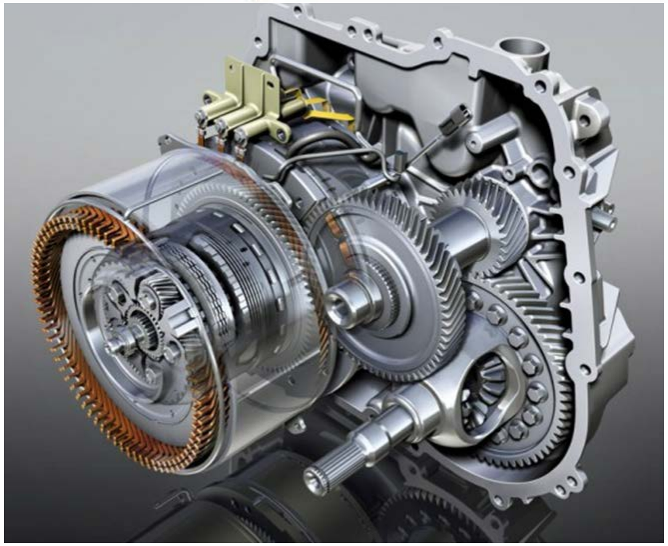
Research Focus Areas *(Reduce cost and maintain performance)*	
Permanent Magnet (PM) Motors	❑ Reduce cost by 75% - required to meet 2020 target ❑ Motor design optimization may reduce cost by 25% to 40%.
Magnet Materials	❑ Magnet material costs are 50% of 2015 target and 75% of 2020 target ❑ Reducing PM cost and increasing temperature capability could reduce motor cost by 5% to15%
Non-PM Motors	Non-PM motor technology yields the greatest opportunity for motor and system cost reduction: ❑ Could reduce motor cost by 30% ❑ Eliminating boost converter (required for IPM machines due to back emf) saves 20% in PE cost ❑ Optimized power factors of non-PM machines can result in up to 15% PE cost savings
New Materials	❑ New materials for laminations, cores, etc. could save 20% of motor cost

ORNL/TM-2011/73, ***Final Report on Assessment of Motor Technologies for Traction Drives of Hybrid and Electric Vehicles***, by R. R. Fessler published March 10, 2011.

Relevance
Making a Better Induction Motor

- Induction motors can show large I^2R losses in the stator winding and in the rotor conductor.
- Most large induction motors use aluminum extensively in the rotor squirrel cage and structure for light weight and ease of manufacturing
- However, the highest efficiency variants use copper in the windings and rotor, rather than aluminum, because of copper's 60% higher conductivity.
- Higher conductivity can lead to a copper based motor that is 23% lighter and 30% smaller than an aluminum intensive machine because of higher power densities (Critical to EVs)
- Copper induction motors can also have better heat removal and an increase in rigidity and strength.





The challenge comes in manufacturing of a copper rotor assembly

Relevance

Current Methods – Manufacturing a typical Aluminum Induction Motor Rotor

- End caps are either welded or die cast to shorting bars
- Die casting is low cost and works great for aluminum

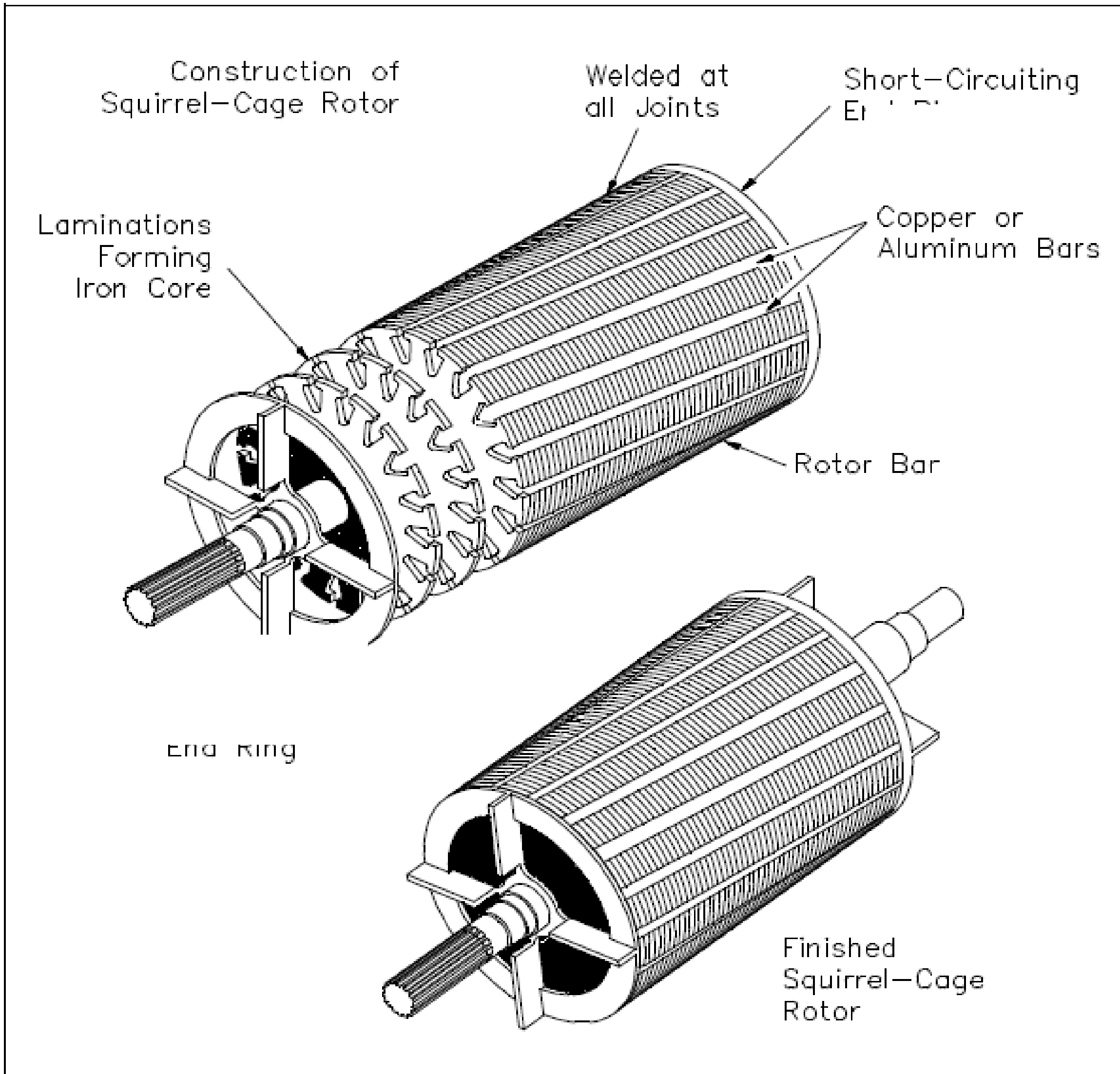
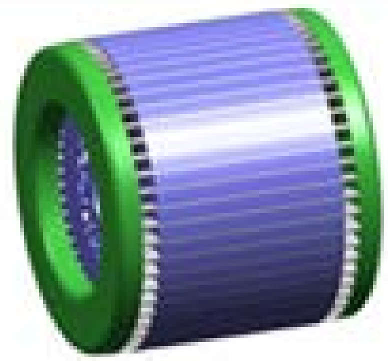


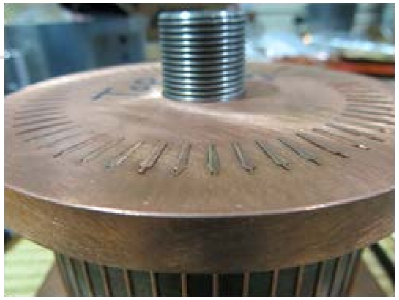
Figure 5 Squirrel-Cage Induction Rotor

Relevance

Copper rotors present a manufacturing challenge

- How is a copper rotor made today?
  - 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 dies!)
    - High temperature can affect the coated laminates below the end caps, shorting them, increasing eddy current losses and reducing efficiency
  - 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)





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 - Objective

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Overall Project Objective

- To develop and deploy high-power induction rotors and stators that are:
  - lighter weight / smaller
  - 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.

Objectives (March 2014 through March 2015)

- Investigate and solve problems related to practical manufacturing concerns
  - rotor fixturing and distortion control, welding strategies that eliminates the exit hole left by the tool pin in the copper end cap, and strategies that minimize copper wastage in post-joining machining processes.
- Develop a software machine control mechanism that can produce a temperature controlled weld in Copper that can hold weld temperature to within +/- 5 degrees C.
  - Implement this software on a FSW machine platform.

2014/2015 Milestones and Gates

- 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. → **Completed**

- 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. → **Completed**

- 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. → **Delayed to 2015**
  - Stationary Shoulder tool has been designed and constructed but problems have been encountered in the fixturing of the end cap for welding. Experimental trials of different fixturing options are being investigated.

- 2015 Milestone 4th quarter 2015 – Deliver 4 fully welded rotors to GM for mechanical and electrical efficiency testing. Rotors will be fabricated with a conventional shoulder tool and utilize either a ramp or plug weld to heal the exit hole. → **On track**

Approach and Strategy for Deployment

- Develop the fundamental understanding needed to successfully apply solid state joining techniques for the manufacture of electric motor components
- 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
- Transfer process technology to industry through CRADA partnership

This project is 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.
  - 2015 Milestone/Deliverable: 4 full sized copper rotor assemblies for testing at GM
- Task 2 Develop the process to allow dissimilar material joining, primarily copper to aluminum to improve component performance and weight savings.
  - 2015 Milestone/Deliverable: If coupon level Cu-Al joints can be made with good electrical conductivity, then deliver similar full-size hybrid Cu-Al rotors for testing at GM

Technical Accomplishments and Progress
Primary challenges for FSW

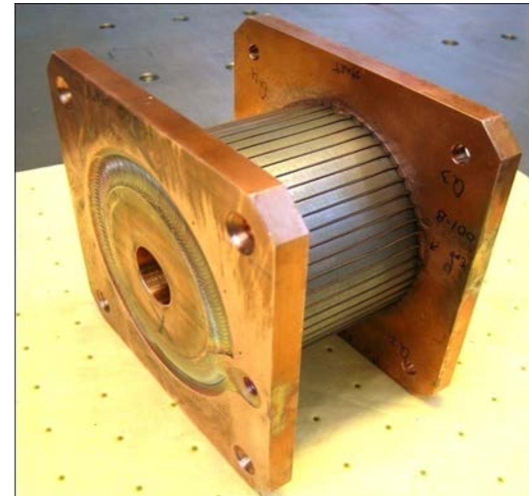
Focus of FY 13/14 work

- 1) **Nugget Size – Electrical continuity**
  - The joint design for the highest electrical cross section dictates a specific tool design (and tool materials)
  - Specific tool designs can lead to narrow process parameter windows for defect free welds

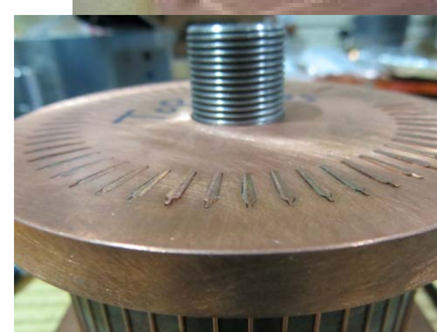
- 2) **Control of distortion and over-heating is needed during welding**
  - Control of boundary conditions critical (actively cooled fixtures)
  - Adaptive control of the weld power and tool temperature is critical

Focus of FY 14/15 work

- 3) **Maximizing the "buy to drive" ratio – Copper is expensive**
  - Design fixturing to minimize copper use
  - Exit hole issues when you don't use a runoff tab

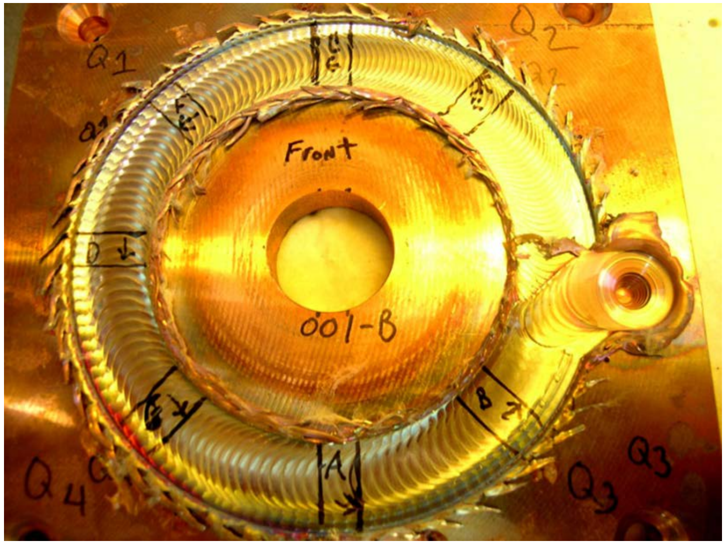


Rotor fabricated by Friction Stir Welding

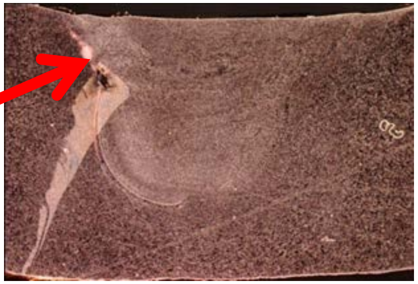


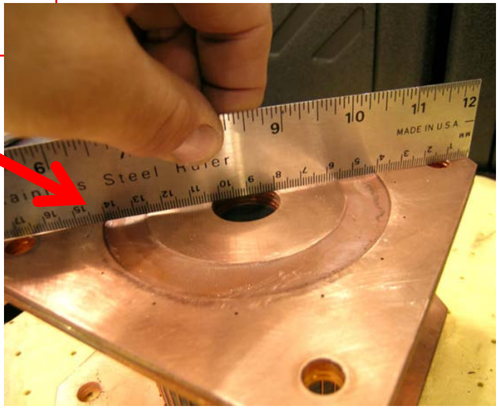
Technical Accomplishments and Progress
Control of distortion and heating during welding

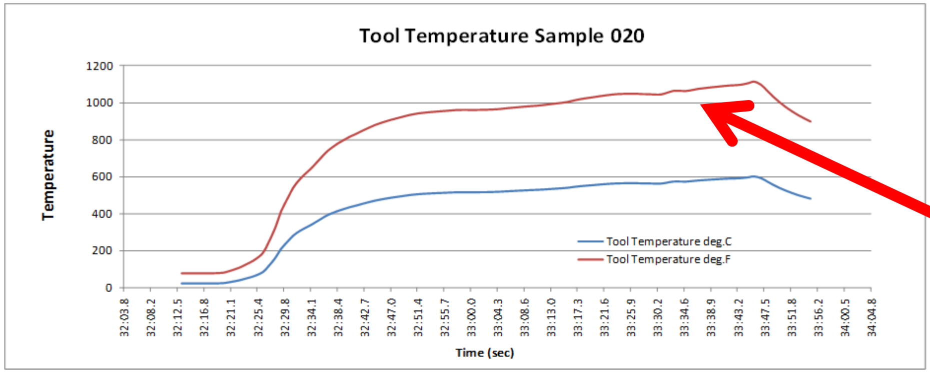
- Another challenge discovered in the rotor fabrication trials is excess heat build up during welding



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





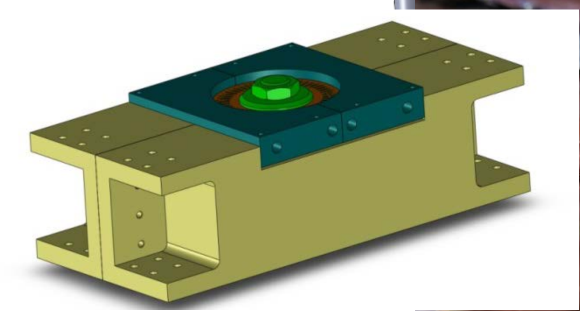


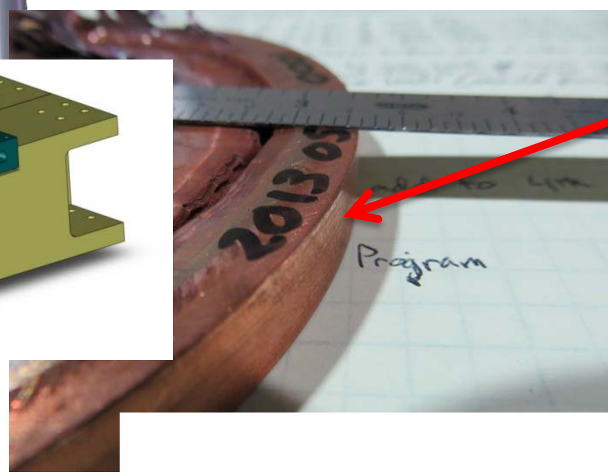
Also, because this is a circular weld, the tool moves into previous heat field as it comes around part.

Technical Accomplishments and Progress

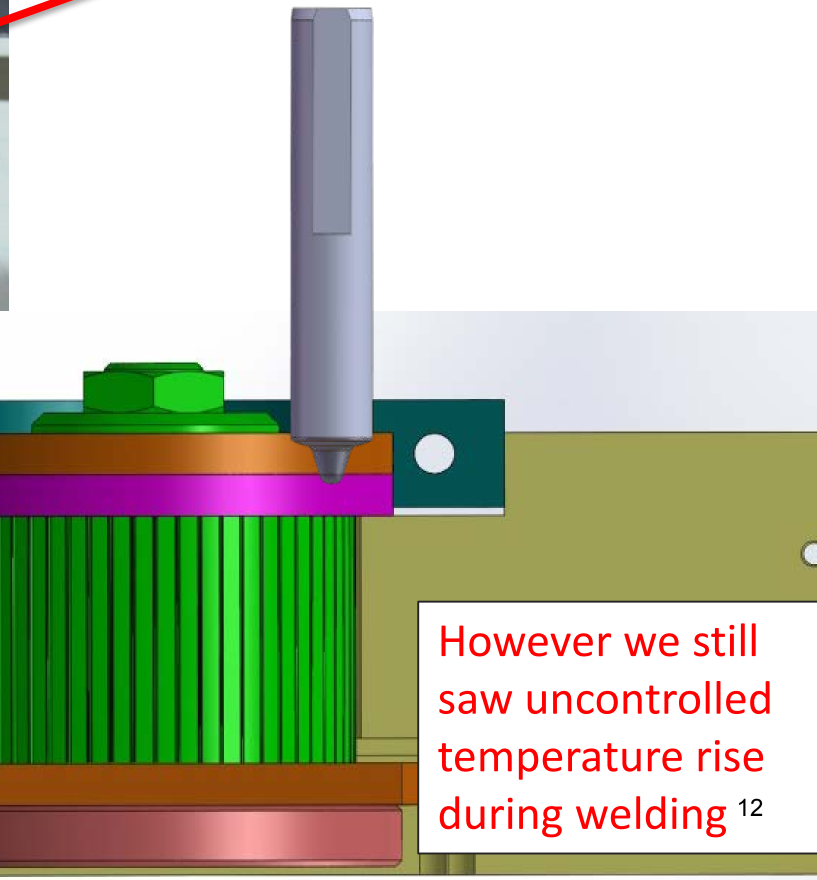
Control of distortion and heating during welding - cooled fixtures

Actively cooled fixtures were designed and built to address control of the temperature boundary conditions, and control of distortion





Cooled fixture allowed for good edge retention of end cap



- Gap allows cooled clamp to pinch end cap between clamp and pink spacer ring.
- Reacts weld load and reduces distortion

However we still saw uncontrolled temperature rise during welding

Technical Accomplishments and Progress

Solution to rising temp : Temperature Control Algorithm

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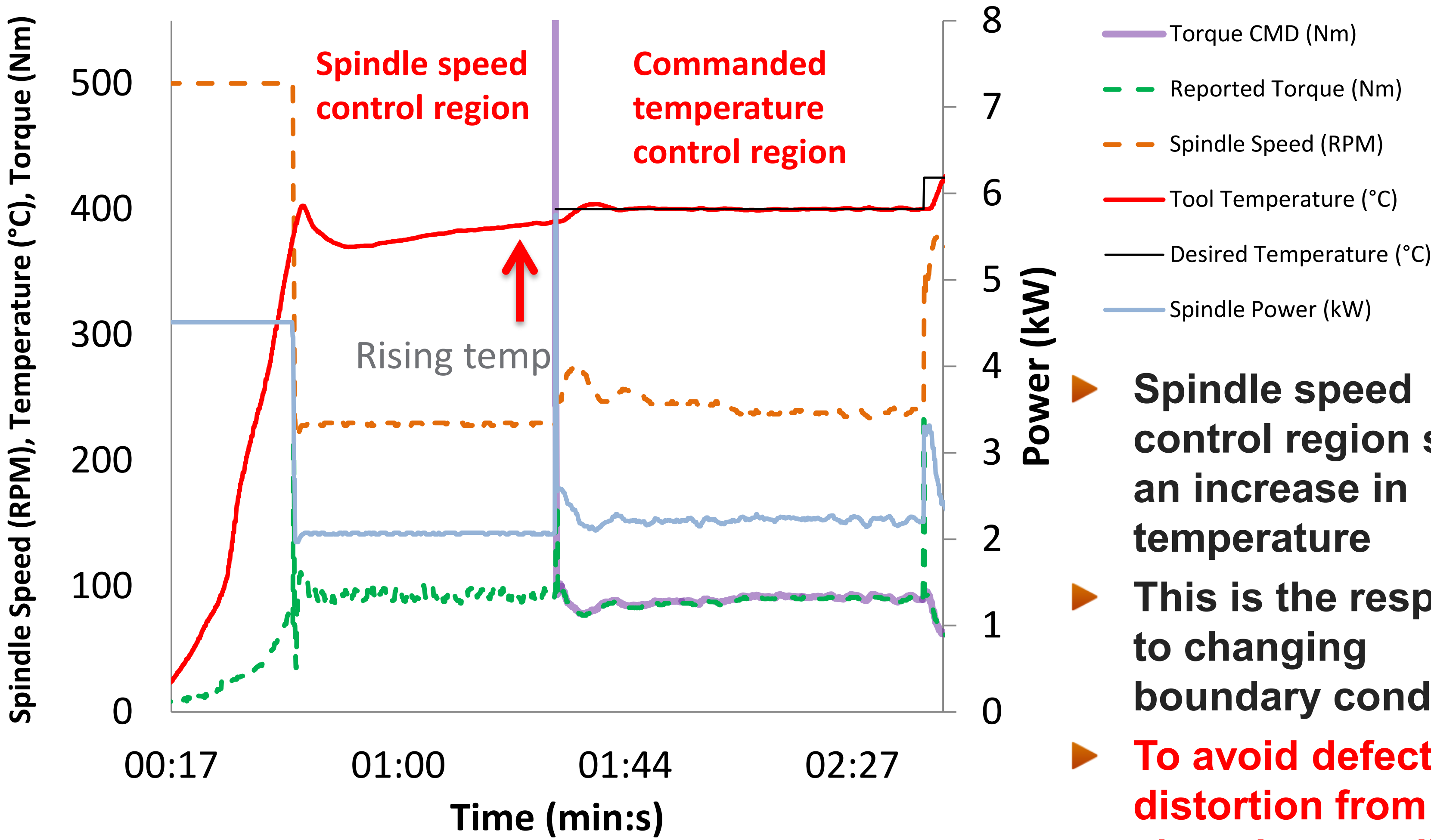
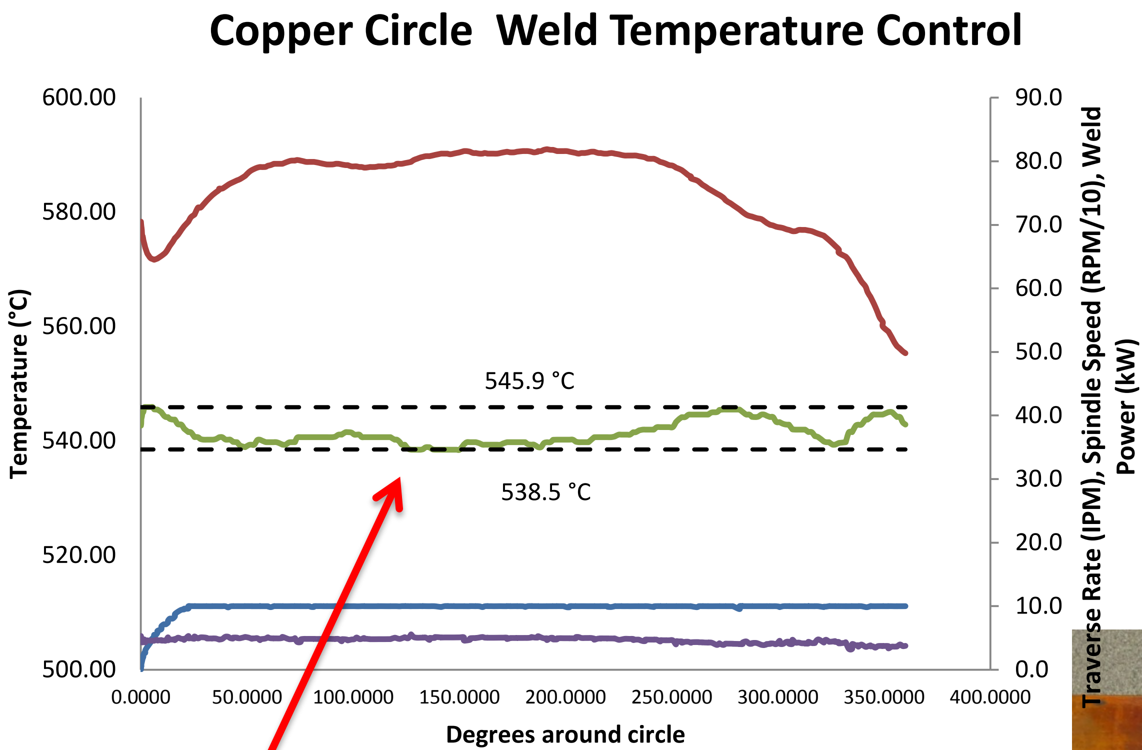


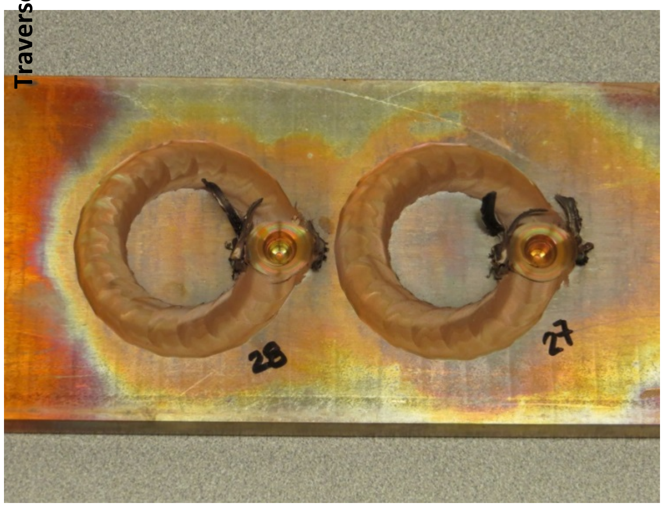
- Spindle speed control region shows an increase in temperature
- This is the response to changing boundary conditions
- **To avoid defects and distortion from changing conditions, temperature control is critical**

- System controls torque to produce a commanded power or commanded tool temperature
- This results in a steady temperature in the weld and results in a consistent microstructure and weld geometry

Technical Accomplishments and Progress
Temperature Control Algorithm on solid copper plate



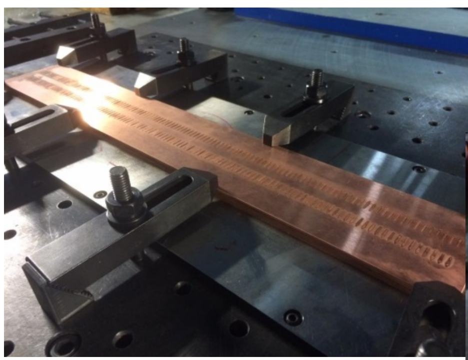
Temperature Control Milestone Achieved: Demonstrate the software to produce a temperature controlled weld in Copper that can hold weld temperature to within +/- 5 degrees C during the welding.
(Start-up transient is not yet under good control)

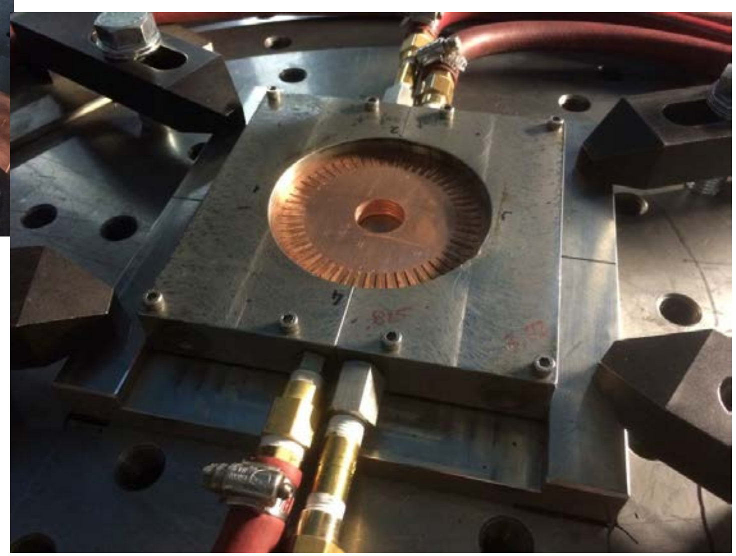


Solid copper plate

Technical Accomplishments and Progress
Temperature control development on laminates with shorting bars

- Linear welds were used to develop auto-tune sequence and establish PID control settings for temperature control
- Once parameters were established, circular welds were done on a rotary table using a full sized endcap mockup (with shorting bars)





Technical Accomplishments and Progress

End cap mockups were successfully welded

- End cap mockup welds were accomplished on 5 piece copper laminate stackups with subsized shorting bars to model actual rotor fabrication conditions
- End caps show almost no distortion

Technical Accomplishments and Progress
Dealing with the Exit Hole

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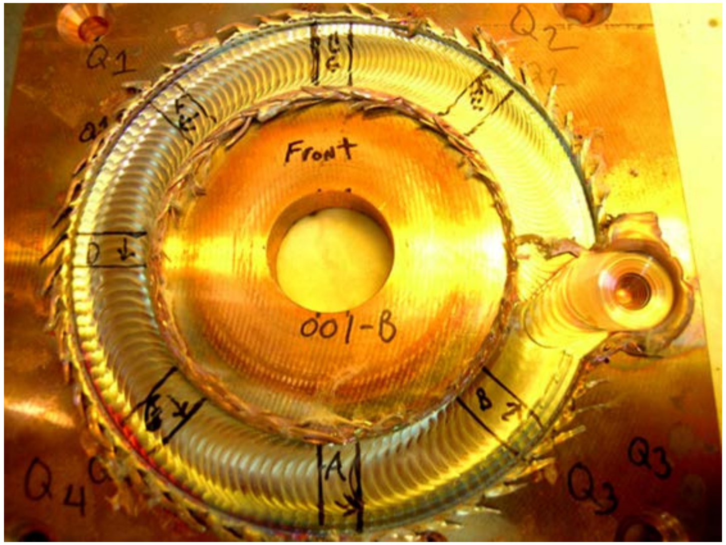
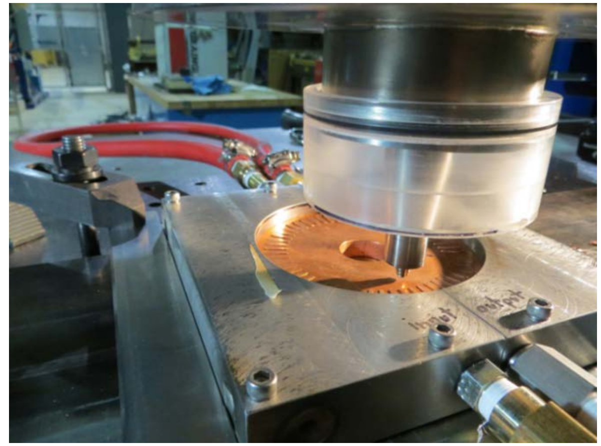


Run Off tab



- Run off Tab
  - Disadvantages
    - If tab is part of end cap, then excess material needs to be machined off – copper waste
    - If not part of end cap (ie tab insert) then faying surface defect pulled into end cap on retreating side of weld

<u>Two solutions to exit hole if no runoff tab :</u>

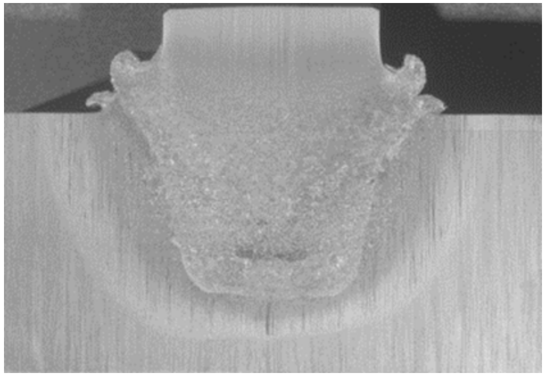
1. Exit ramps (out of plane) (Presented last year)

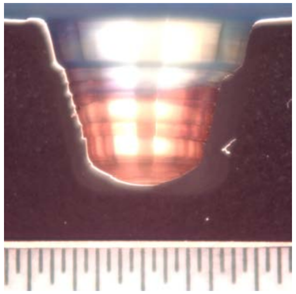
- No volumetric defects – This is a successful, but expensive method of preventing an exit hole

2. Plug welds using a tapered plug

Friction taper plug 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 a dynamically recrystallized layer rises up along the length of the tool, creating a dense plug.
- There is literature reporting the technique applied to steels, aluminum, magnesium.



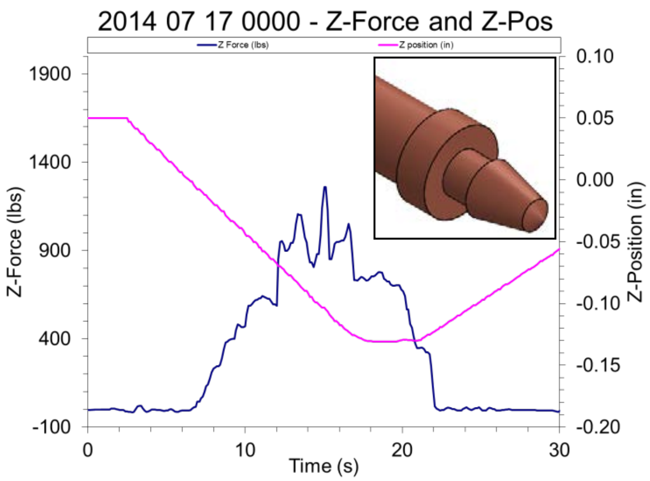


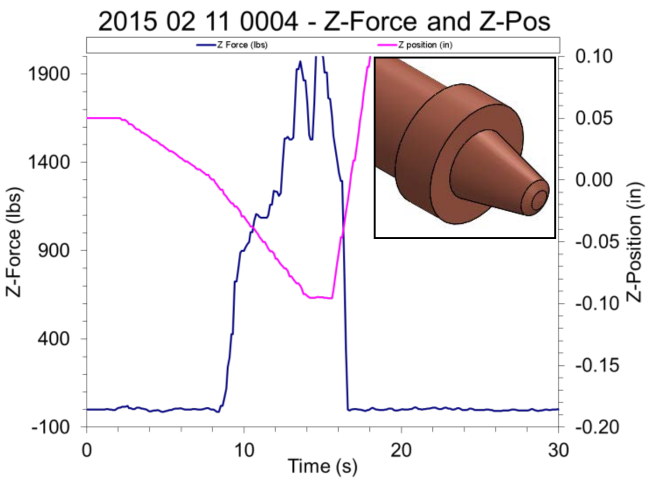
Our tool exit hole

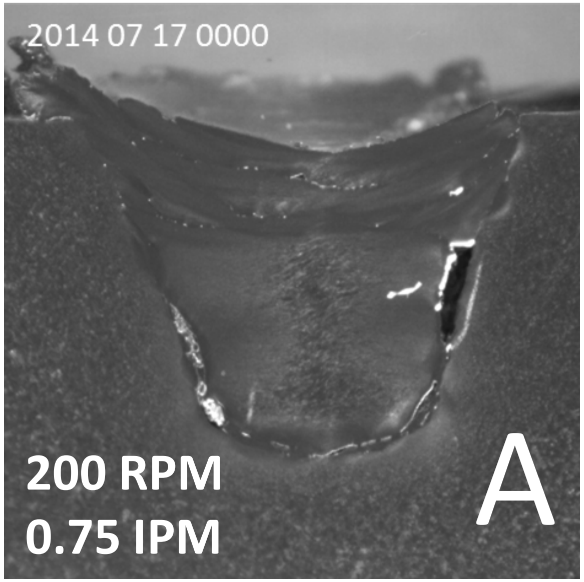
The friction plug needs to be designed so that it has a taper slightly smaller than the hole, and a bottom diameter slightly smaller than the pin bottom

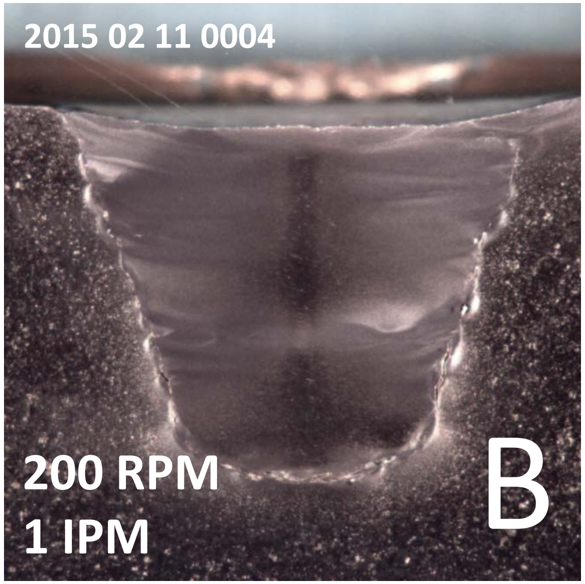
Technical Accomplishments and Progress

Dealing with the Exit Hole – Plug welding









Discovery during 2014/2015

- Higher forging loads help consolidation.
- Higher feed IPM (keeping RPM constant) translates into higher forging forces.
- Plug B had an optimized shape that allowed a more stable weld
- Shape is everything
- **Successful plug can be made at full density**
- **This may be lower cost to implement both in less complex hardware than a ramp and in less copper used**

Responses to Previous Year Reviewers' Comments

- ”The project team identified several challenges along the way which impacted the project schedule”
  - RESPONSE: This project is trying to move a technology from TRL 4 to TRL 6 by taking a known, but new technology, FSW, and using it to fabricate full size rotors for testing in actual motor platforms. <u>This TRL4 to TRL6 jump requires understanding the myriad of conditions that make the process robust for manufacturing</u> (weld window, response to disturbance in the manufacturing process, practical considerations for high volume manufacturing like copper waste in machining, etc). In that respect it is somewhat different than a proof of concept project.
  - As the weld conditions, tools and fixture needs were discovered, experimental iteration was needed to optimize conditions. This led to schedule delays. Project funds have been allocated to tasks with contingency for discovery and problem solving, so from a budget perspective, we are on target, but schedule contingencies in retrospect were insufficient. The project was extended 1 year through FY15 to cover the schedule change. Progress has been made to solve each of the challenges encountered so far. At this point we don't see any major issue that will impact the final delivery of the rotors to GM for testing.
- “One reviewer queried whether overcasting the endcaps would be feasible, another reviewer added that the casting route needs to be explored further..”
  - Casting of smaller copper rotors is currently in production. GM has chosen to look at the solid state joining alternatives because overcasting copper is a significantly greater challenge than aluminum. Copper casting is much higher temperature potentially causing degradation to the steel laminates and liquid copper is highly reactive with the dies and molds leading to very high costs in casting. A solid state joined rotor is potentially a lower cost rotor and this project is design to establish the performance, process methodology, fixture needs and throughput potential of the process. From that GM should be able to establish ballpark cost estimates.

Collaboration and Coordination with Other Institutions

Technology Transfer / Collaborations

FSW process development, tool design, and coupon testing
PNNL

3-D and Full Size Part Fabrication
PNNL
GM

Statistical Analysis of Process Robustness (Failure Probability Tools)
PNNL

Motor component testing
GM
10000 RPM rotor screening tests
Electrical efficiency testing

Commercial Component Development
GM

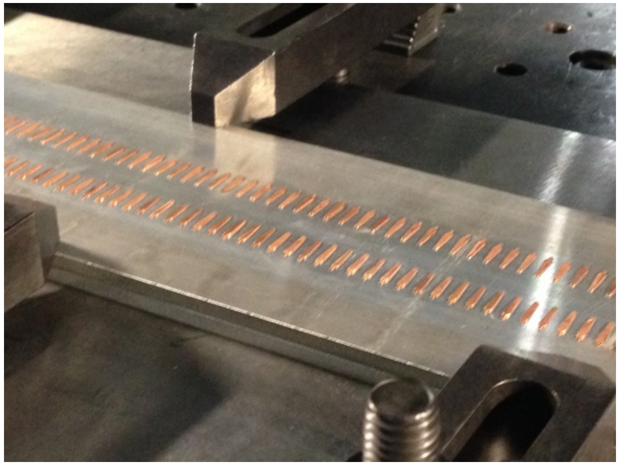
Collaboration

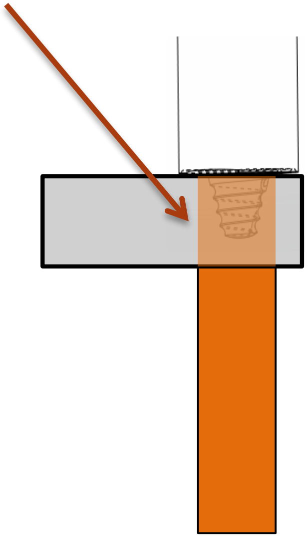
- Biweekly conference calls where laboratory work scope and tasks are discussed
- GM provides materials including all machined copper plates, rotor subassemblies, plug welding blanks, laminated steel rotor cores, pre-production fixturing.
- PNNL executes FSW process development, tool design and optimization and software process control development
- GM provides all component scale testing including 10,000 RPM rotor screening tests and electrical efficiency tests
- Over the 4 year project GM has participated at approximately 50% of the total budget through in-kind contribution

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.

Remaining Challenges and Barriers
Dissimilar material rotor

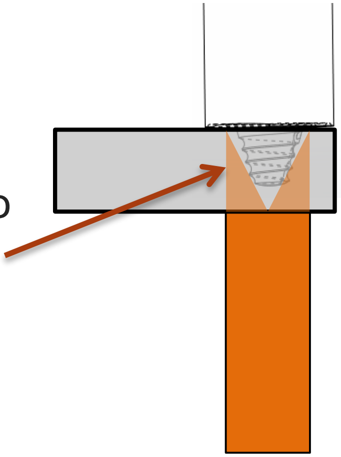
- The experiments below simulate an aluminum end cap with copper shorting bars
- Tool pin consumes and breaks up top part of shorting bar





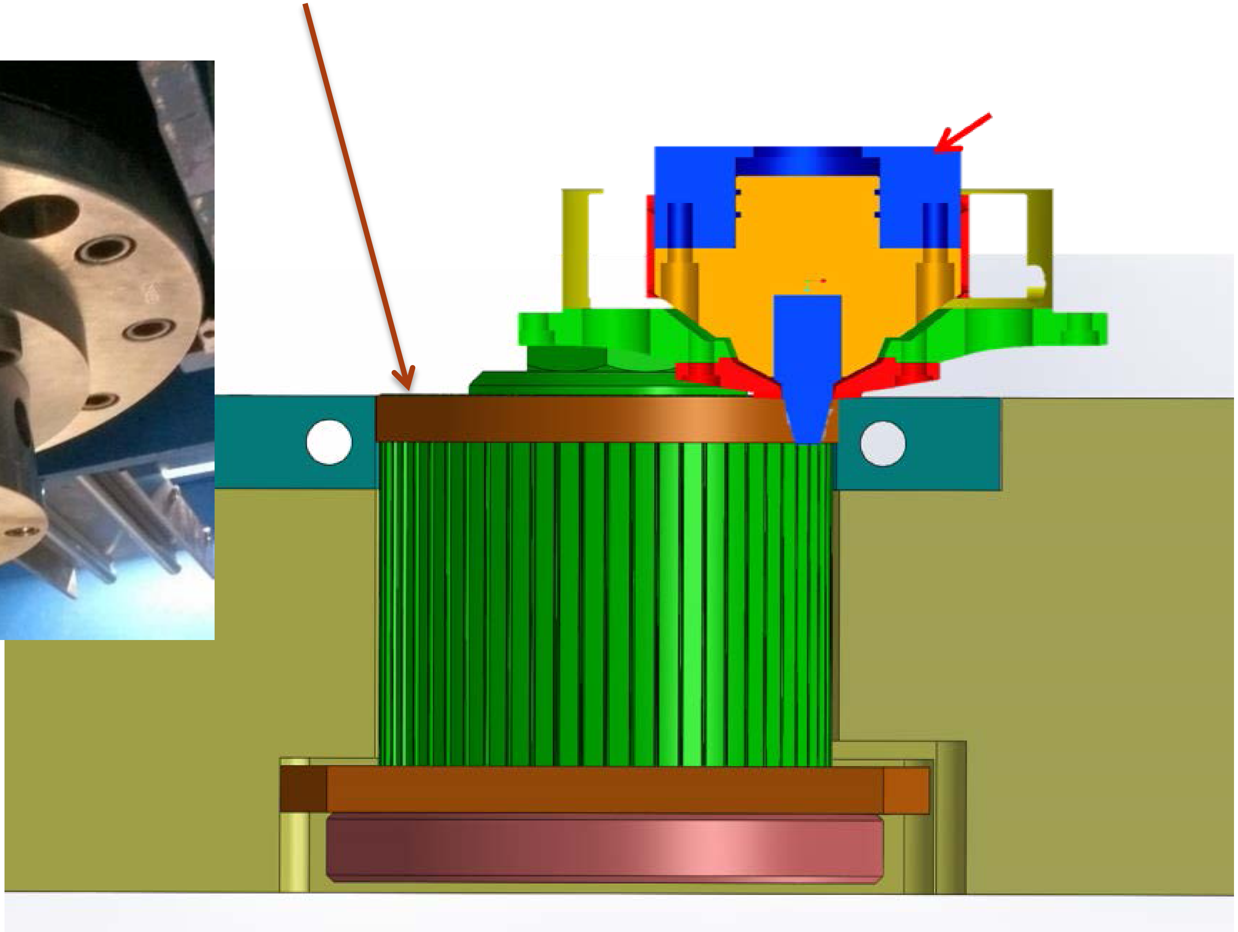
Not successful !

- Not out of ideas yet
- Will cut “v” groove in top of copper shorting bar so FSW tool stirs only aluminum.
- Potential for diffusion/forge bond between the Cu and adjacent Al



Remaining Challenges and Barriers
Stationary Shoulder Tool

- Stationary Shoulder tool has been designed and constructed but problems have been encountered in the fixturing of the end cap for welding. Experimental trials of different fixturing options are being investigated.



Proposed Future Work in 2015

- Complete construction of a fixturing system to use with the 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.
- Complete the dissimilar weld between an aluminum end cap and “v-groove” copper shorting bar. If it does not work with a reasonable series of iterations, abandon this concept.
- 2015 Milestone 4th quarter 2015 – Deliver 4 fully welded rotors to GM for mechanical and electrical efficiency testing. Rotors will be fabricated with a conventional shoulder tool and utilize either a ramp or plug weld to heal the exit hole.

- 2015 Milestone 4th Quarter 2015 – Transfer to GM all process conditions and weld process control methodologies to make the rotors in GM manufacturing facilities.

Summary

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The overall goal of the project is to enable more widespread use of large, highly efficient, copper-based induction motors for EV traction drives

- This project develops a new solid-state joining technology that has the potential to fabricate copper-based induction rotors with:
  - Higher efficiencies and power densities than aluminum-based induction motors
  - A lower manufacturing cost than current copper-based motor manufacturing methods (copper end cap casting or brazing)
  - Better strength, durability and cooling potential than aluminum based electric machines

- The project also addresses practical manufacturing concerns including: process parameter robustness, fixturing and copper wastage so that the technology can be transferred to industrial partners with a minimum of additional process optimization. (Help with the TRL 4 to 6 gap)

Key 2014/2015 Technical Results

Technical Challenge	2014/2015 Accomplishment	Result / Impact
Circular welds overheat when tool re-enters previous weld zone, defects created	Implemented adaptive control of the weld power and tool temperature	Increased process robustness to changing boundary conditions. Enables TRL 4 to 6 transition
Part distortion occurs with high temperatures	Further developed actively cooled fixtures	Drastically reduced part distortion.
Maximizing the "buy to drive" ratio	Design fixturing and tooling to minimize copper waste	The less copper that needs to be removed during final machining, the lower the cost. Maps to DOE goal of lower $/kw
Exit hole mitigation	Developed plug welding as a strategy to fill hole left by tool after welding	Saves copper over "exit ramp" strategy. Lower cost and enables TRL 4 to 6 transition

Future Work 2015/2016

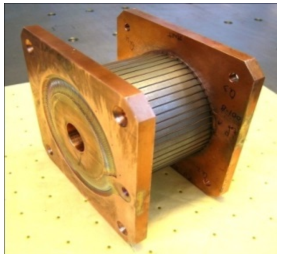
Upcoming Challenges/Milestones/Deliverables
Delivery of 4 full size rotors to GM for testing
Develop and demonstrate a stationary shouldered tool assembly for further minimizing material wastage and part deformation
Transfer technology to GM

Technical Backup Slides

Approach and Strategy for Deployment

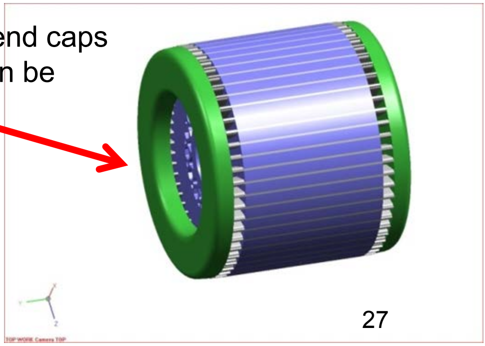
Task Breakdown

- **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
- **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.

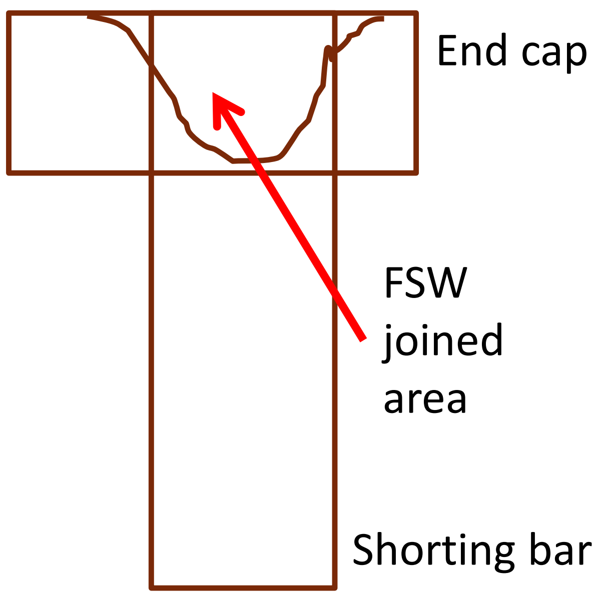
Significant weight savings could occur if end caps could be aluminum as long as tradeoff can be made with the lower conductivity

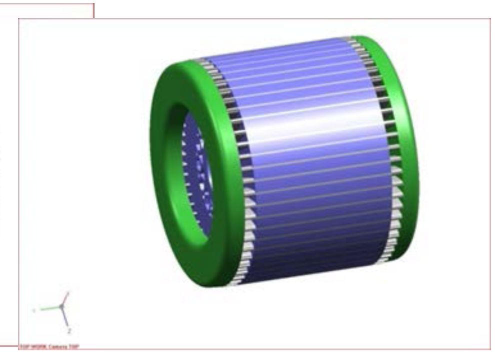


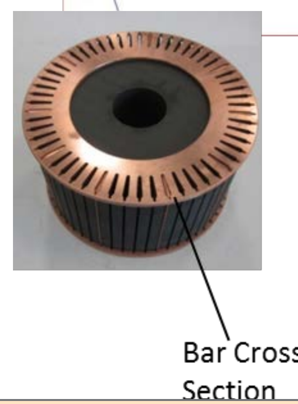
Final stage of both Tasks is to deliver full sized rotors to GM for electrical efficiency testing and transfer process technology to industry

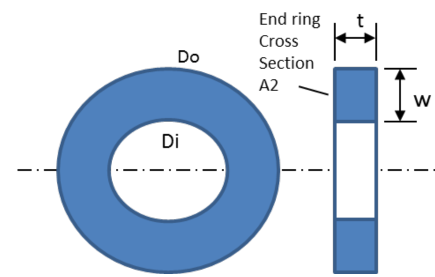
Technical Accomplishments and Progress

- 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

Technical Accomplishments and Progress

Dealing with the Exit Hole – Ramp out of Plane (2014 results)

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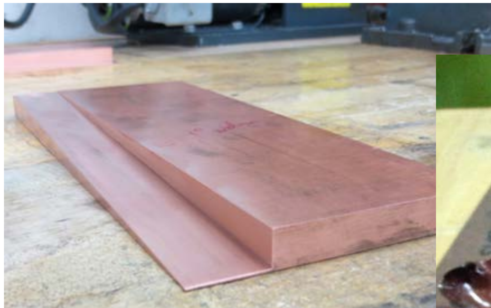
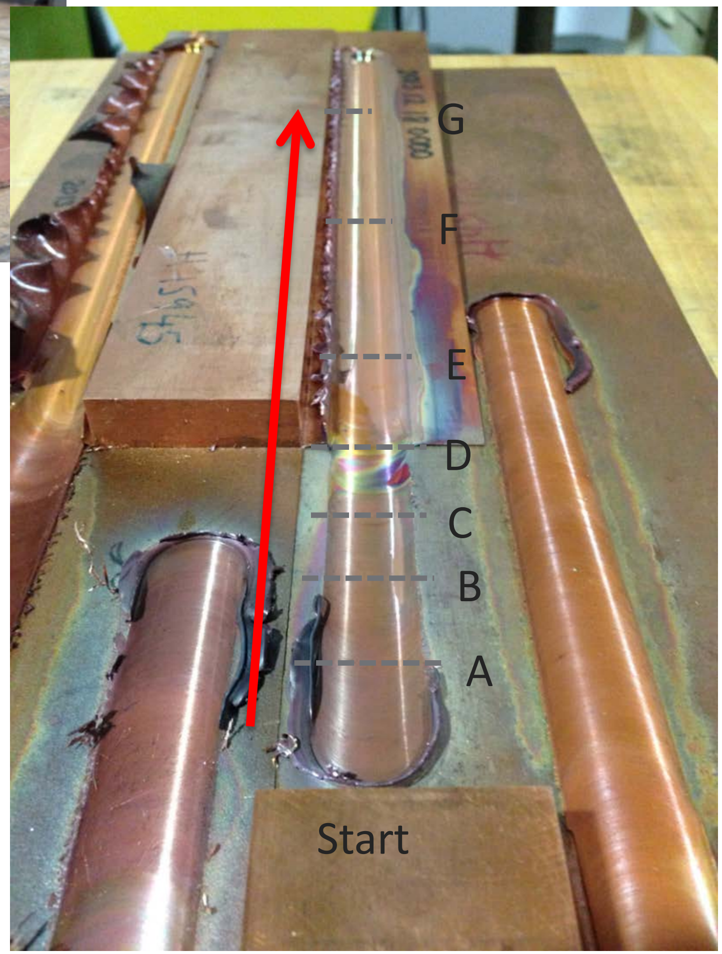
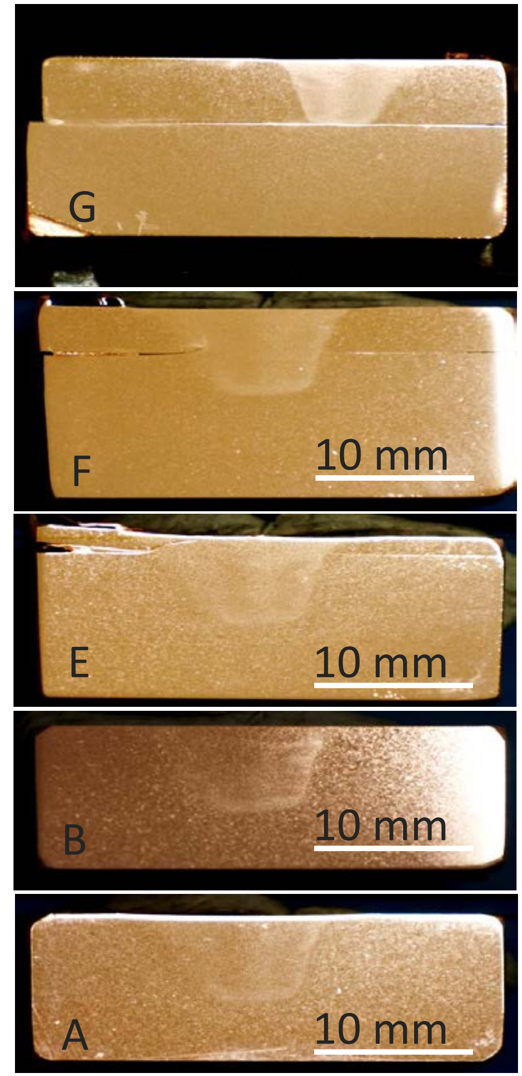




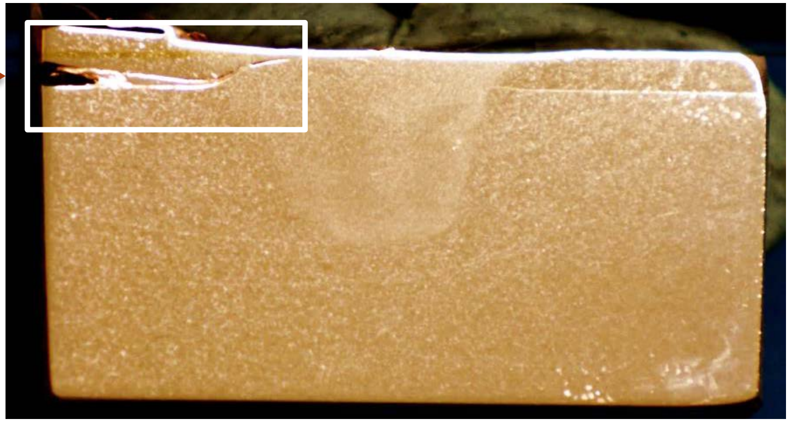
- Weld started in base plate and rode up the ramp
- Horizontal surface between base and wedge on cross sections E and F don't dive inside the material.
- No volumetric defects – This is a successful, but expensive method of preventing an exit hole

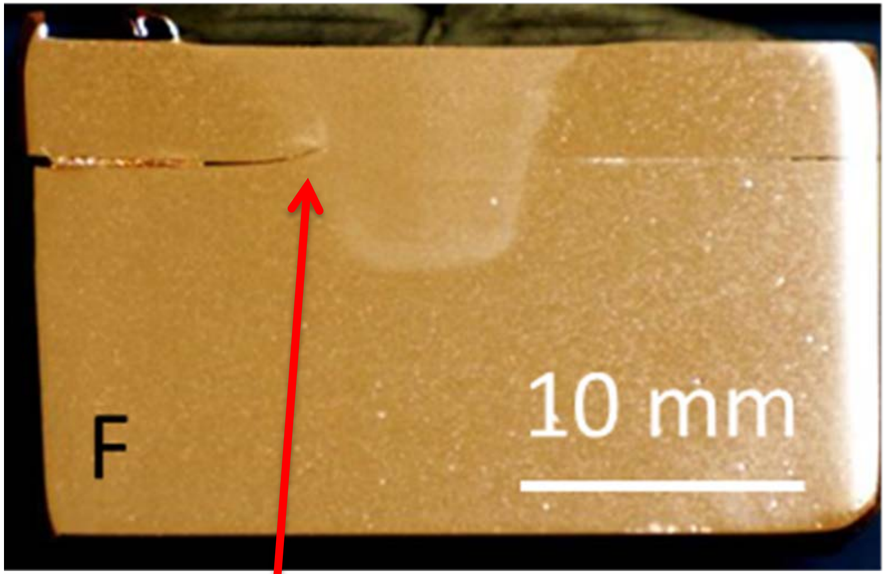


Technical Accomplishments and Progress

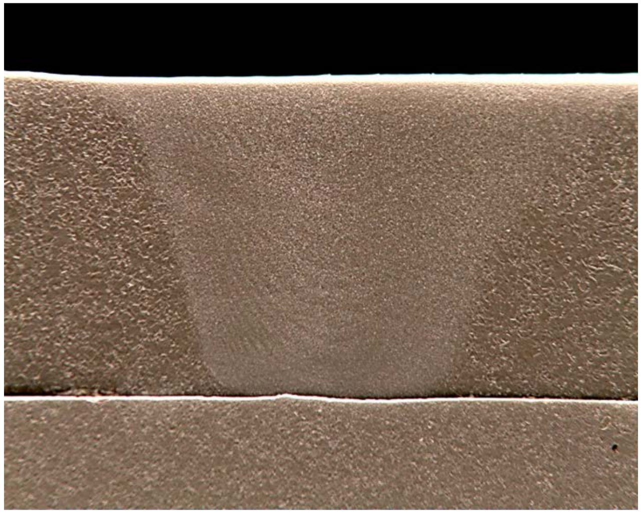
Dealing with the Exit Hole – Ramp out of Plane

- 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

END