Project ID: PM004_grant_2016

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

(Agreement ID 23726)

GLENN J GRANT

DAVID CATALINI

KEN ROSS

PACIFIC NORTHWEST NATIONAL LABORATORY

BLAIR CARLSON, JOHN AGAPIOU, ROBERT SZYMANSKI

GENERAL MOTORS RESEARCH AND DEVELOPMENT

2016 DOE VEHICLE TECHNOLOGIES PROGRAM

ANNUAL MERIT REVIEW AND PEER EVALUATION MEETING

JUNE 9, 2016

WASHINGTON, DC

Overview

Timeline

- Start: FY2011
- Project end date: Sept 2016
- Percent complete: 90%

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
- DOE Funding for FY16: $0

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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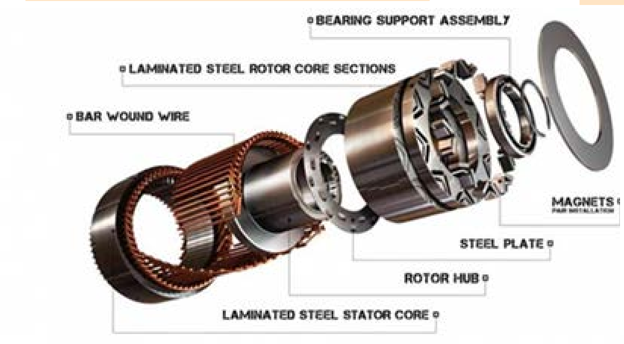
Two primary motor classes used in EVs – Permanent Magnet Motors and Induction Motors

Permanent Magnet Motors



Induction Motors

- The changing demands of the different modes in the drive cycle can lead, in some cases, to a multiple motor solution in the same vehicle (IC, PM, and Induction motors)
- Advantages of Induction Motors:
  - Induction motors can provide high energy conversion rate, useful for power augmentation during acceleration, stop-start function, and as a supplementary source of drive torque during high efficiency (cylinder shut down) cycles
  - Much lower cost than permanent magnet motors
  - 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

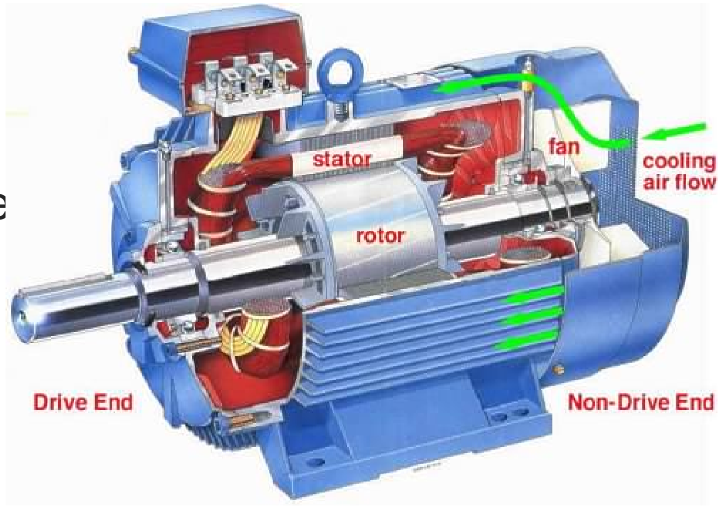
Advanced Power Electronics and Electrical Motors R&D Area

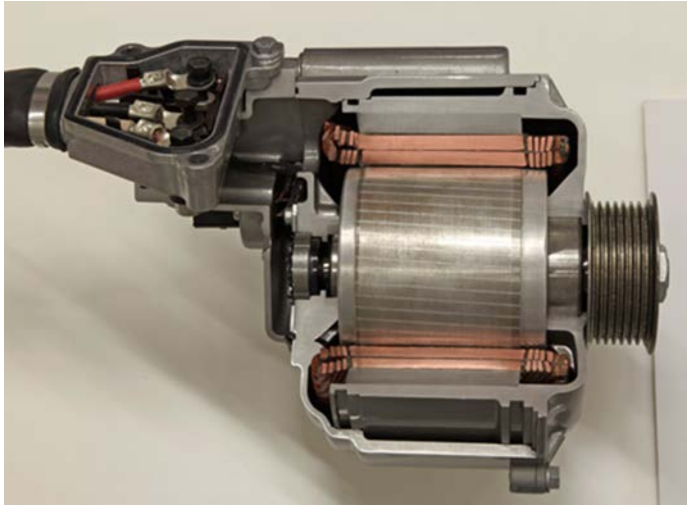
Research Focus Areas *(Reduce cost and maintain performance)*	
Permanent Magnet (PM) Motors	❑ Reduce cost by 75% - required to meet 2020 target ❑ Motor design optimization may reduce cost by 25% to 40%.
Magnet Materials	❑ Magnet material costs are 50% of 2015 target and 75% of 2020 target ❑ Reducing 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

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

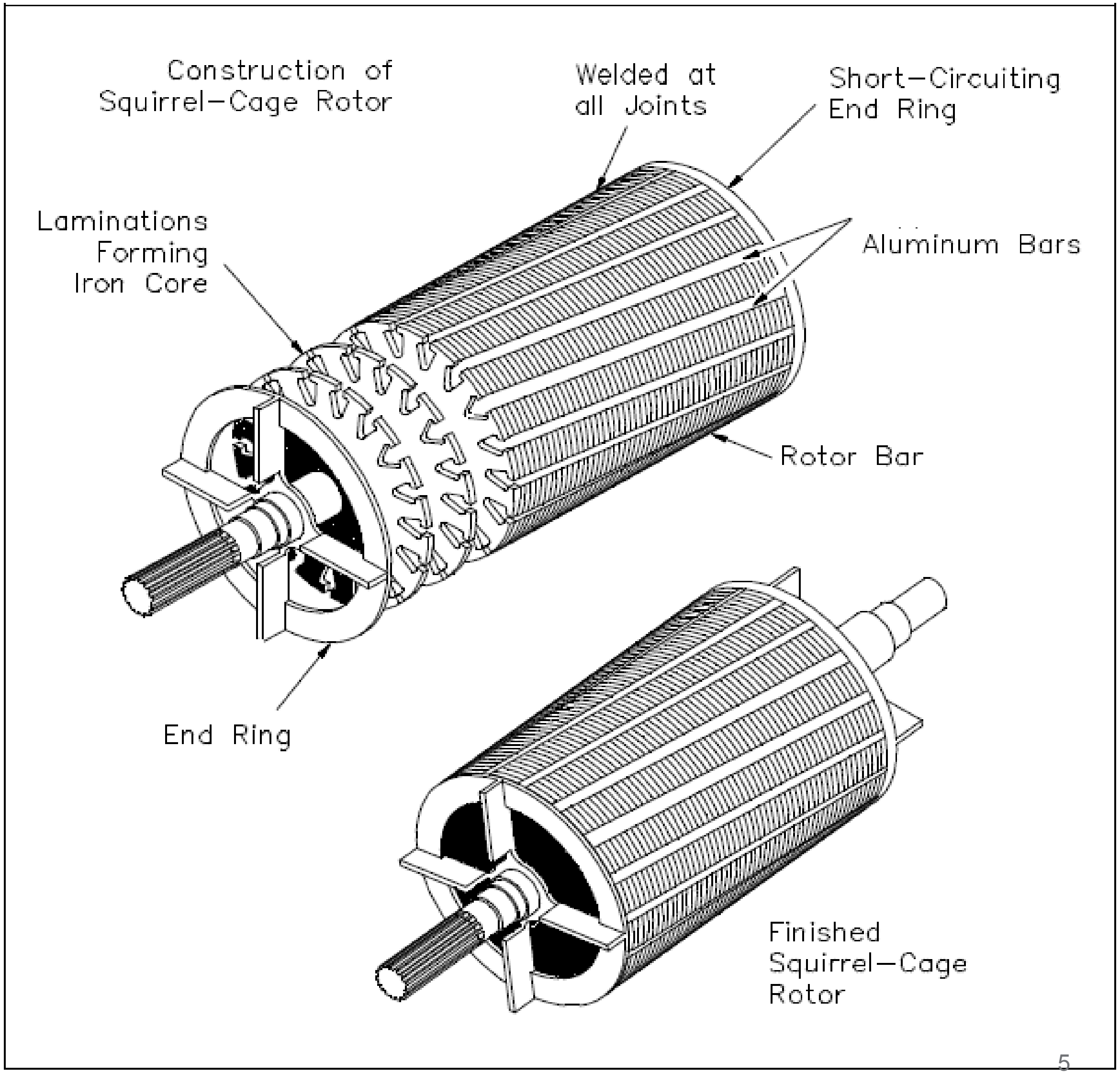


Figure 5 Squirrel-Cage Induction Rotor

Relevance
Manufacturing Challenges for Copper Rotors

- 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. Copper dies give 1/10th the life of dies for aluminum (you need expensive dies for copper!)
    - 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

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 for testing in current GM electric motor platforms.

Objectives (March 2015 through March 2016)

- 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.
- Refine the FSW tool and weld process to optimize electrical continuity – iterate with GM testing
- 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) 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 2016**

- 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. → **Completed**

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

The final efforts are divided into two primary task areas:

- Task 1 Further develop and refine the solid state joining process to join copper end caps to copper shorting bars with high electrical continuity and zero weld defect. Iterate with GM motor testing to refine manufacturing process. Deliver the rotors to GM.
  - 2015 Milestone/Deliverable: 4 full sized copper rotor assemblies for testing at GM
  - 2016 Deliverable: Optimized rotors with current electric steel laminates and geometry
- Task 2 Complete construction of a stationary shouldered tool assembly, and demonstrate that defect free welds can be made.
  - 2016 Milestone/Deliverable: Rotors made with the stationary shoulder tool that have welds within 4 mm of the weld fixture wall, minimizing material wastage and part deformation

Technical Accomplishments and Progress
Primary challenges for FSW

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Focus of FY 13/14 work

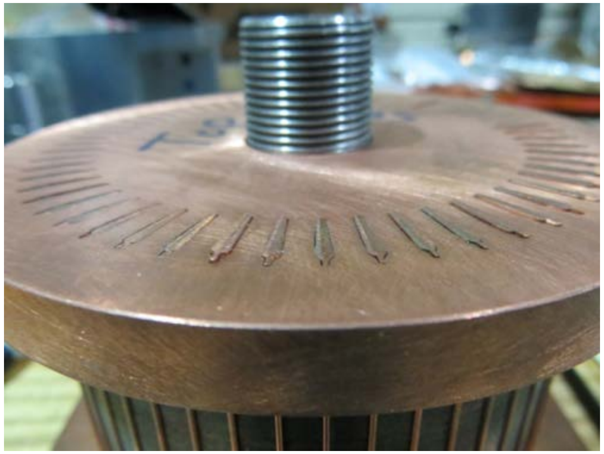
- 1) **Nugget Size – Electrical continuity**
  - The joint design for the highest electrical cross section dictates a specific tool design (and tool materials)
  - Specific tool designs can lead to narrow process parameter windows for defect free welds

- 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 15/16 work

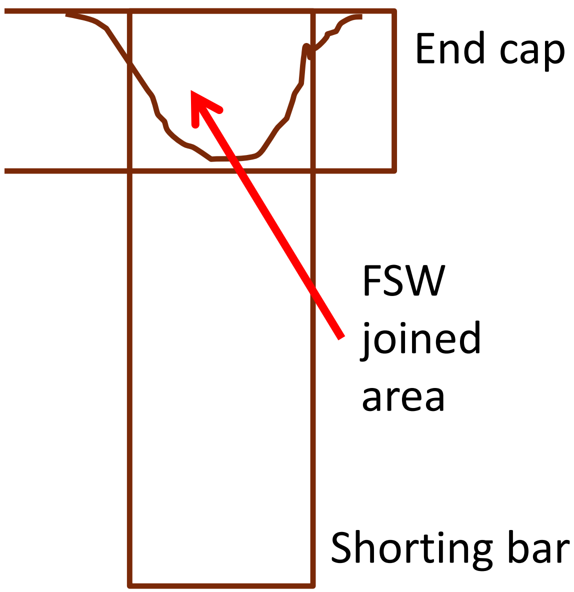
- 3) **Maximizing the "buy to drive" ratio – Copper is expensive**
  - Design fixturing to minimize copper use
  - Develop the runoff tab process

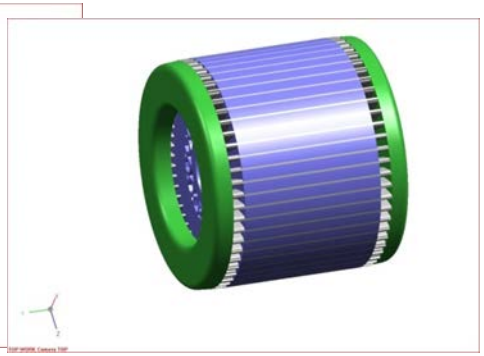
Rotor fabricated by Friction Stir Welding

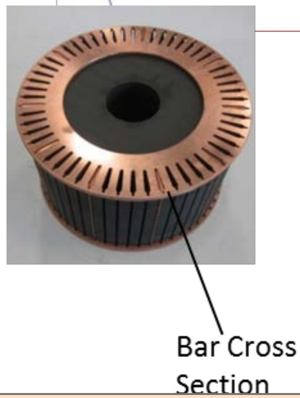


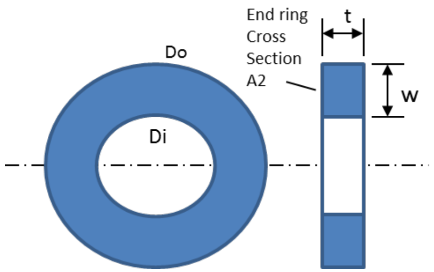
Technical Accomplishments and Progress
Further optimized the Electrical Cross Section

- 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

Further optimized the Electrical Cross Section -Tools Designed for the "right shaped" Nugget

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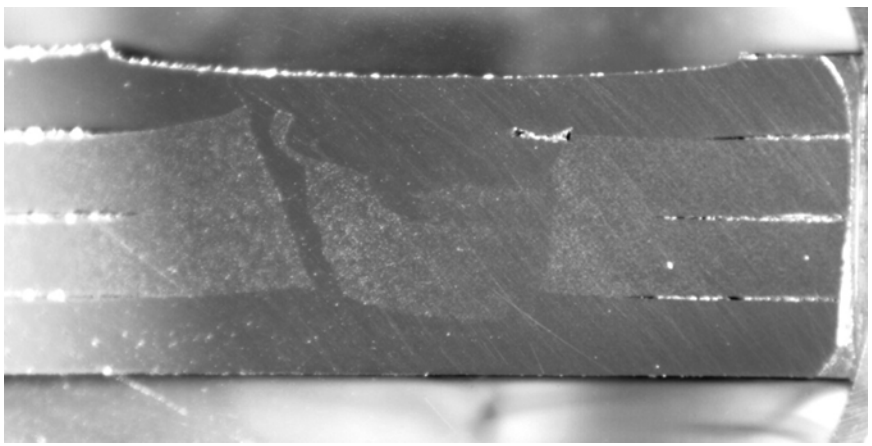
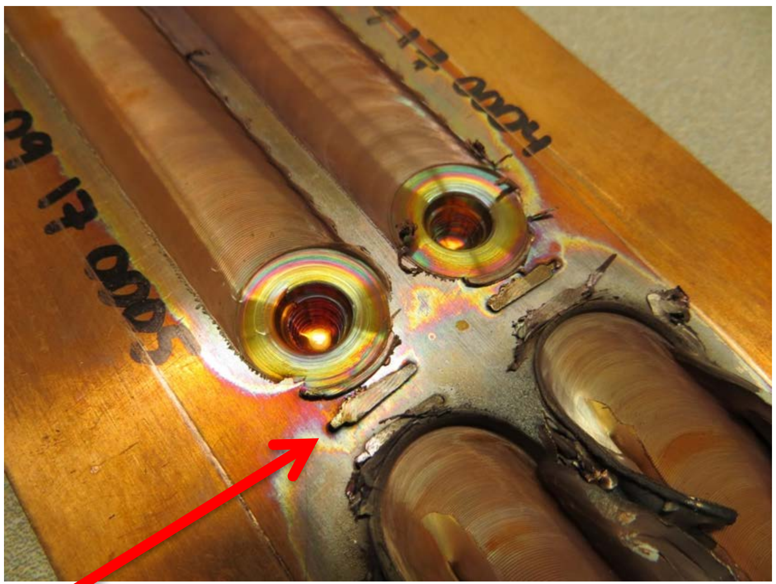
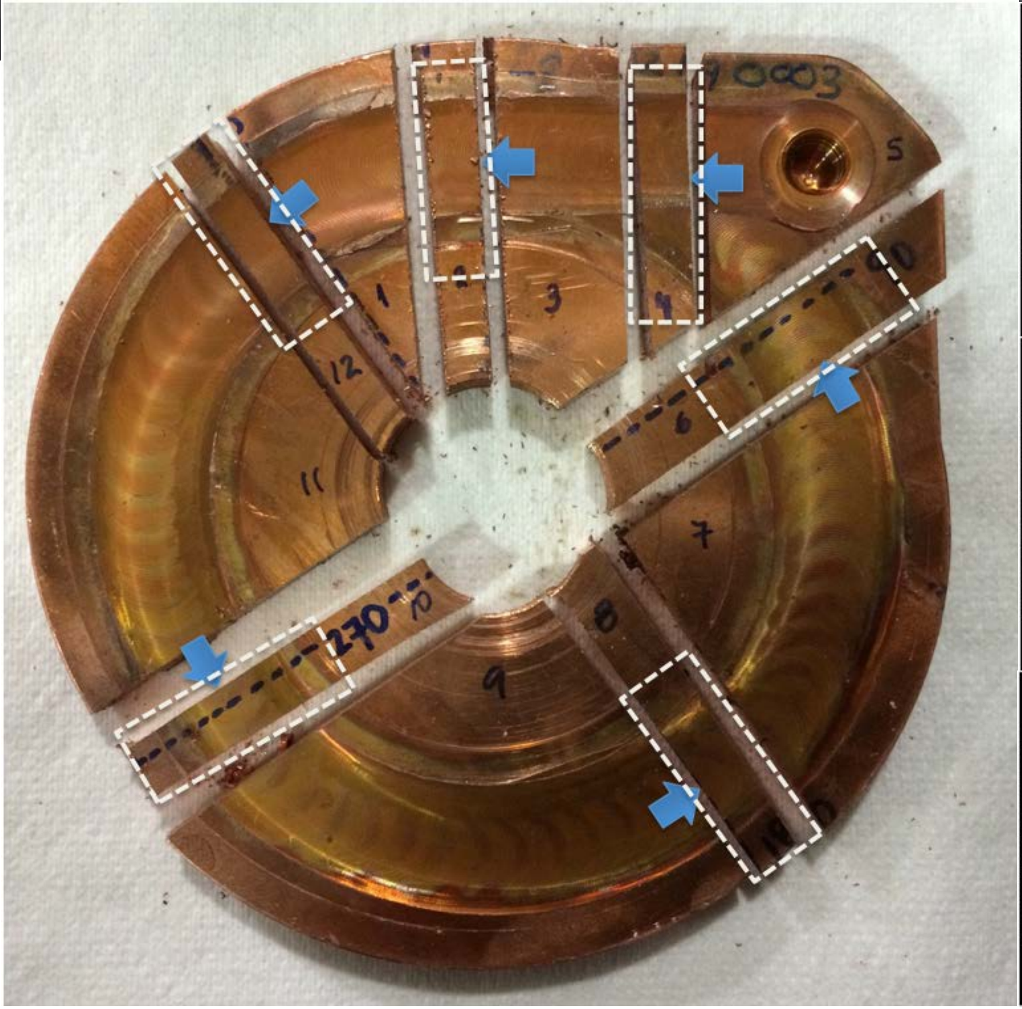
- The weld process and power requirements for specific tools and fixture conditions were defined.
- Defect free welds can be produced that show good metallurgical bonding across shorting bars and end cap laminate gaps

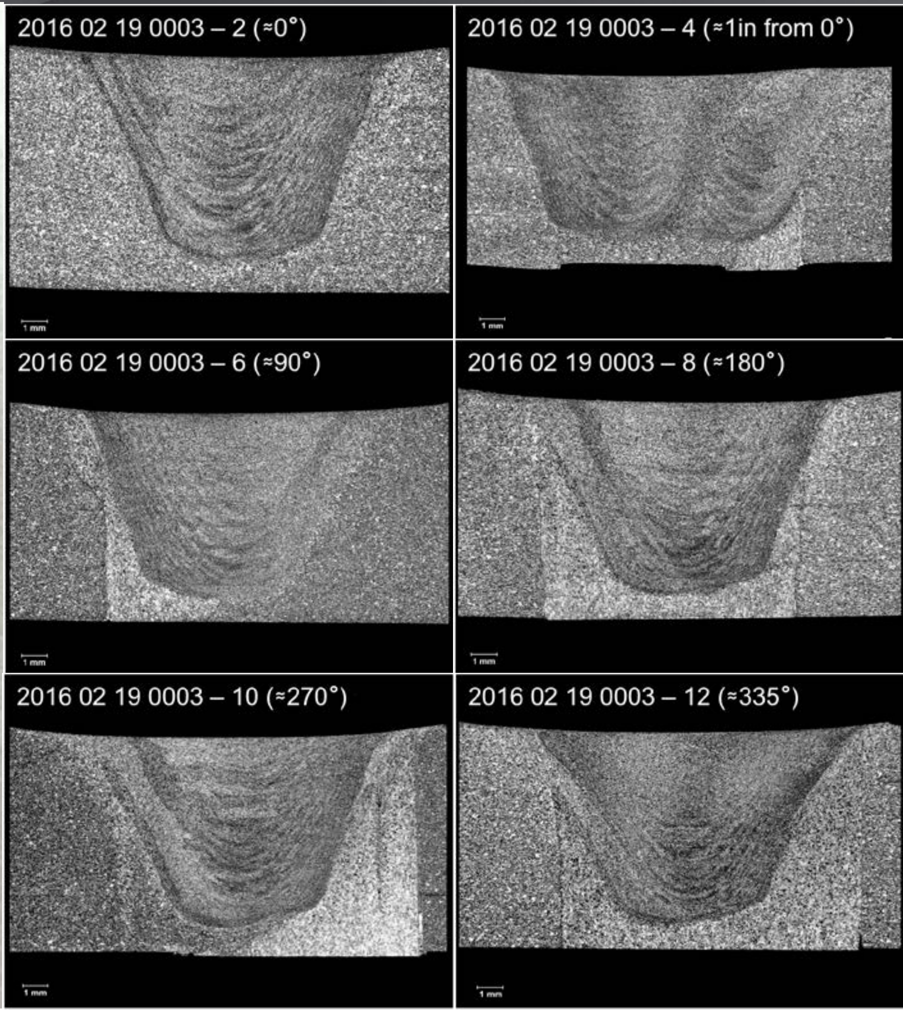




Lots of challenges to fill gaps around shorting bar tops

Tool design iteration led to good welds



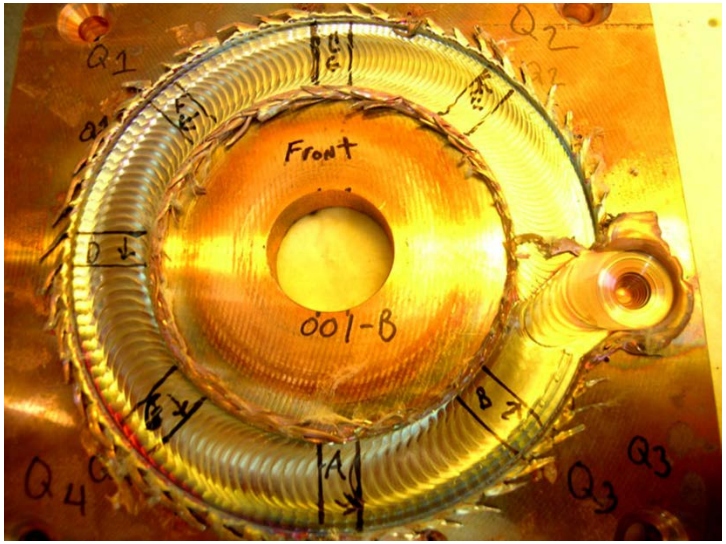


Cross sections of a final weld on a rotor.

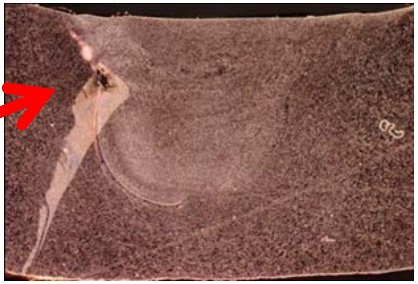
Tools with aggressive threads and counter-flow features worked the best

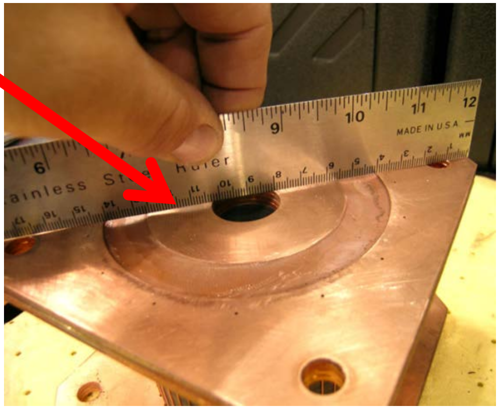
Technical Accomplishments and Progress
Control of distortion and heating during welding

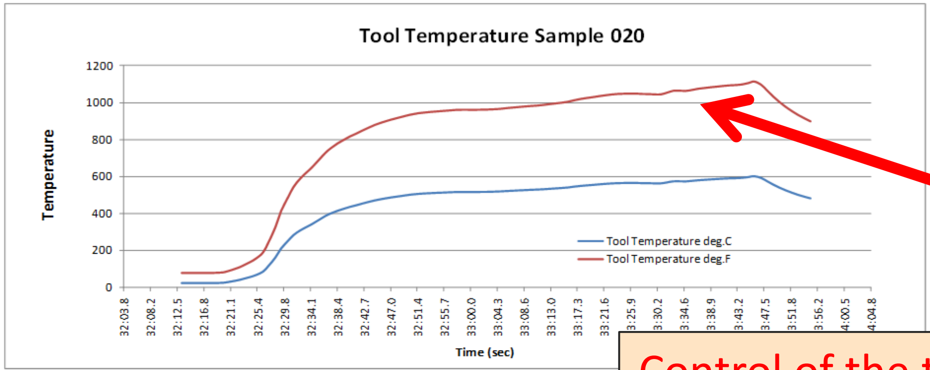
- Another challenge discovered in the rotor fabrication trials is excess heat build up during welding



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







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

Control of the temperature is required for defect free welds

Technical Accomplishments and Progress

Control of distortion and heating during welding - cooled fixtures

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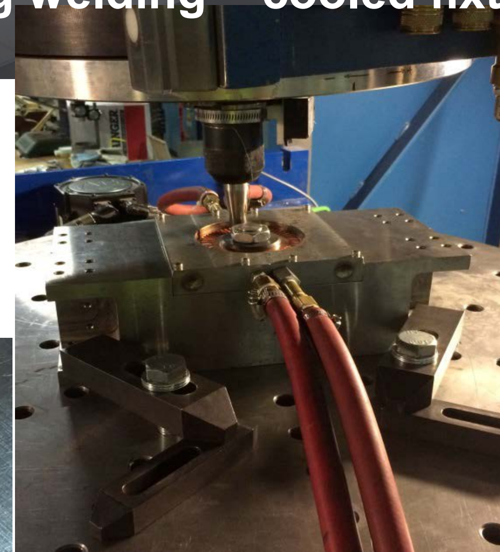
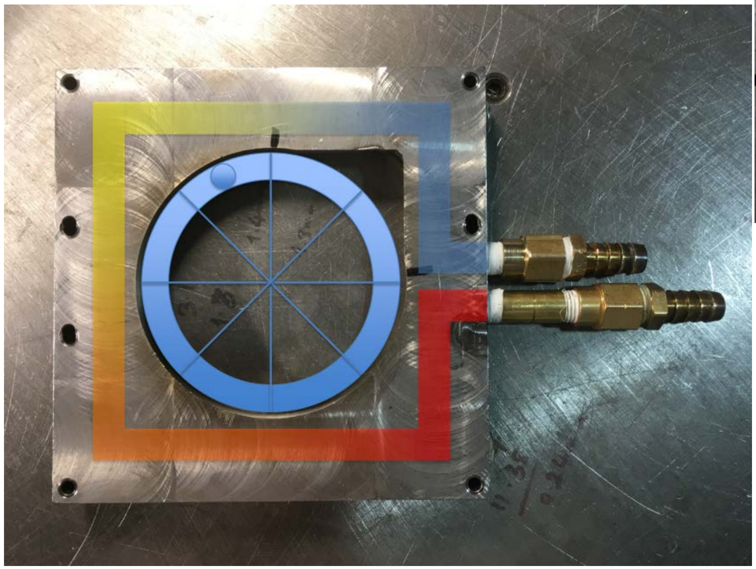
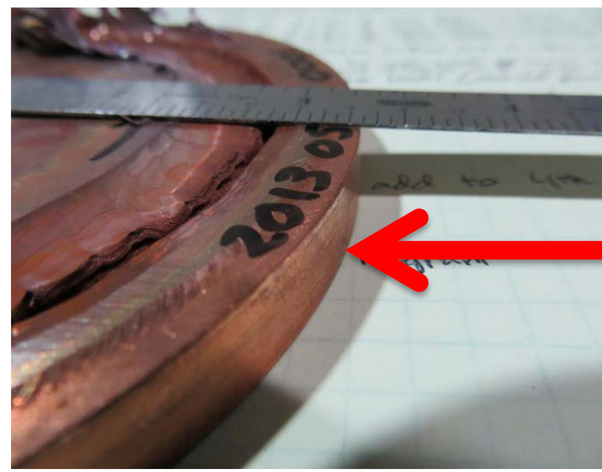
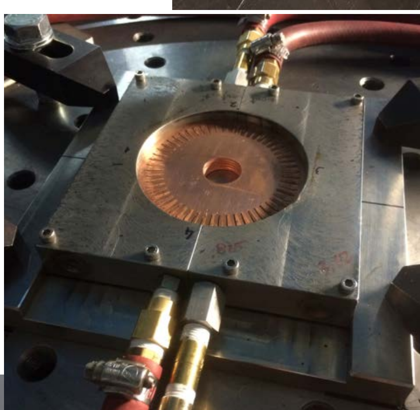
Actively cooled fixtures were designed and built to address control of the temperature boundary conditions, and control of distortion







Cooled fixtures allowed for good edge retention of end cap and eliminated 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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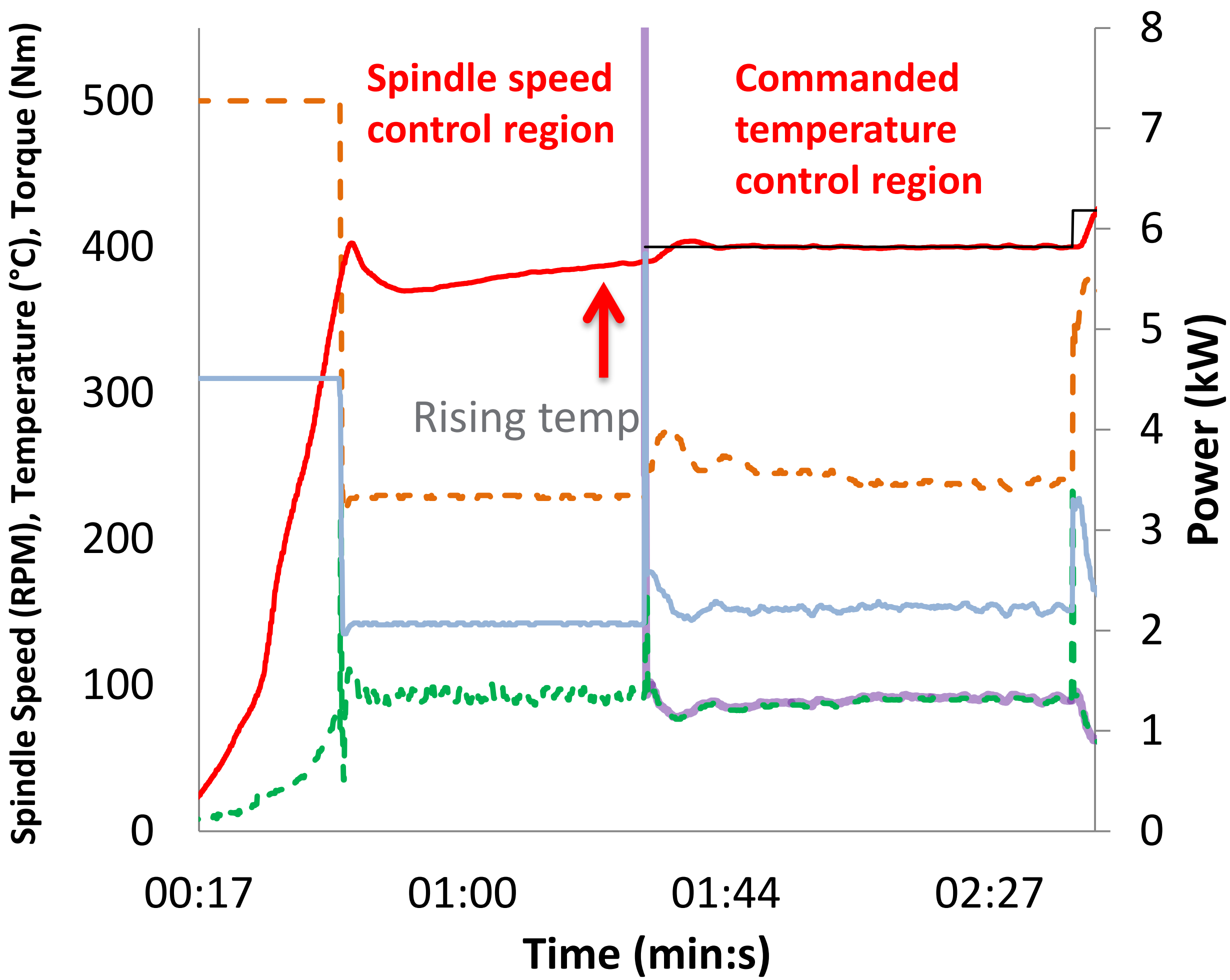
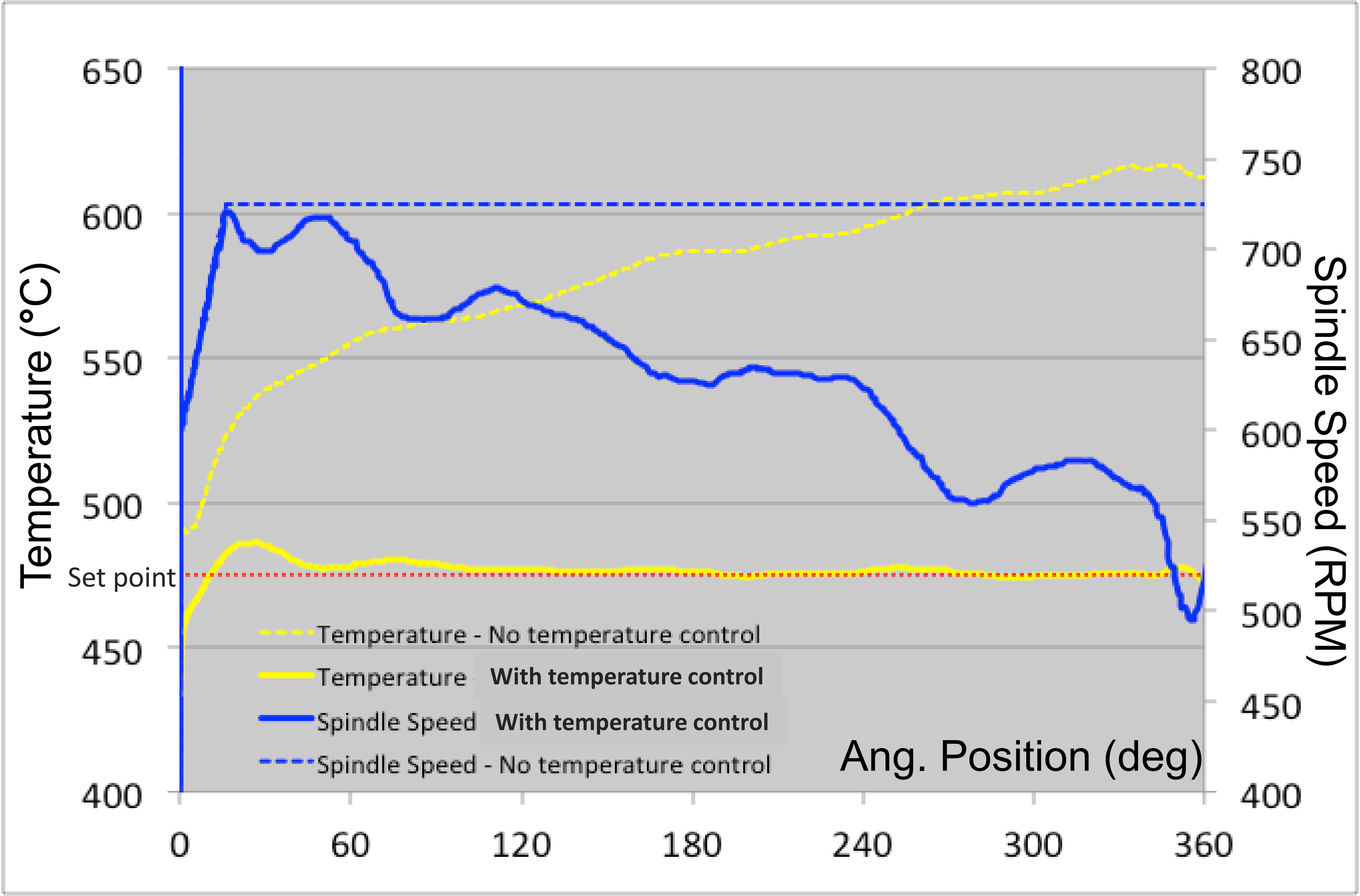


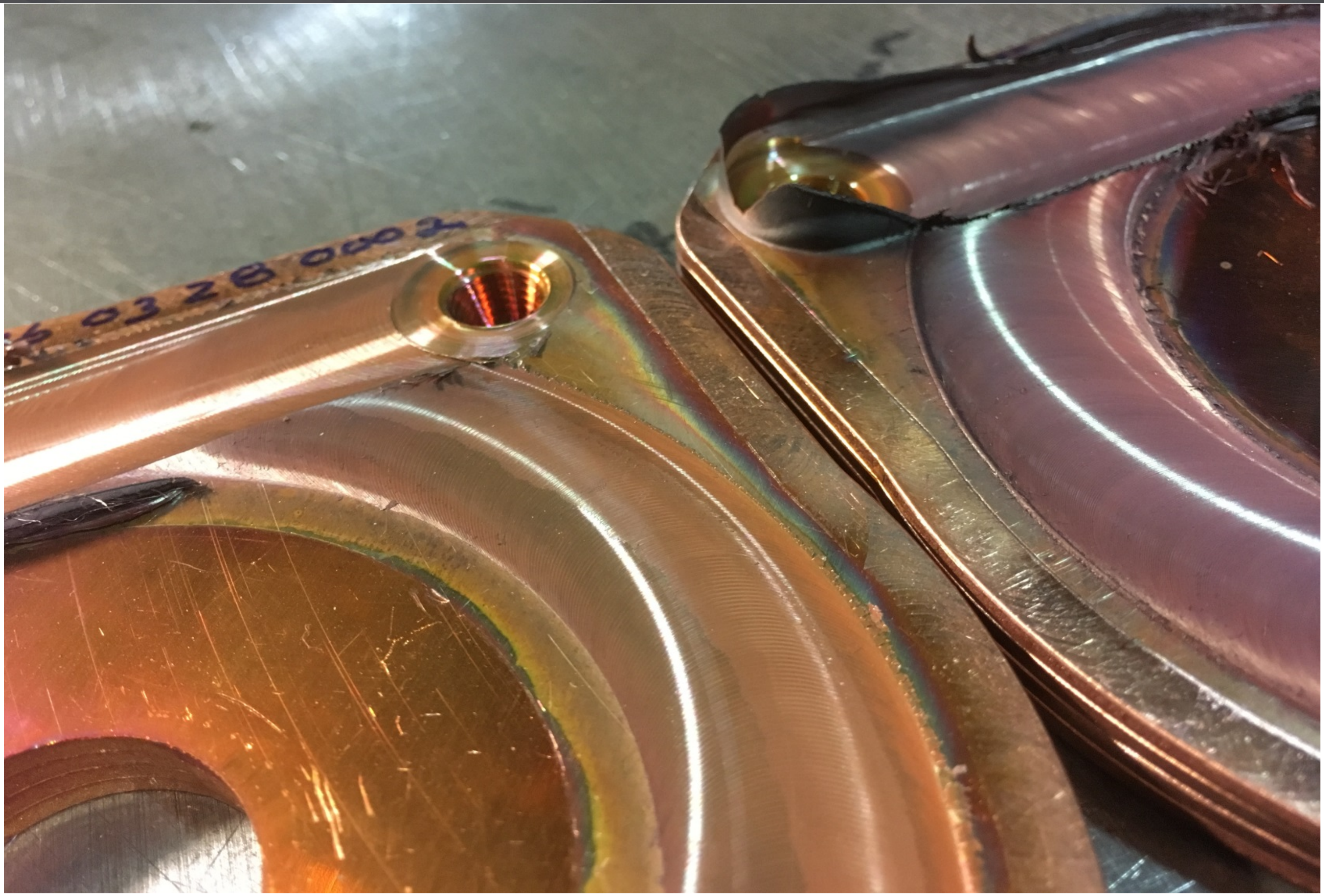
- **Spindle speed control region shows an increase in temperature**
- **This is the response to changing boundary conditions**
- **To avoid defects and distortion from changing conditions, temperature control is critical**

- **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**

Comparison of a rotor weld with and without active temperature control

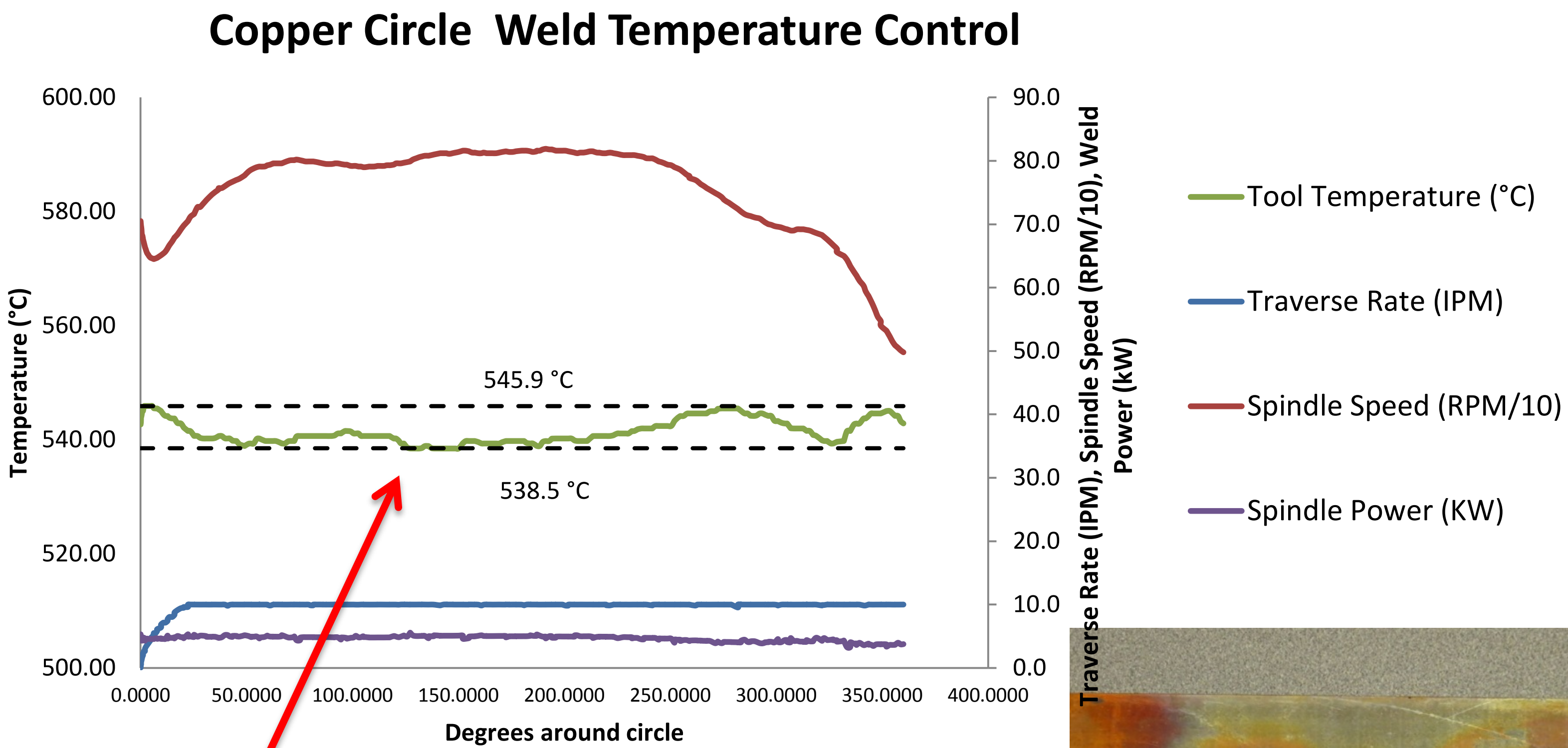


With and Without Temperature Control

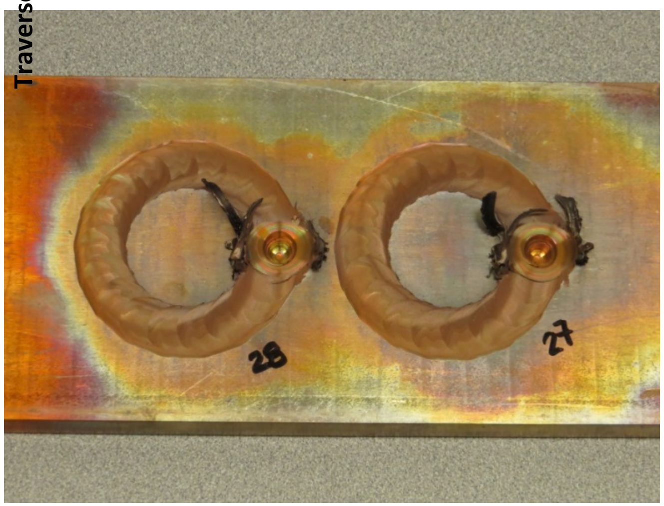


On the left, a weld done with temperature control, and on the right weld done at constant spindle speed. Notice the excessive flash at the end of the weld on the right.

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

Exit Holes minimizing the amount of copper removed in final machining

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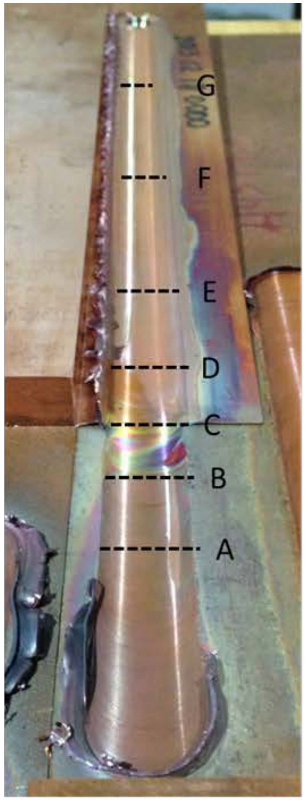

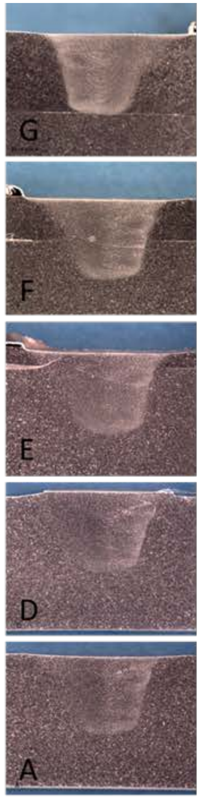

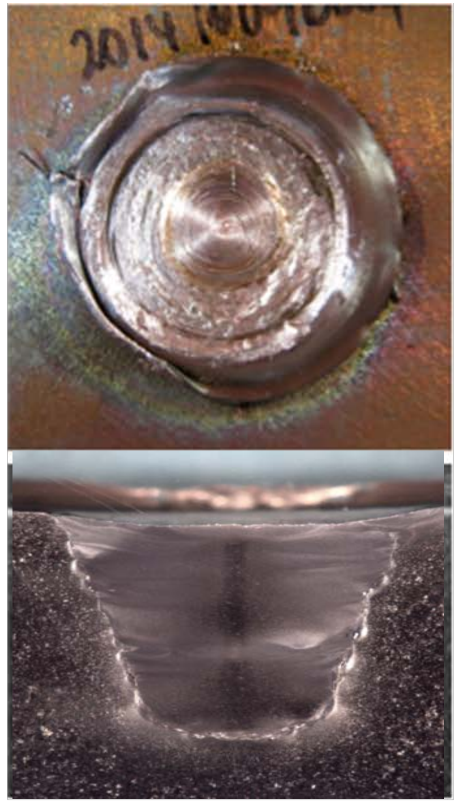

Three Strategies for dealing with the tool exit hole:

1. Exit ramps (out of plane)
2. Plug welds with taper plug
3. Run off tab

Technical Accomplishments and Progress

Exit Holes -minimizing the amount of copper removed in final machining

- **Issues:**
  - **Ramp – Complex solution, mechanical placement of ramp required during welding**
  - **Plug Weld – additive process, but requires a shank that is waste. Microstructure of the plug boundary is difficult to control**

Best solution is run off tab

- High speed machining is very fast and simple compared to the above.
- A run-off tab represents the lowest scrap generating methodology for dealing with the exit hole

Technical Accomplishments and Progress
Rotor Testing at GM

The optimized rotors have now passed all electrical and performance tests at GM

- <u>Mechanical strength</u> – Destructive testing at 10,000 RPM
- <u>Balance</u> – Can the rotor be machined into final configuration and display appropriate balance characteristics
- <u>Resistance test</u> - The resistance for the rotor across end cap and 180 apart is good. Same as cast copper rotor
- <u>Electrical continuity and homogeneity of welds</u> - Induction test identifies quality of bar to end cap weld. All welds are the same and similar to the cast rotor performance.

Responses to Previous Year Reviewers' Comments

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- "In spite of the barriers and delays, the reviewer observed that progress appeared to have been made in controlling temperature and distortion and exit process. After almost four years, however, the reviewer believed it would have been better to see joining of an actual copper end cap, rather than the mockups…. Nor did the reviewer feel it had been made clear <u>why there was no iterative plan for General Motors (GM) to test the four fully welded rotors and then come back to Pacific Northwest National Laboratory</u> (PNNL) to further mitigate any potential deficiencies."
  - RESPONSE: We didn't outline this well in the 2015 presentation but yes, 2016 has been heavily focused on process optimization using the output of testing and characterization done at GM. We work very closely with GMRD. Every couple of weeks we receive materials (end caps, electric steel laminates, shorting bars, etc) and ship back finished rotors for evaluation. The results of these evaluations direct us to make changes in the process. During 2016 we significantly changed and refined to tool designs to eliminate defects based on iterative characterization with GM
- "…Terming the project high-value, the reviewer described it as primarily a manufacturing / tooling / fixturing effort, with little discussion of materials composition, structure or properties."
  - RESPONSE: Yes. 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.

Collaboration and Coordination with Other Institutions

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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

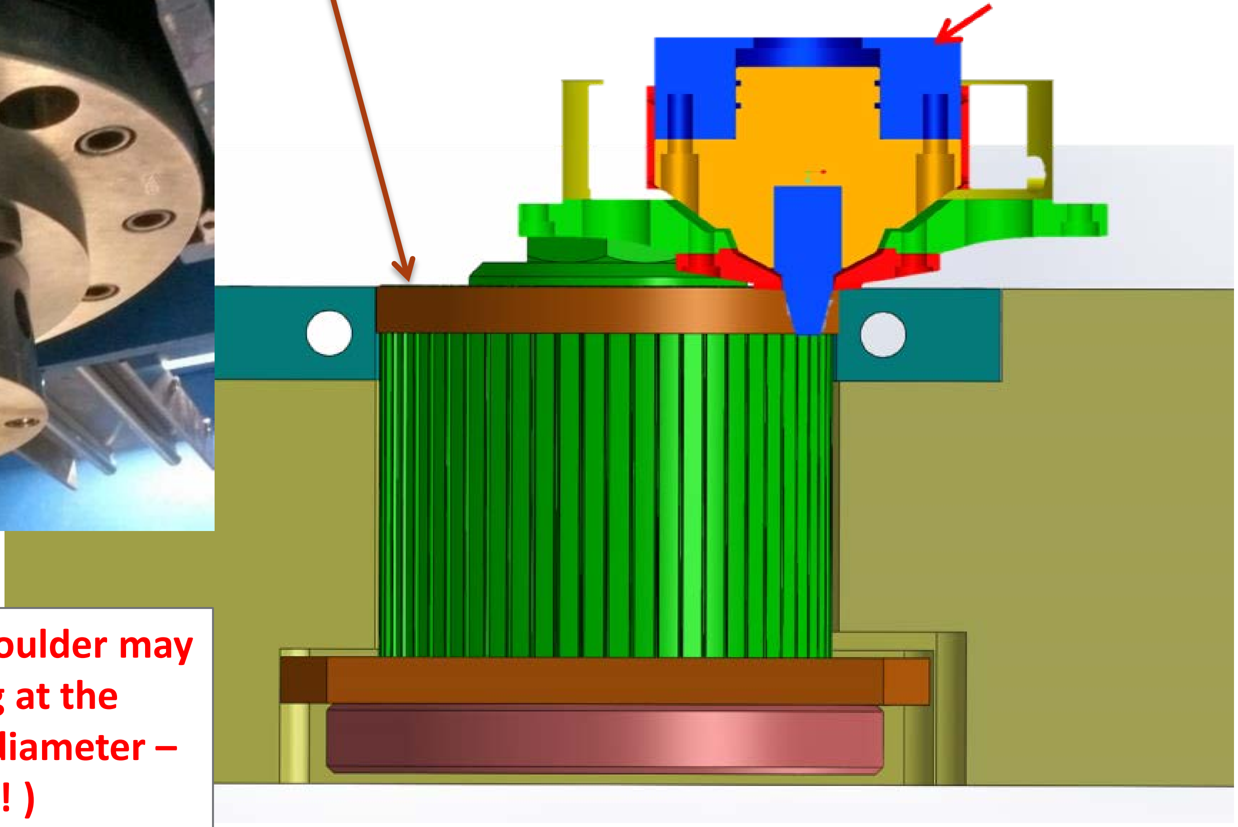
- Biweekly conference calls where laboratory work scope and tasks are discussed
- GM provides materials including all machined copper plates, rotor subassemblies, plug welding blanks, laminated steel rotor cores, pre-production fixturing.
- PNNL executes FSW process development, tool design and optimization 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
Stationary Shoulder Tool

- Stationary Shoulder tool has been designed and constructed. Experimental trials of different fixturing options are being investigated.

Stationary shoulder rides on the end cap / fixture interface with the pin in close proximity to the fixture vertical wall



Stationary shoulder may allow welding at the shorting bar diameter – no machining!)

Proposed Future Work in 2016

- 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.

- 2016 Milestone 1st quarter 2016 – Deliver 4 “optimized” , fully defect free and weld temperature controlled rotors to GM for electrical performance testing. Rotors use runoff tab concept.

- 2016 Milestone 4th Quarter 2016 – 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 Electric Vehicles

- 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 2015/2016 Technical Results

Technical Challenge	2014/2015 Accomplishment	Result / Impact
Circular welds overheat when tool re-enters previous weld zone, defects created	Further refine adaptive control of the weld power and tool temperature	Increased process robustness to changing boundary conditions. Enables TRL 4 to 6 transition
Welds completely free of volumetric defect	Optimized our tool design and process to produce 100% weld density	This maximizes the electrical cross section and leads to high efficiency. Maps to DOE goal of Increased Efficiency, increased power density above 5 kW/L
Exit hole mitigation	Developed runoff tab concept and necessary weld control as a strategy to move exit hole to machined off area	Saves copper over “exit ramp” and plug weld strategy. Lower cost and enables TRL 4 to 6 transition

Future Work 2015/2016

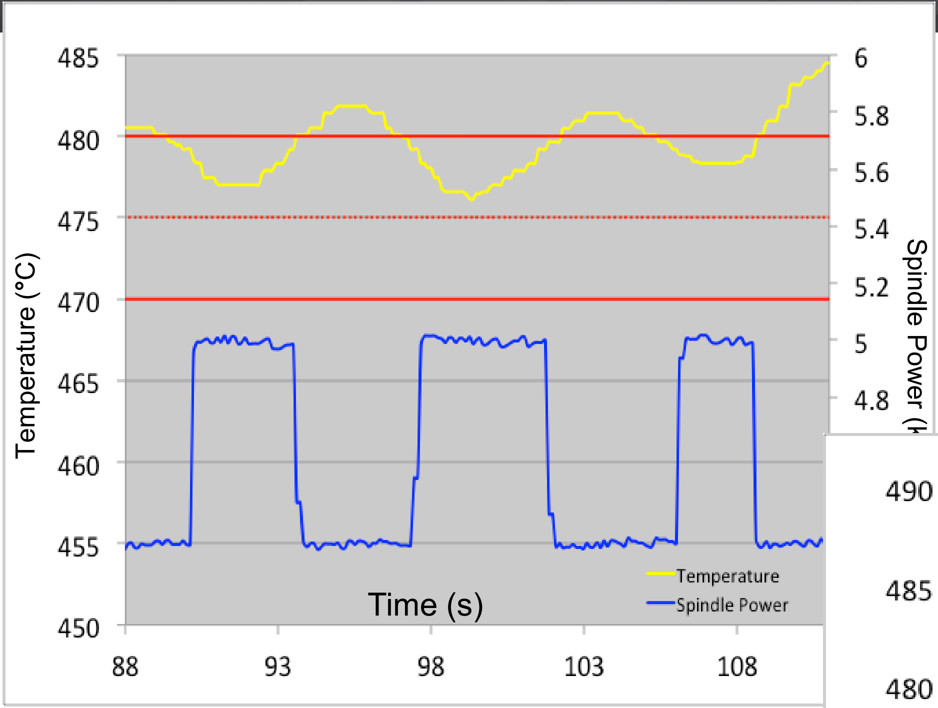
Upcoming Challenges/Milestones/Deliverables
Delivery of 4 full size “optimized” ,fully defect free and weld temperature controlled rotors to GM for testing
Develop and demonstrate a stationary shouldered tool assembly for further minimizing material wastage and part deformation
Transfer technology to GM

Technical Backup Slides

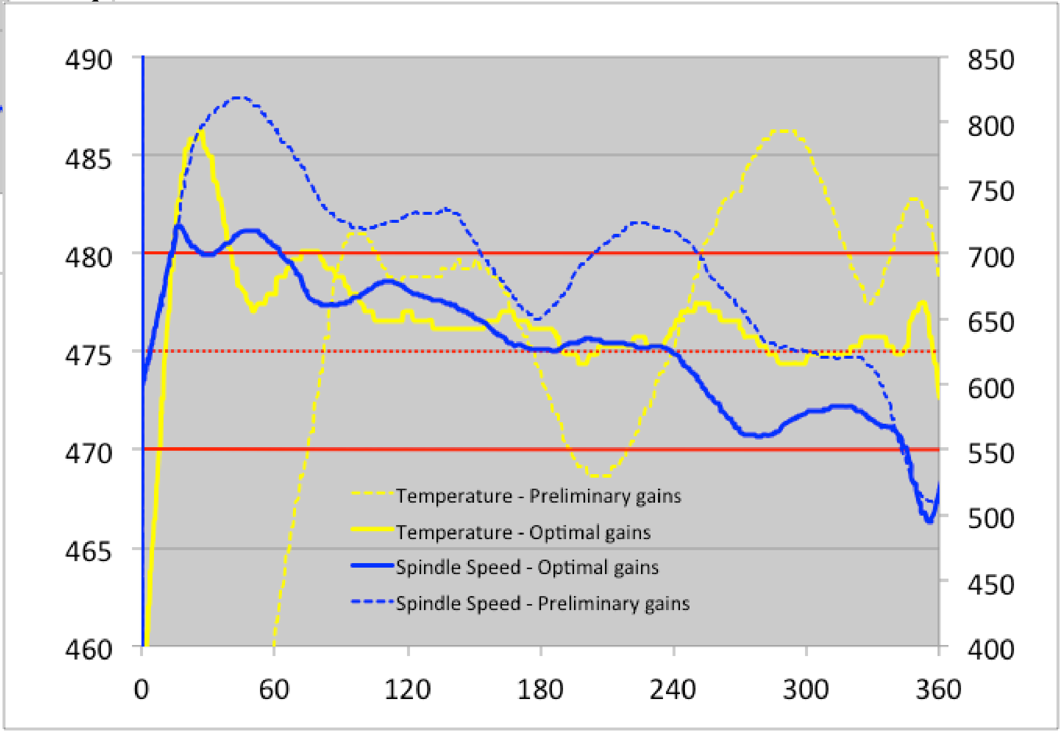
Beyond the control of boundary conditions: Active Temperature Control

- A key feature in the development of a viable weld process has been the implementation of a weld temperature control feedback systems that allows the weld to maintain a constant weld temperature through the start-up, around a circular weld path, then across a tie-in with previously welded material, and finally to a turn-out on a runoff tab.
- Because boundary conditions vary significantly along the weld path, any weld done with constant weld process parameters results in local volumetric defects in areas where those fixed parameters result in temperature and strain insufficient for good material flow.
- Process upsets are inevitable in any process, but due to the high thermal conductivity of copper and the relatively short circular weld path it is especially important to control weld power and temperature in this application.
- Without an adaptive control of weld torque/power to produce a constant weld temperature, the copper rotor weld would be difficult to complete without volumetric defects which would lead to poor thermal and electrical continuity, and poor motor efficiency.

Optimizing the controller

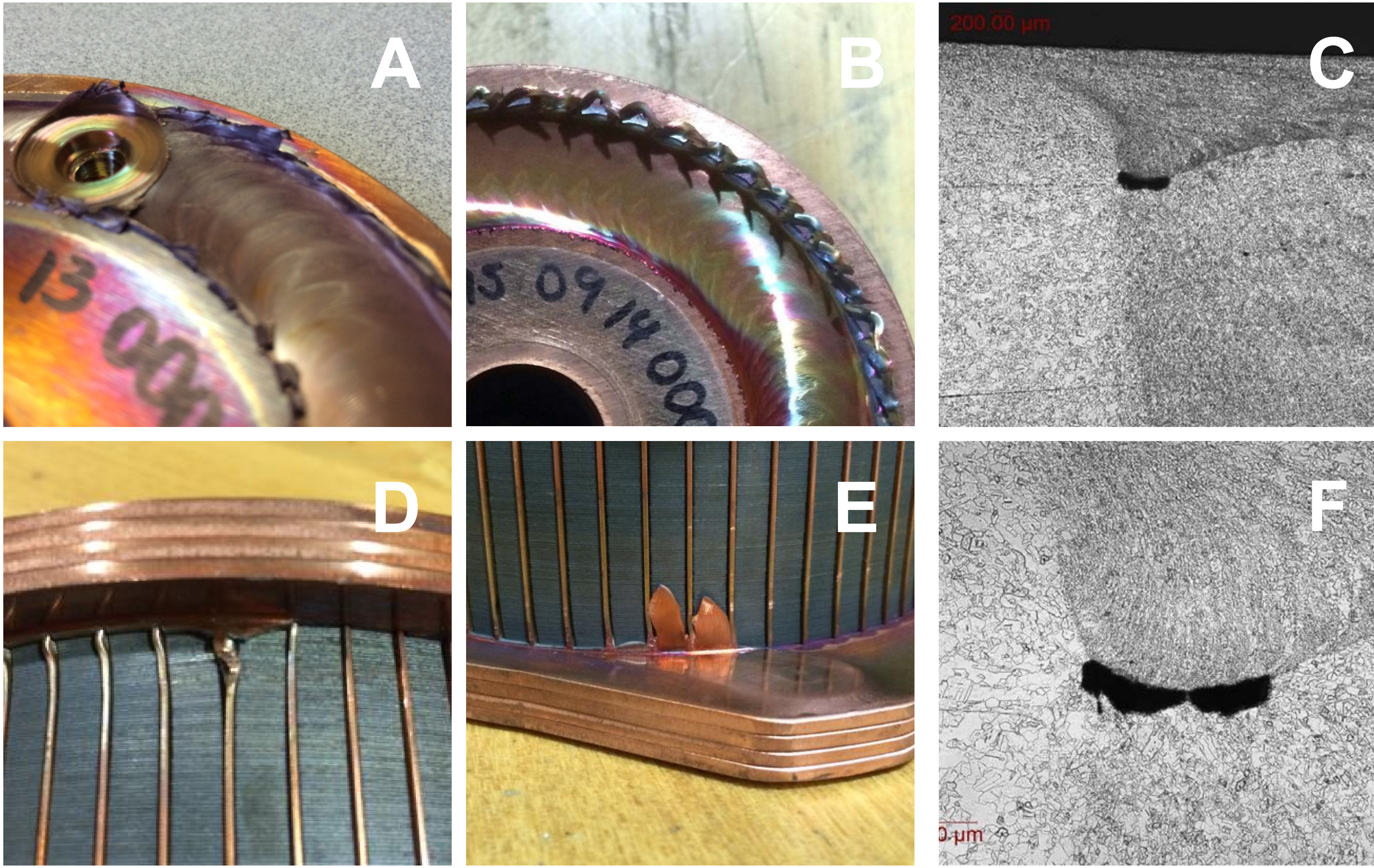


Algorithm Tuning



Optimized PID settings show better control of weld temperature to set point

Defect Styles



A, tool temperature too high during start; B, tool cuts the top of the shorting bars during traverse; C and F, material flow defect and on occasion it could breach the surface; D, excessive distortion during plunge; E, material extruded during tool traversing towards the side tab.

END