# Novel Manufacturing Technologies for High Power Induction and Permanent Magnet Electric Motors
(Agreement ID 23726)


Glenn J Grant

Pacific Northwest National Laboratory


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**Project ID: PM004_grant_2013**

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# Overview

## Timeline

- Start: FY2011
- Project end date: Sept 2014
- Percent complete: 40%

## Budget

- Total project funding
  - DOE - $1,225k
  - GM - $1,306k (in-kind)
  - Minimum 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

## 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 through better soft magnetic materials

## Partners

- CRADA with General Motors Research
- Project lead: PNNL

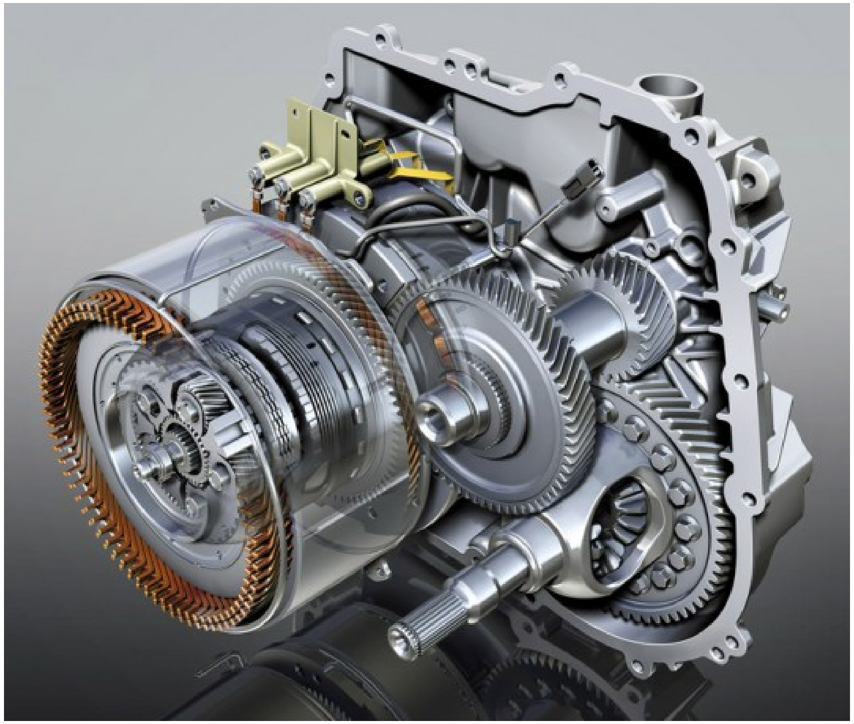
# Relevance

## Project Objective

- To develop and deploy high-power induction and permanent magnet 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 three 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.
- Task 3 Develop a unique solid state process to create appropriate microstructures and magnetic performance in bulk soft magnetic materials that may be able to improve the efficiency or reduce the cost of stack laminates in the rotor/stator assembly.

# Relevance

- This Project:
  - Will develop a lower cost manufacturing technique to fabricate rotors and stators
  - Will develop fabrication techniques that will allow multi-material designs for weight and cost savings
  - Will explore a new manufacturing process to fabricate soft magnetic materials for rotor and stator laminates.

Maps to:

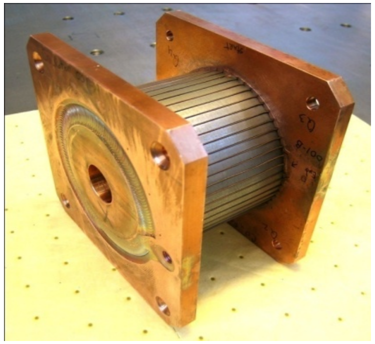
Advanced Power Electronics and Electrical Motors Area

| Research Focus Areas<br>*(Reduce cost and maintain performance)* | |
|---|---|
| **Permanent Magnet (PM) Motors** | ❑ Reduce cost by 75% - required to meet 2020 target<br>❑ 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<br>❑ 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:<br>❑ Could reduce motor cost by 30%<br>❑ Eliminating boost converter (required for IPM machines due to back emf) saves 20% in PE cost<br>❑ 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.

# 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.

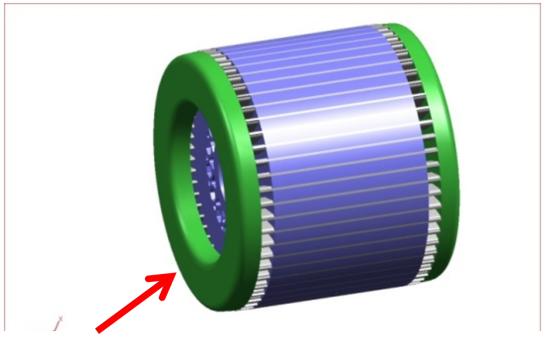


  - Task 1 will develop the FSW process parameters, as well as evaluate proper tool materials and techniques to produce defect-free FSWs in copper alloys
  - The fundamental information gained will be used to develop techniques to manufacture prototype copper rotor and stator assemblies
  - Components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

# Approach and Strategy for Deployment
## Task Breakdown

- Task 2 - Friction Stir Welding (FSW) of Dissimilar Copper to Aluminum Joints.
  - The approach will follow in parallel 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.

- Task 3 - Solid-state fabrication to produce bulk, low cost soft magnetic materials for rotor cores
  - Develops a new solid state fabrication process that has the potential to lower the cost and improve the performance of current electric steel laminate alloys and configurations
  - Develop the process technique (solid state high deformation microstructural modification – FSP and FCE) to produce ultra fine-grained bulk solids.
  - Test coupon scale materials for appropriate electric/ soft magnetic properties.

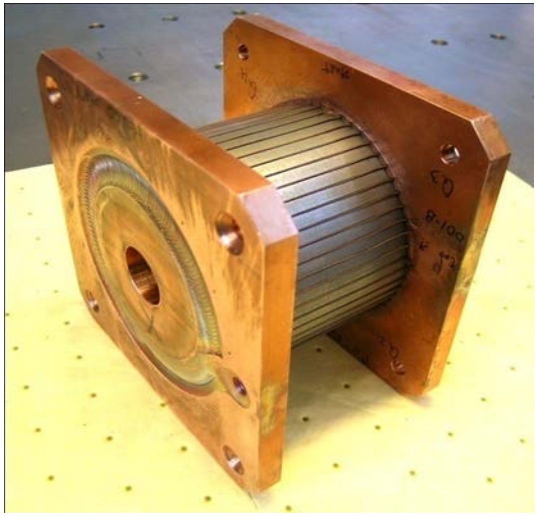


Significant weight savings could occur if end caps could be aluminum

# Technical Accomplishments and Progress
## Friction Stir Welded Rotors  Task 1 Copper

- Primary joining process investigated is the joint between the copper end caps and the “shorting bars” that traverse the rotor longitudinally.
- Joints between shorting bars and end caps are problematic
  - Fusion welding produces heat levels that are detrimental to the electric steel laminate coatings
  - Brazing so far has not shown the strength and durability to survive the 10,000 RPM qualification tests
  - Casting is possible but defects around the end cap to bar joint are not predictable

During 2012 we have focused on developing the FSW welding process and overcoming barriers discovered during experimental work



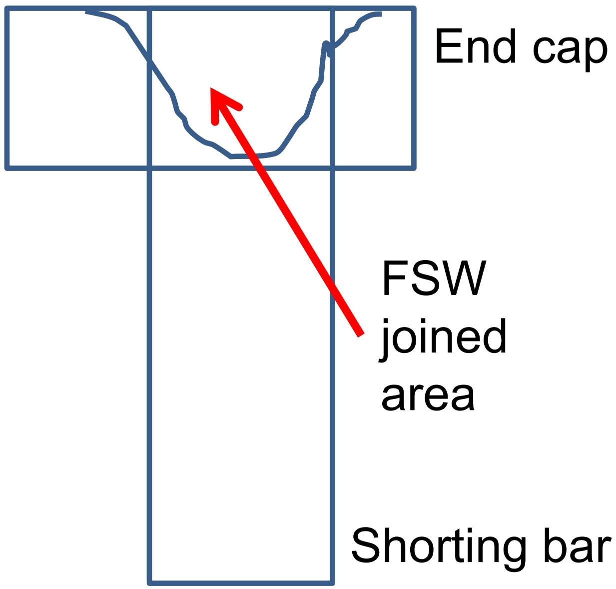
Rotor fabricated by Friction Stir Welding

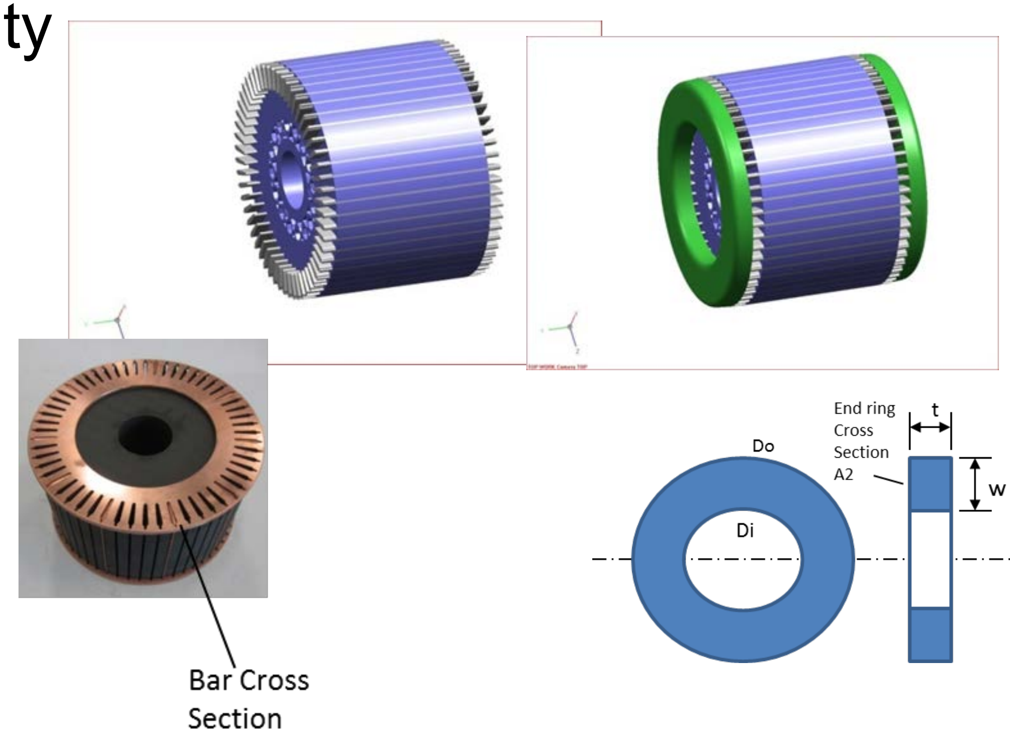
# Technical Accomplishments and Progress

- **Primary challenges and discoveries in FSW joining of the end cap to the laminate/shorting bar assembly**
  - Joint design for the highest electrical cross section at the minimum weight penalty dictates 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 is needed for a stable process

# Technical Accomplishments and Progress

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

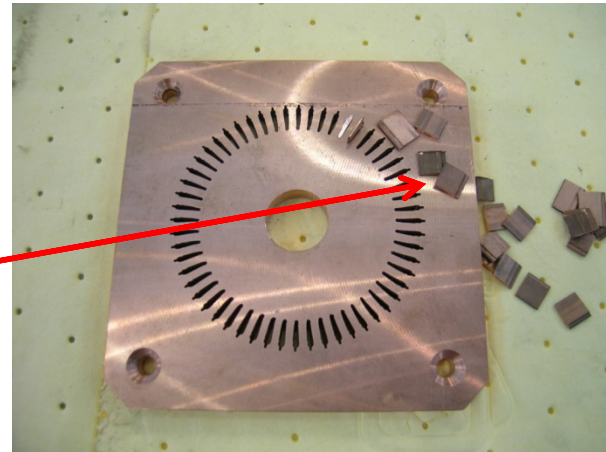


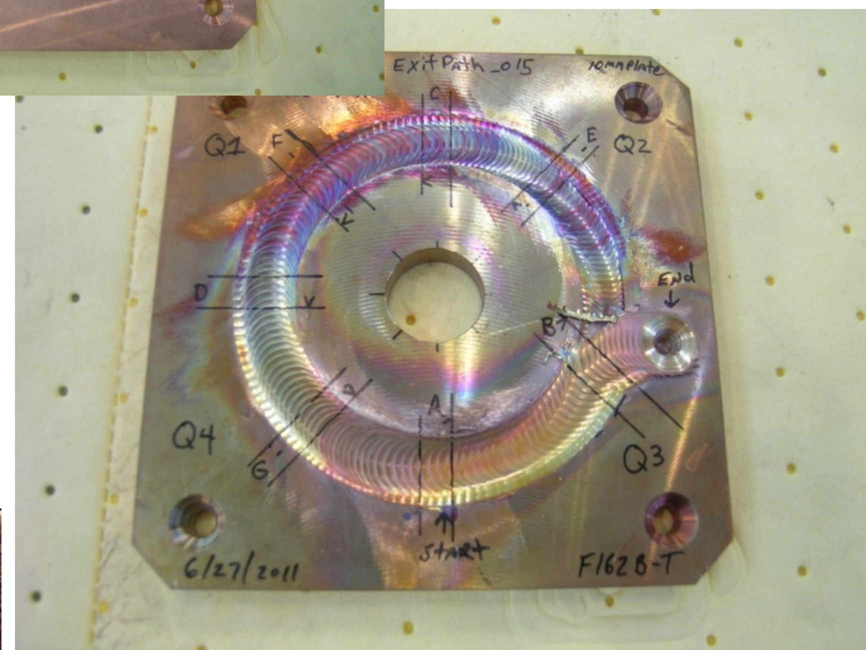




> - It is desired to have the minimum end cap thickness for weight savings.
>
> - The end cap thickness is dictated by motor efficiency FEA calculations, assuming 100% electrical cross section with the shorting bar. The FSW joined area is less than this100% overlap, so to optimize weight you need to optimize joint / tool design to get the maximum width joint with the appropriate depth

# Technical Accomplishments and Progress
## Rotor Fabrication Trials

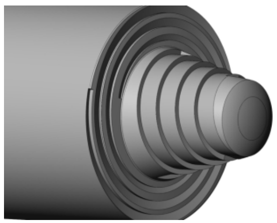
- Circular Welds performed at wide ranges of parameters
- "Short" shorting bars used to simulate rotor assembly
- Some parameters and tool designs produce gaps and voids in welds which are bad for electrical cross section

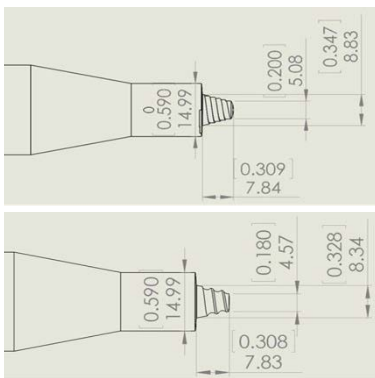


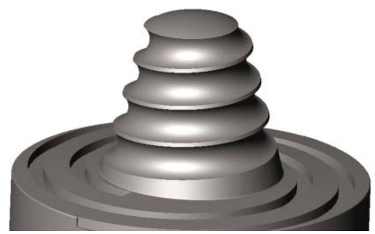



# Technical Accomplishments and Progress

- Tool evolution





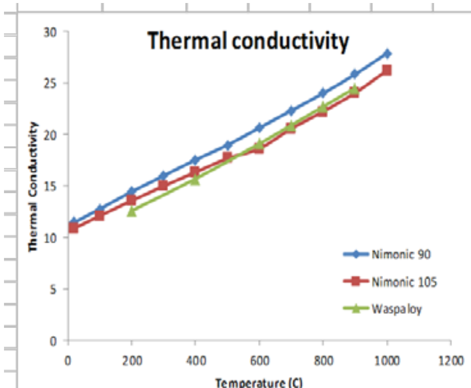
Tool shape has evolved to coarse threads with flats on the pin and raised features on the shoulders. Pin tips are wide to get maximum width at the bottom of the weld for electrical cross section while shoulders are narrow to limit heating and to fit in fixturing.

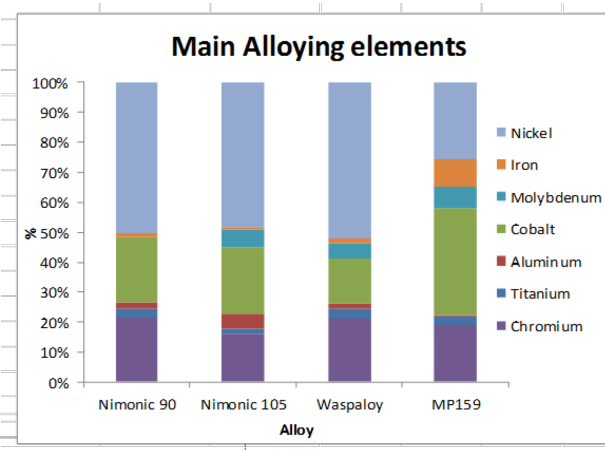
# Technical Accomplishments and Progress

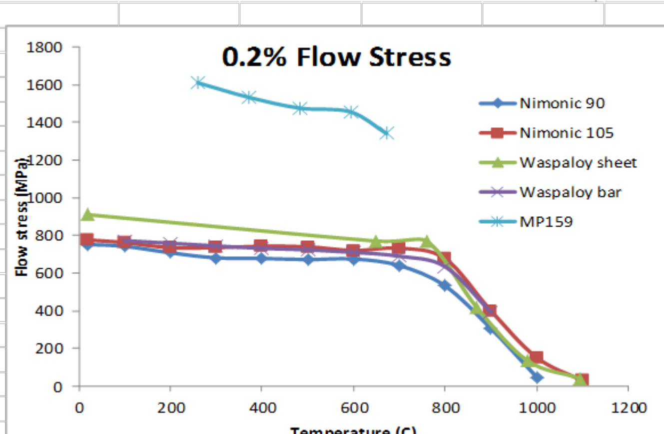
- Tool Durability and thermal requirements are driving tool composition to high strength, low conductivity materials (need to maintain heat in the base of the joint)

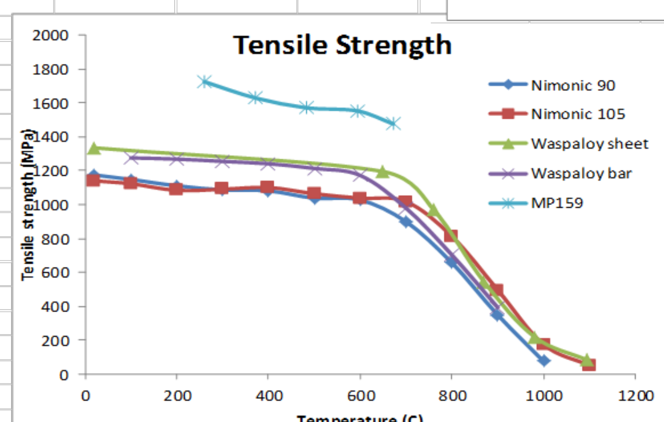
H13 tools fail

- Nimonic and MP159 have been downselected as tool materials



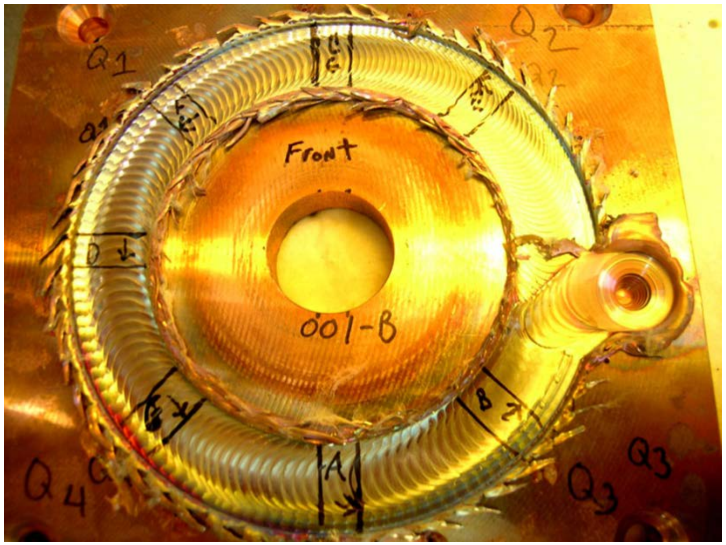



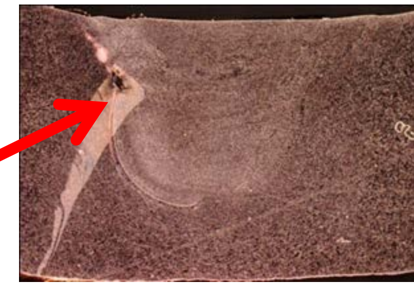
# Technical Accomplishments and Progress

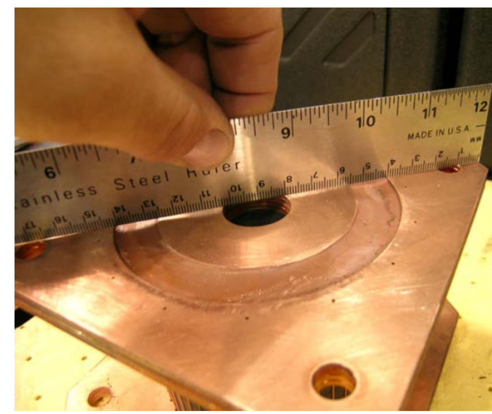
## Control of distortion and heating during welding

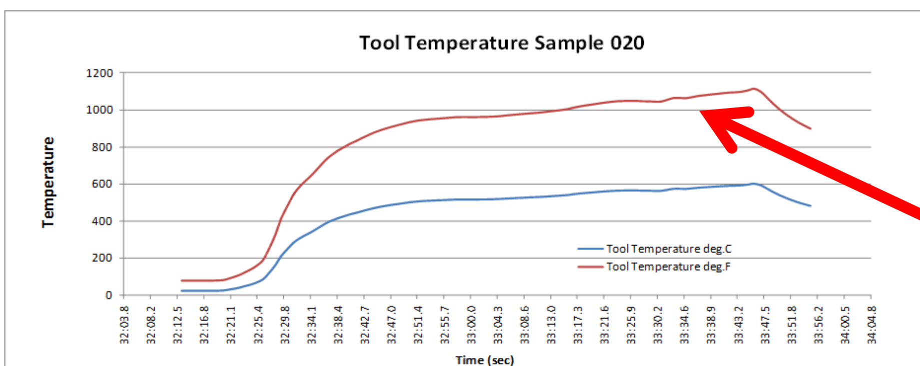
- Another challenge discovered in the rotor fabrication trials is excess heat build up during welding




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





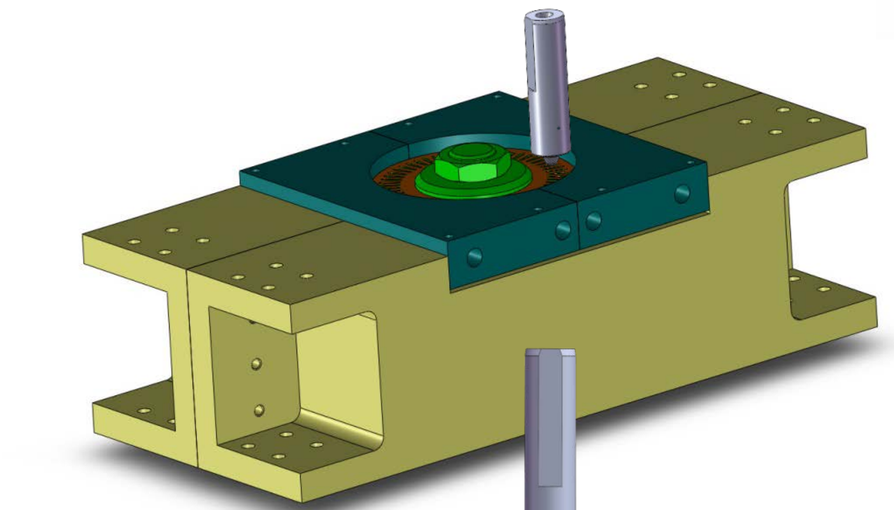


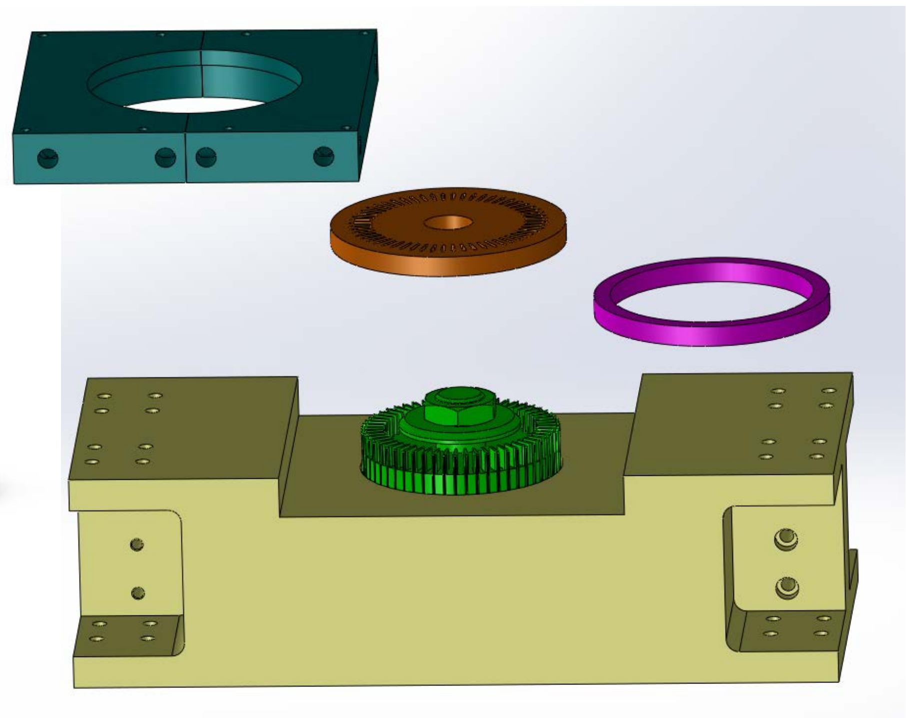

Also, because this is a circular weld, the tool moves into previous heat field as it comes around part.

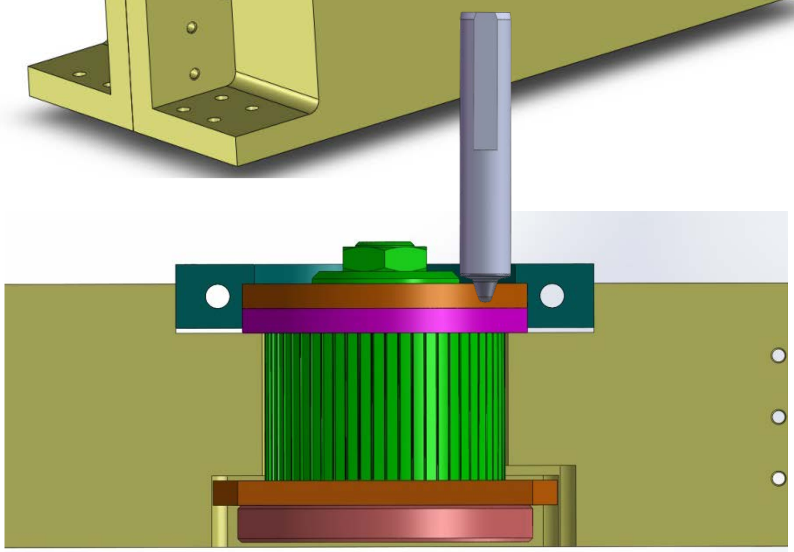
# Technical Accomplishments and Progress

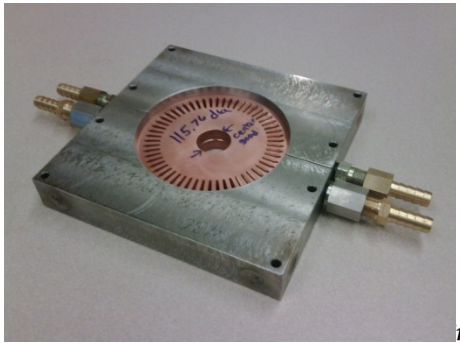
## Control of distortion and heating during welding

To address control of temperature boundary conditions, we use an actively cooled fixture









# Technical Accomplishments and Progress
# Control of the FSW process

**Primary realization from process parameter development is no one set of weld parameters works throughout the weld.**
**A single weld process parameter cannot cover changing conditions, so inconsistent microstructures result (and therefore, inconsistent mechanical performance)**

**We believe the best solution is adaptive control of weld temperature**

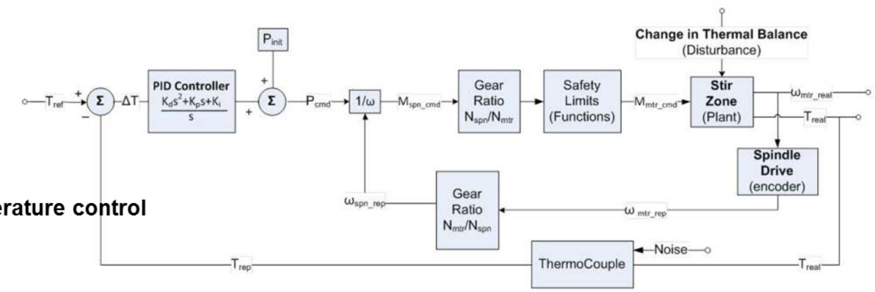
## How?

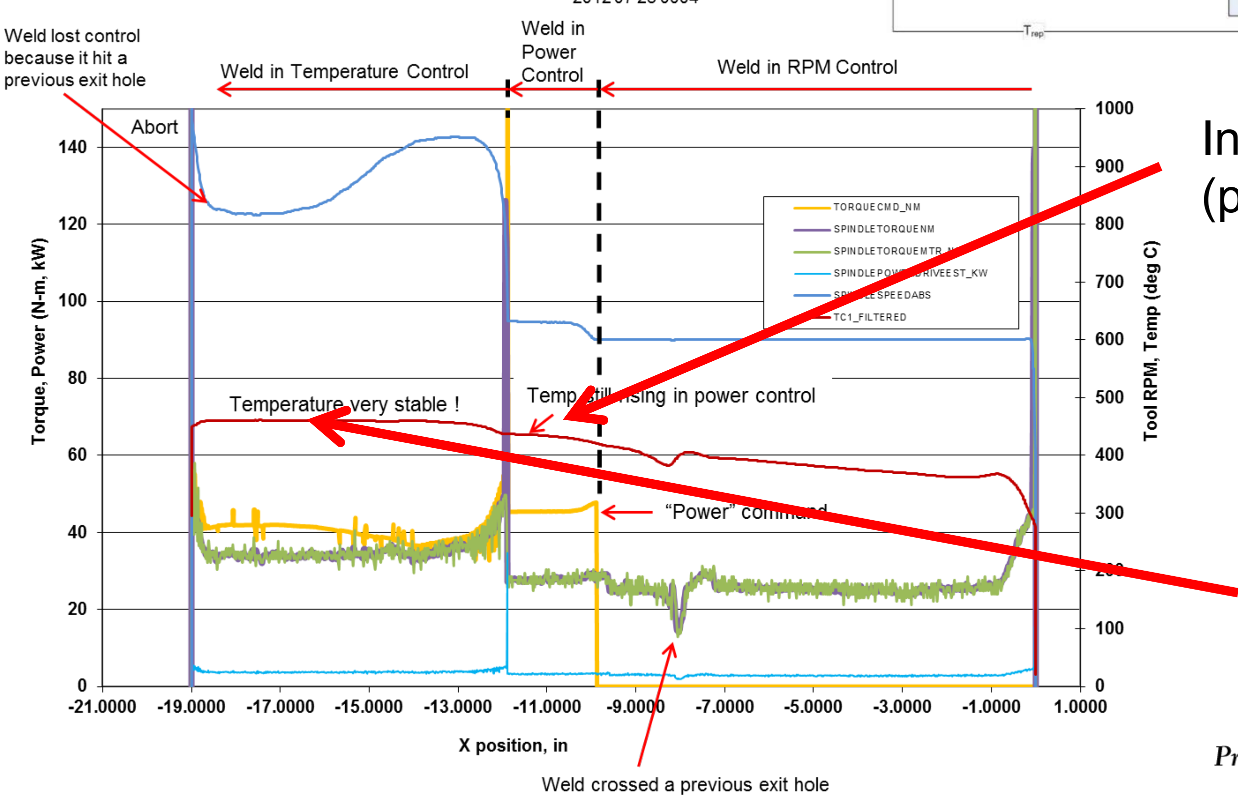
- Key issue is the temperature weld (peak temp, time at temp, and cooling rate)
- What governs the temperature?
  - Power input -- spindle torque x angular velocity
  - Thermal losses of the process
    - Conduction through workpiece
    - Radiation from workpiece
    - Conduction through tool
    - Conduction through the anvil
- Temperature is a result
- So we need a method to control power

# Technical Accomplishments and Progress

## Control of the FSW process

- Nested loop controller controls torque to maintain a commanded power.
- The outer loop maintains a commanded temperature.
- This results in a steady temperature in the weld and results in a consistent microstructure




Inner loop (power)

Temperature control (both inner and outer loops)

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# Milestones and Gates

- 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

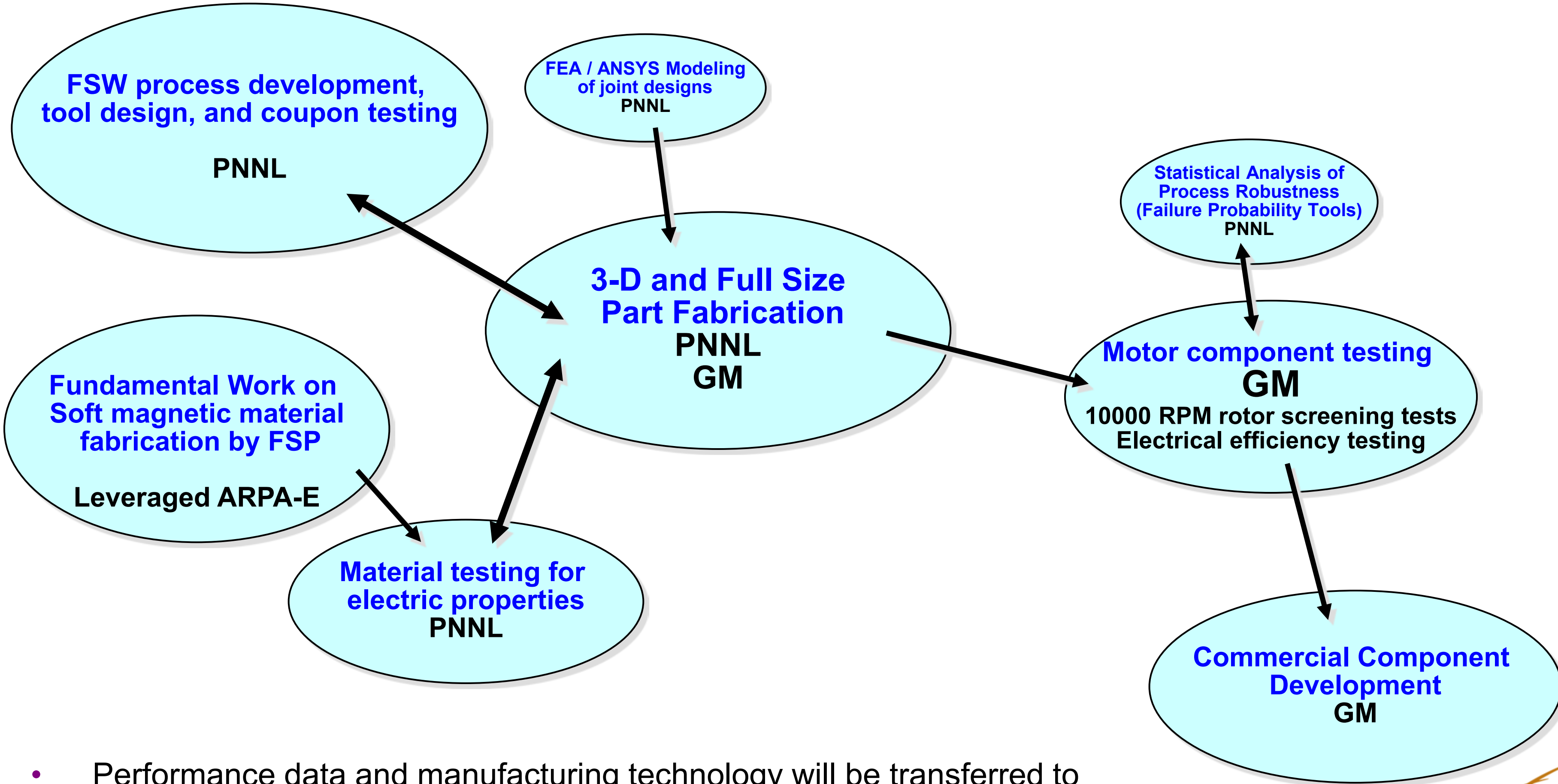
- 1st Go/No Go Gate has been achieved with the mechanical testing of a Friction Stir Welded Rotor at GM.

  Test was completed on a friction stir welded rotor using a custom screening test that involves running the rotor up to 10000 RPM in a blast proof fixture. The rotor tested was machined from a preliminary friction stir welded end cap design that due to manufacturing considerations will not be the prototype part design. The successful test however has been accepted as passing our first Go/No Go gate

- Milestone: Develop, fabricate, and test actively cooled welding fixture to allow for FSW welding of copper and aluminum rotor parts – Completed
- Milestone: Demonstrate a robust weld process on copper / aluminum dissimilar material welds and verify that mechanical properties pass metrics established by the team. - On schedule
- Milestone: Task 3 Solid state processing of rotor - stator core materials will begin in late 2013

# Collaboration and Coordination with Other Institutions

## 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.

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# Future work for FY12/13

- Although we have passed our Go/No go gate on the FSW welded copper rotor strength tests (10,000 RPM screen), the weld process is not yet robust enough for production applications. Future tasks include:
  - Establish process windows for the copper end cap to copper shorting bar joint using both active cooling in tool and fixture, and employing temperature control algorithms
  - Finalize tool design and material that produces highest level of electrical cross section possible to minimize end cap thickness and weight
- Begin process parameter development for the hybrid rotor (Copper to aluminum joints)
- Begin process development for Task 3 (solid state fabrication of rotor core materials).

# 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