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

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2012 DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting

May 15, 2012

Washington, D.C.

Project ID: PM004_grant_2012

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Overview

Timeline

- Start: FY2011
- Project end date: Sept 2014
- Percent complete: 5%

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: $445k

Barriers

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

- Need Decreased Cost – bring electronic propulsion systems costs below $8/kW
- Need Decreased Weight – bring specific power to 1.3 kW/kg by 2015
- Need Increased Efficiency – bring power density to 5 kW/L by 2015 through better soft magnetic materials
- Need Cooler Operation for better packaging and weight savings – through better heat rejection or lower heat generation
- Need Increased Durability – through better thermal fatigue performance and high temperature material strength

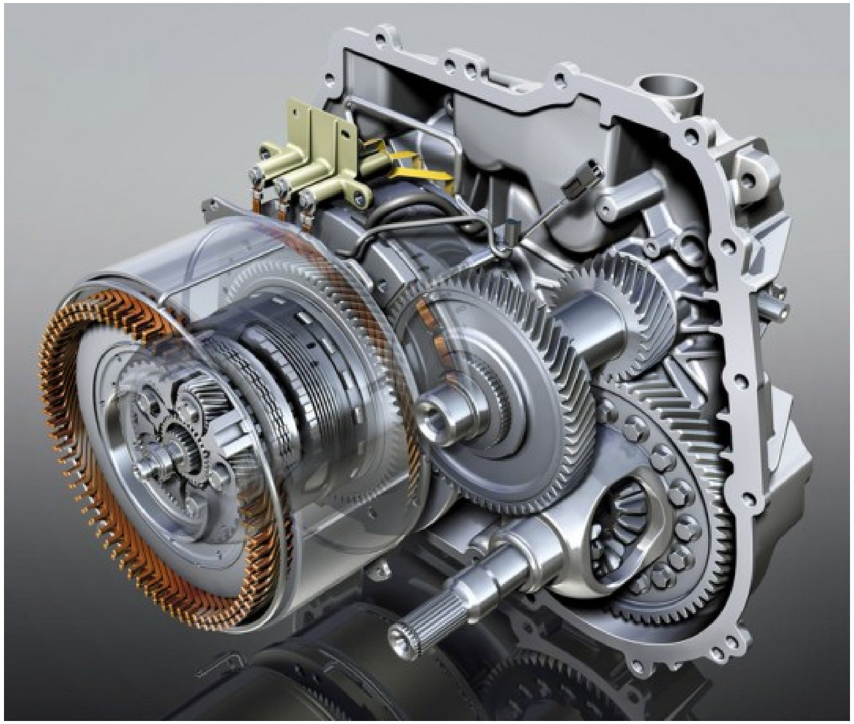
Partners

- CRADA with General Motors Research
- Project lead: PNNL

Relevance

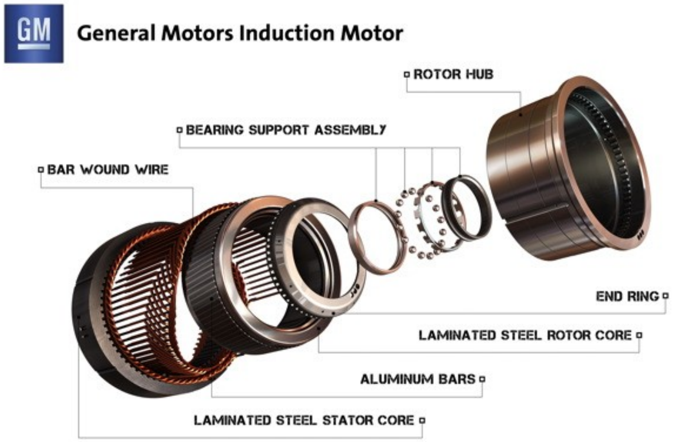
Project Objective

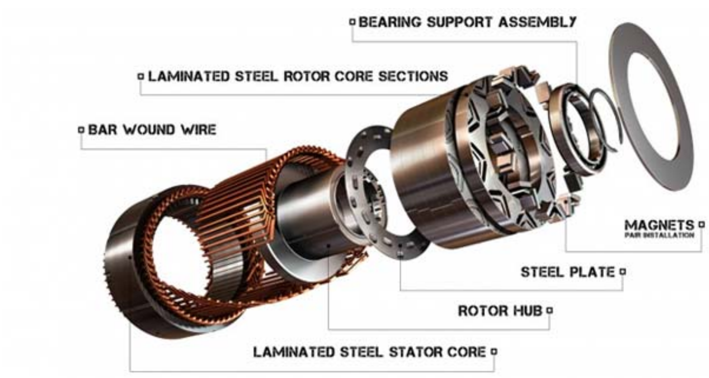
- To develop and deploy high-power induction and permanent magnet rotors and stators that are:
  - lighter weight
  - higher performance
  - are a lower cost to manufacture than current rotor/stator assemblies
- Achieve these objectives through the application of novel solid state joining and fabrication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



Background

- An electric motor is a complex assembly requiring a wide range of manufacturing techniques including casting, machining, welding, soldering, stamping, etc.
- New manufacturing techniques can cause step changes in the overall cost of the motor if the new technique can create a fundamental shift in the way a subsystem is constructed.
- For example, an electric motor has numerous components that are sensitive to high temperature.
  - Fusion welding, which requires very high temperature to melt the materials being joined, cannot be accomplished directly adjacent to heat sensitive parts like sensitive electronics, wiring and insulation, or where coated laminates or substrates are located nearby
  - This might require the part to be assembled through a much more complicated multistep process
- If another joining technology were available that did not heat the part, then the multistep assembly could be avoided, saving cost.





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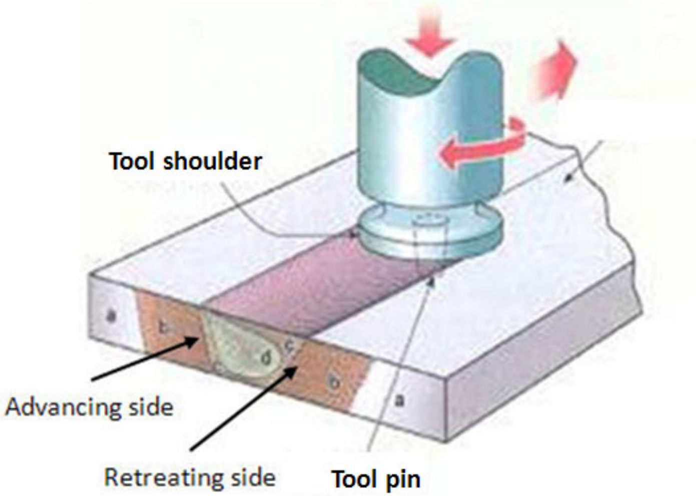
Background

- One example of a joining technology that could satisfy the need for lower adjacent part temperatures is **Friction Stir Welding**.
- Joint specific power and temperature can be controlled to much lower levels than some competing welding techniques, and manufacturing costs have been shown to be lower as well.



In addition,

- Next generation of rotor designs may be copper/aluminum hybrids or have aluminum components to reduce the rotating mass. It is anticipated joints will be needed between copper and aluminum.
- Solid-state joining techniques like FSW are logical to develop for specialized dissimilar joints that cannot be fusion welded due to the radically different melt temperatures of the components.

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 *(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.

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 will focus on solid state joining of Copper materials used in the rotor assemblies of high power induction motors.
- Task 2 will focus on dissimilar material joining primarily of copper to aluminum with an emphasis on components and assembly performance improvement.
- Task 3 will 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

Project Tasks impact these Barriers

- Task 1 Low-cost, solid-state Cu-Cu joining and fabricate Cu intensive induction motor rotors
- Task 2 Low-cost, solid-state Cu-Al Joining and fabricate hybrid rotors
- Task 3 Explore new manufacturing process to fabricate soft magnetic materials for rotor and stator laminates.

- Need Decreased Cost – bring electronic propulsion systems costs below $8/kW
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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. This fundamental knowledge is expected to lead to strategies and techniques that will be used to produce a joining process with:
    - 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.
  - The project will develop the FSW process parameters, as well as evaluate proper tool materials and techniques to produce defect-free FSWs in copper alloys specified by project partners
  - The fundamental information gained will be used to develop techniques to manufacture copper rotor and stator assemblies
  - Components will be evaluated and tested by industry collaborators to demonstrate efficiency benefits and commercial applications.

Approach and Strategy for Deployment
Task Breakdown

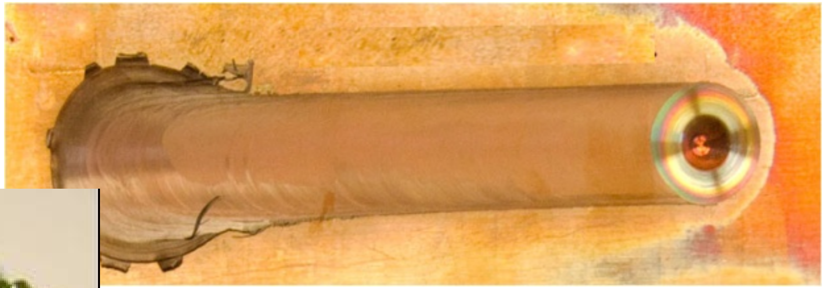
- Task 2 - Friction Stir Welding (FSW) of Dissimilar Copper to Aluminum Joints.
  - The approach will follow in parallel the Task 1 Cu/Cu joining development.
  - The fundamental information gained will be used to develop techniques to manufacture copper /aluminum hybrid assemblies.
  - Components will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

- Task 3 - Solid-state fabrication to produce bulk soft magnetic materials
  - Focus on using new fabrication technologies with potential to lower the cost and improve the performance of current laminate alloys and configurations
  - Develop the process technique (mostly high deformation microstructural modification) to produce ultra fine-grained bulk solids.
  - Test coupon scale materials for high resistivity and other appropriate electric/ soft magnetic properties.

Technical Accomplishments

Task 1 Copper - Copper Joining

- The project began in late fiscal year (FY) 2011 and has focused primarily on defining the specific tooling and process methods to join copper materials in the geometries appropriate for the application
- The project team is investigating a wide range of tool materials, tool designs and process parameters so that a robust process can be established.
- Tool materials include Tungsten-based materials, FerroTiC, Superalloys and cermets.
- Two tool designs investigated in this project include the stepped spiral tool (on the left) and the three flat tool (bottom). (Pictures are for illustration only; actual designs will vary.)

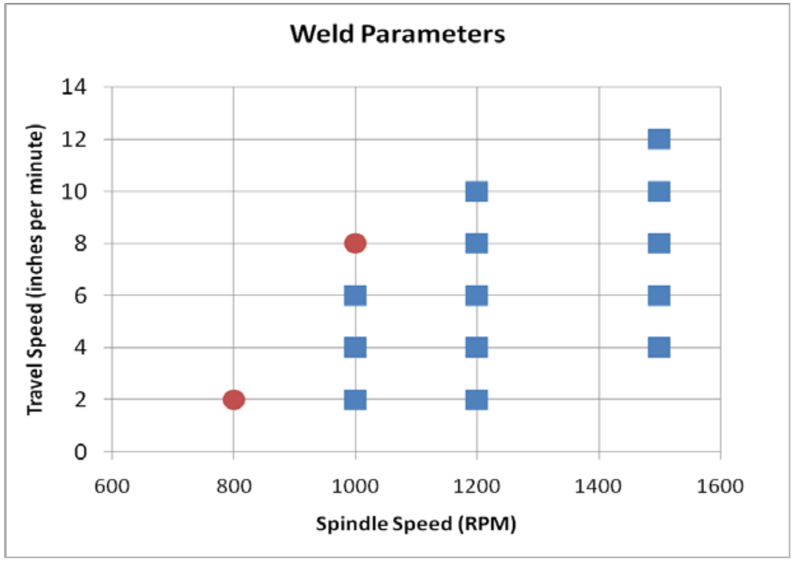


Technical Accomplishments

Process space

- Weld parameters investigated include changes to RPM, IPM, Forge Load, and tool position.
- These variables dictate the material flow, void or defect formation, and ultimate mechanical /electrical properties of the joint.

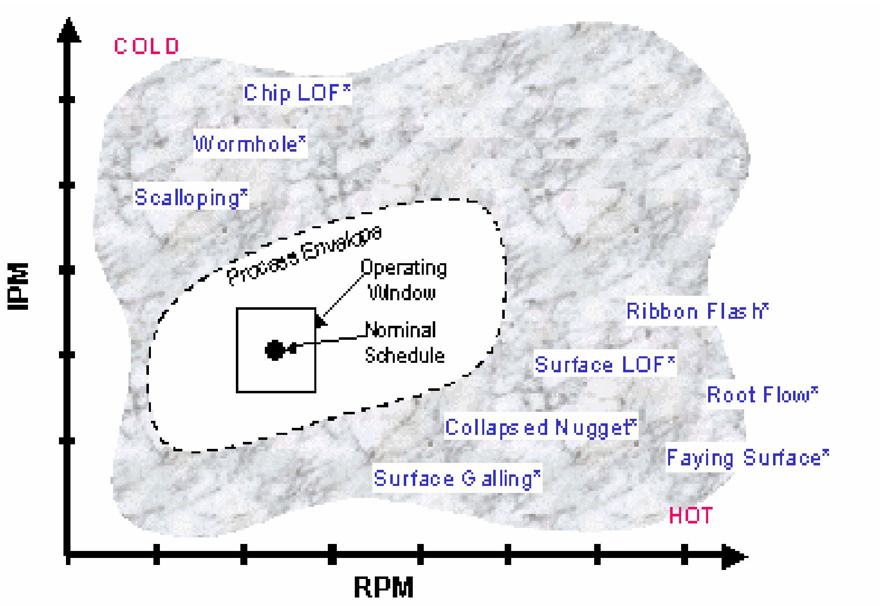
- Coppers high conductivity favors high travel speeds



A process window established for C101 copper using a FerroTic® tool with a 0.25-in. deep penetration. The circular dots indicate conditions in which either the tool failed or the weld had significant defects. Square symbols are successful welds

Welds, with optimum mechanical properties, will exist within the region of the square symbols.

Technical Accomplishments



- Process envelope needs to be established to know if process is robust
- How far away from the nominal schedule can you get before weld defects are created

Additionally, tool robustness can shrink the process window

Conventional tool materials used to FSW aluminum do not have the high temperature strength to survive some welding conditions for copper.

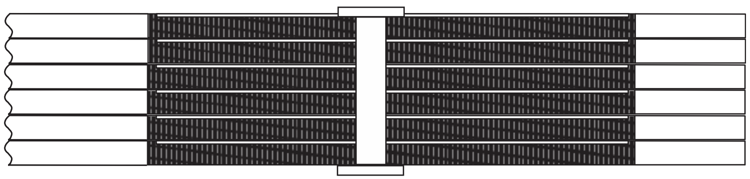
Below shows a typical FSW tool composed of H13 steel. While this tool will survive some limited weld conditions, there are other process conditions that will overheat the tool and cause the probe to twist off due to lower material strength at high temperature.

Tool failures were observed for several tool materials, including tungsten-based materials. Solving this challenge will be one of the early focus areas of this project.

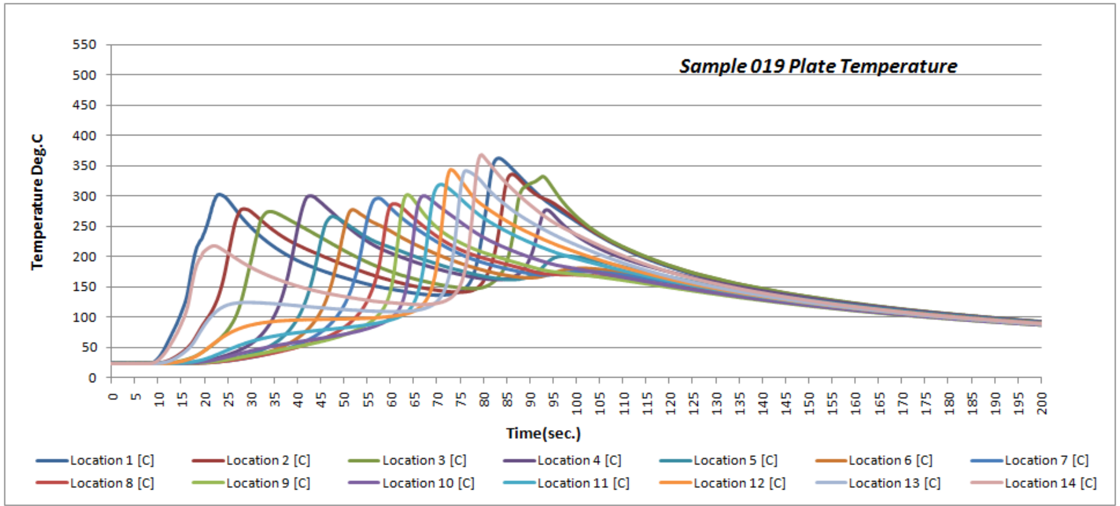
Technical Accomplishments

Additional concerns for manufacturing

- Joining of multiple stack-ups is key to several subsystems of an electric motor, so understanding how this is done is part of the fundamental development task



- Temperature achieved through the weld process and temperature transients are also being characterized



Process parameters dictate adjacent part temperatures

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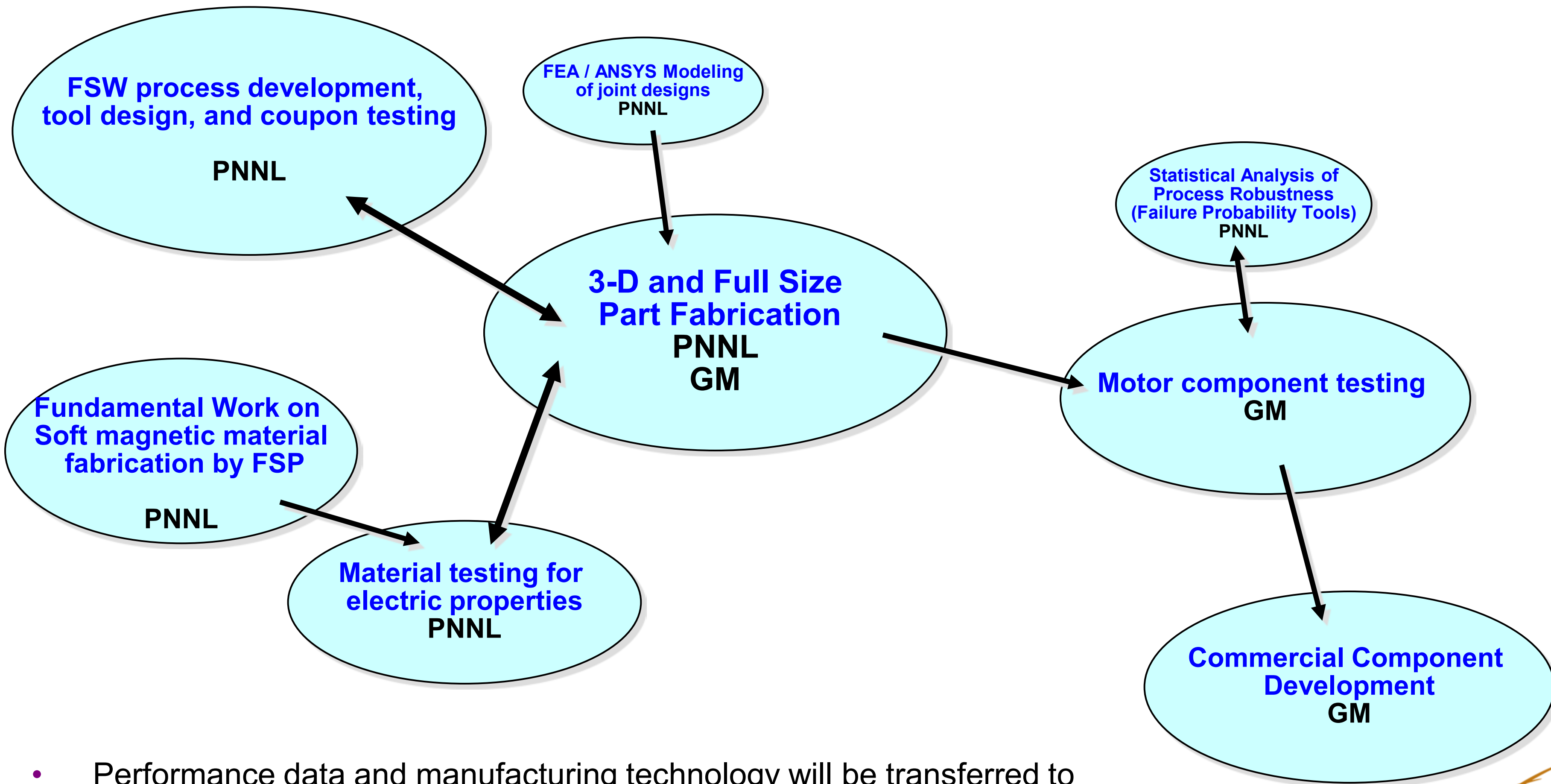
Collaboration and Coordination with Other Institutions

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.

Future work for FY12/13

- Establish Process windows for copper to copper joints
  - Complete experimental trials on tool material, tool design, process parameters through a guided Design of Experiment (D.O.E.) Process.
  - Output of D.O.E. is primarily joint properties, but several other considerations around the application will also constrain the optimization process.
  - Go/no go gate is planned at end of process development stage approximately 20 months from project start
  - Go/No go gate is based on a detailed set of mechanical performance criteria that the joints must achieve dictated by a specific part geometry.
- Establish Process windows for copper to aluminum joints following parallel process as above.

Summary

- Motor designs are a compromise between performance and cost (both cost of materials and cost of manufacturing).
- New manufacturing processes can be critical in this balance because they can simultaneously be enabling of lower cost materials, and introduce a lower cost manufacturing process. In many cases, the new manufacturing process may even directly increase the efficiency of the part by producing an assembly that displays better thermal, mechanical or electric/magnetic performance.
- This project will use new solid-state joining and processing technologies to achieve both increased performance and a lower manufacturing cost.
- Specifically, 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 and commercial applications
- The manufacturing methods developed will lead to motors that will display
  - lighter weight
  - higher performance
  - a relatively lower cost to manufacture