University of Pittsburgh

AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

Enabling Soft Magnetics for Wide Bandgap (WBG) and Ultra-Wide Bandgap (UWBG) Power Electronics

Sandia National Laboratory Power Electronics and Energy Conversion Workshop

Presentation Date: August 3rd, 2023

Presenter:

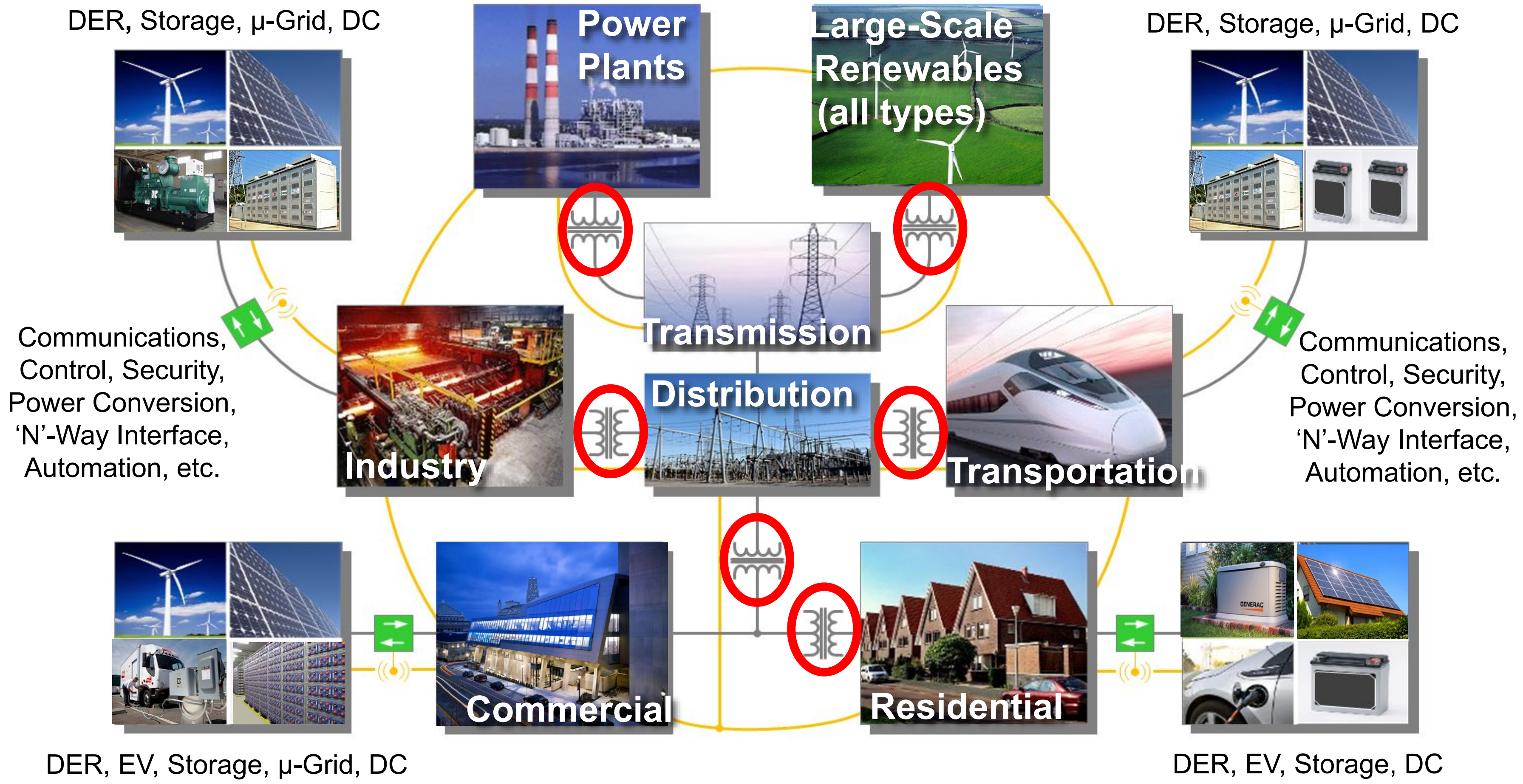
Prof. Paul R. Ohodnicki, Jr.,

University of Pittsburgh

Presentation Overview

- Electrification Trends and Magnetics Technologies
- Existing State of Art and Future Needs
- Nanocrystalline Alloys and Component Designs
- New Ideas in Ferrite-Based Soft Magnets
- AMPED Consortium and Workforce Development
- Summary and Future Prospects

Motivation: Electrification in the 21st Century



DER, Storage, μ-Grid, DC

DER, Storage, μ-Grid, DC

Communications, Control, Security, Power Conversion, ‘N’-Way Interface, Automation, etc.

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DER, EV, Storage, μ-Grid, DC

DER, EV, Storage, DC

Magnetics Plays a Critical Role in Electric Power Conversion

(Transformers and Inductors are Key Enabling Technologies)

Existing State of Art Soft Magnetic Materials

New Nanocomposite Alloy Compositions and Manufacturing

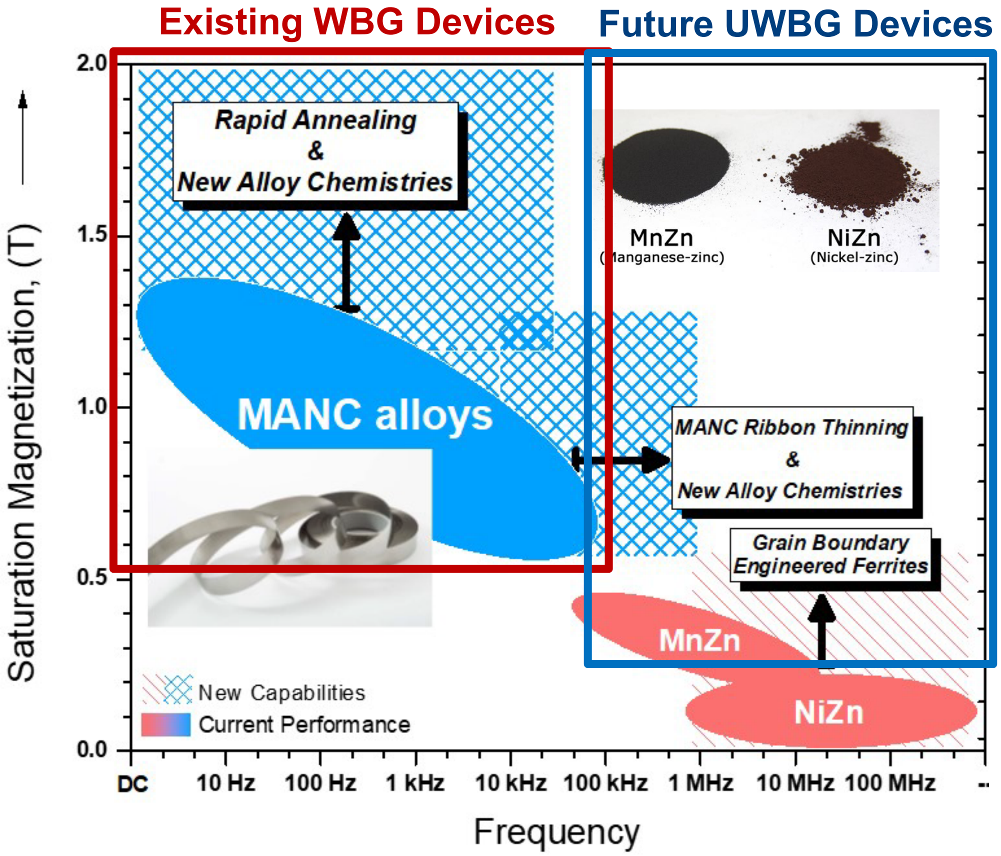
Material Classes	Saturation Magnetization (T)	Resistivity (μΩ-cm)	Upper Temp. Limit (C)	Upper Freq. Limit (Hz)	Mechanical Properties	Manufacturing Scalability
Ferrites (NiZn, MnZn)	0.2-0.4	$>10^3$	100-300	10^6-10^9	Brittle But Machinable	Limited (Powder Process)
Bulk Crystalline Alloys	1-2.5	~10	400-1000	10^2	Excellent	Excellent
Amorphous Alloys	1-1.6	~100	150	10^5	Good	Good
Commercial Metal / Amorphous Nanocomposites (MANCs)	1.3	~100	150	10^5	Brittle	Limited (Brittle Properties)
Emerging MANCs for WBG	1-1.9	~150	150-500	10^5	Good	Good
Ideal for UWBG	1-2	$>10^3$	300-500	10^6-10^7	Excellent	Excellent

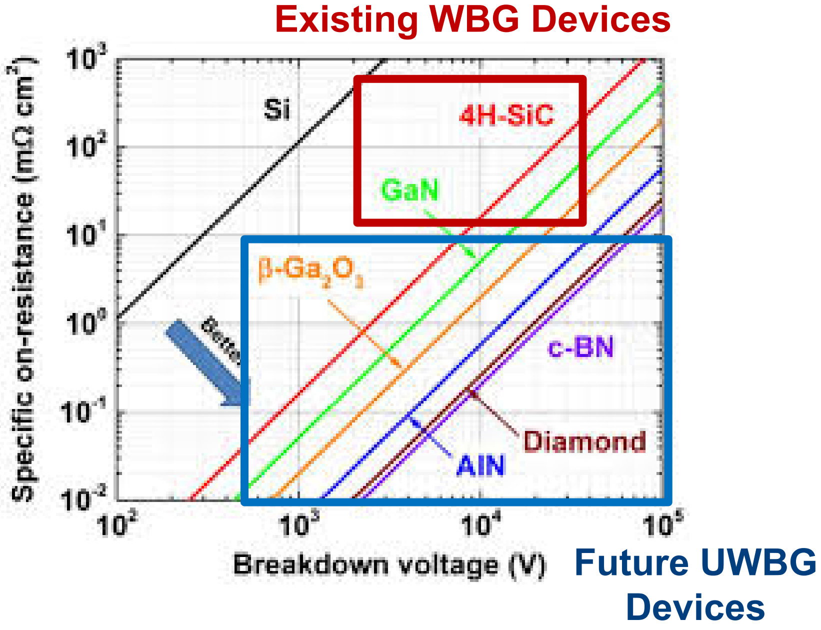
No Existing Materials Can Address this Space

Materials for Wide and Ultrawide Bandgap Power Electronics

WBG and UWBG Power Electronics : Soft Magnetics

Improvements to Existing Materials Can
Address Wide Bandgap Power Electronics,
Ultrawide Bandgap Devices Require New Materials

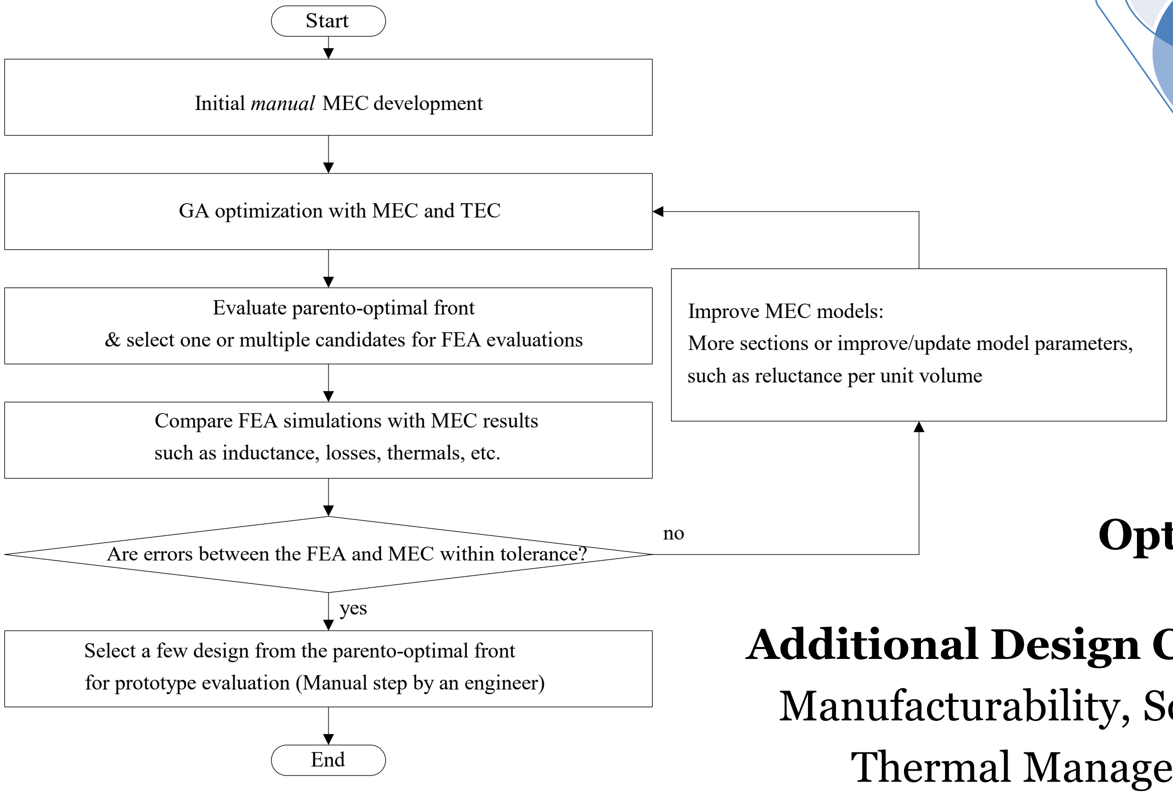




New Materials Research
and Advanced Manufacturing
Strategies are Being Pursued

Optimization of Magnetic Components

Multi-Objective Optimization Methods Can Play a Key Role



Start

Initial *manual* MEC development

GA optimization with MEC and TEC

Evaluate parento-optimal front
& select one or multiple candidates for FEA evaluations

Compare FEA simulations with MEC results
such as inductance, losses, thermals, etc.

Are errors between the FEA and MEC within tolerance?

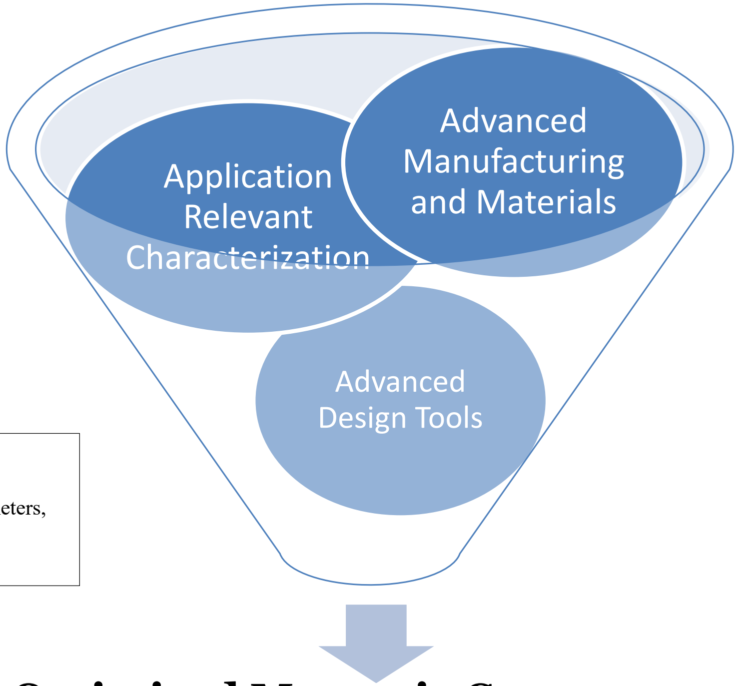
no

Improve MEC models:
More sections or improve/update model parameters,
such as reluctance per unit volume

yes

Select a few design from the parento-optimal front
for prototype evaluation (Manual step by an engineer)

End



Application Relevant Characterization

Advanced Manufacturing and Materials

Advanced Design Tools

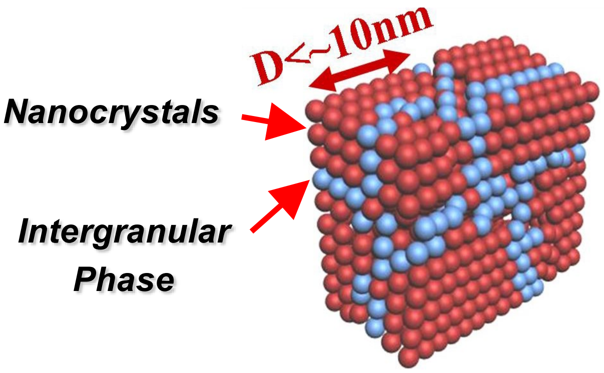
Optimized Magnetic Components

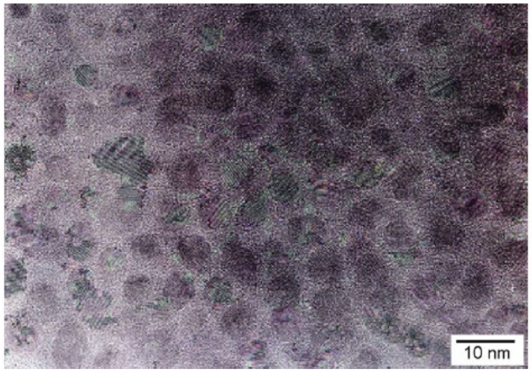
Additional Design Considerations Must Include:

Manufacturability, Scalability, Windings, Insulation,
Thermal Management, System Integration …

Holistic Magnetic Designs Using State of Art Materials and Manufacturing Methods Benefit from Rigorous Design Processes and Tools to Fully Leverage

Metallic Nanocomposites (WBG Magnetics)



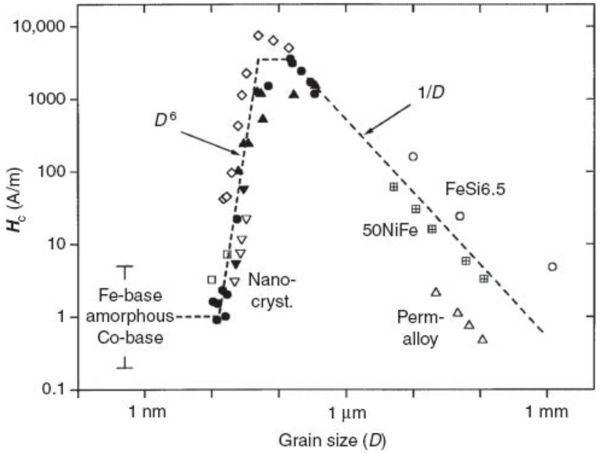


MW-Scale / High Volume Applications Require Manufacturing Scalability

Role of Intergranular Phase:

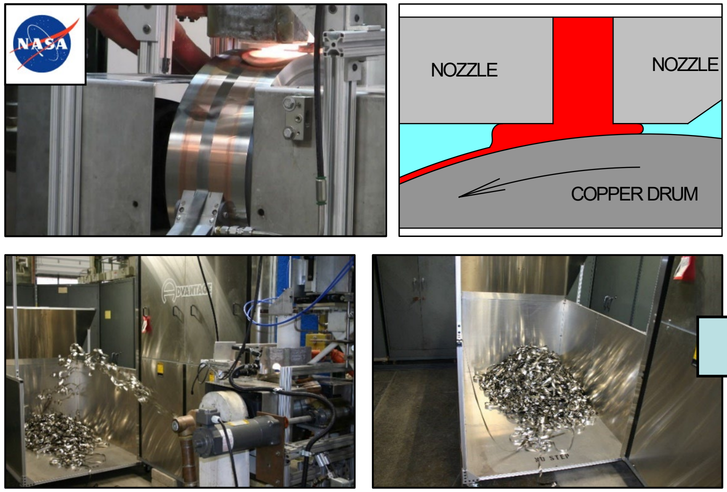
- → Refined Microstructure
- → Source of Induced Anisotropy
- → Intergranular Exchange Coupling
- → Increased Effective Resistivity
- → High Temperature Stable Microstructure

Nanoscale Microstructure Yields Soft Magnetic Properties



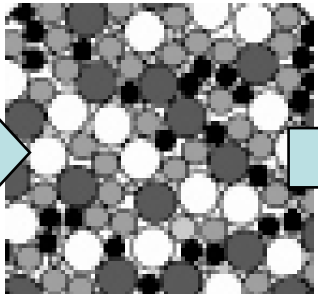
Metal Nanocrystal and Metallic Glass Intergranular Phase Nanocomposites (MANCs) are the **Only Commercially Available Nanocomposites at Scale**.

Amorphous & Nanocrystalline Alloys (WBG Magnetics)



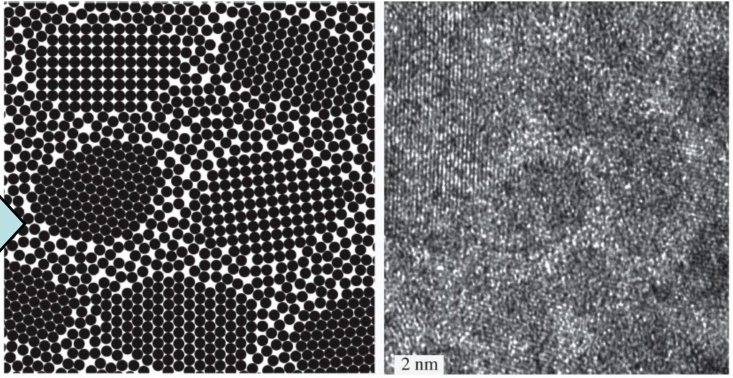
Amorphous Metal Ribbon Fabrication (Rapid solidification)

Commercial Amorphous FeSiB Alloys



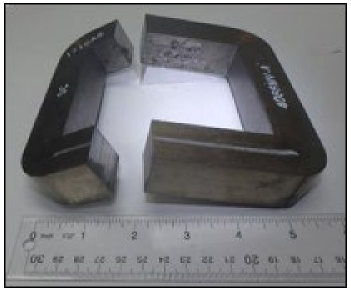
Amorphous Structure (As-cast)

Commercial FeNbSiBCu Nanocomposite Alloys

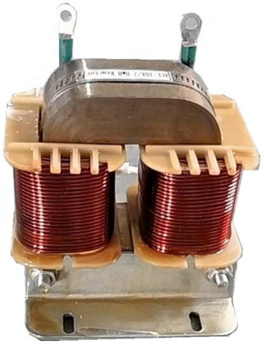


Nanocomposite Structure (Heat treatment)

As-Cast Ribbon



Processed Core

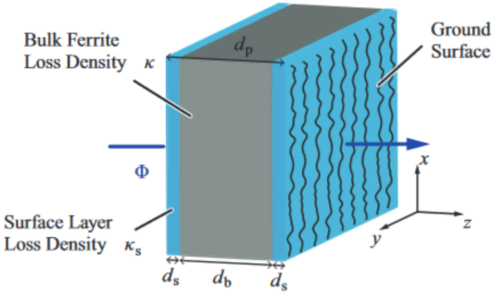


Nanocomposite Core Inductor

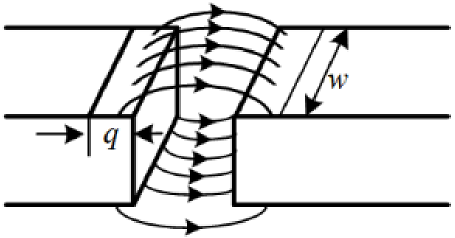
Amorphous Alloys are Synthesized By Rapid Solidification Nanocomposites are Formed By Subsequent Thermal Processing

Inductor Gap Losses : A Driver for Advanced Materials and Manufacturing

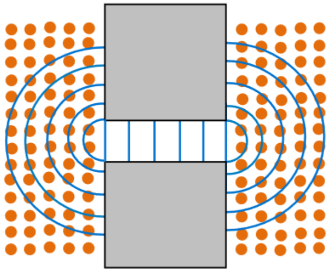
Cut/gapped inductor cores experience additional losses, increase with high frequency



Direct Gap Loss: Result of damage to core during cutting process



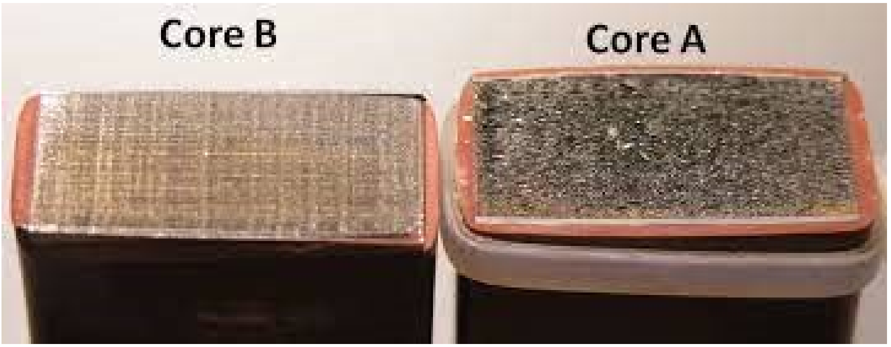
Fringing Eddy Current Loss: Eddy currents induced in core laminations by fringing flux



Proximity Loss: Winding loss induced by fringing flux

Variability in Performance
+
Manufacturing Challenges

High Quality (Etched)	Poor Quality (Unetched)



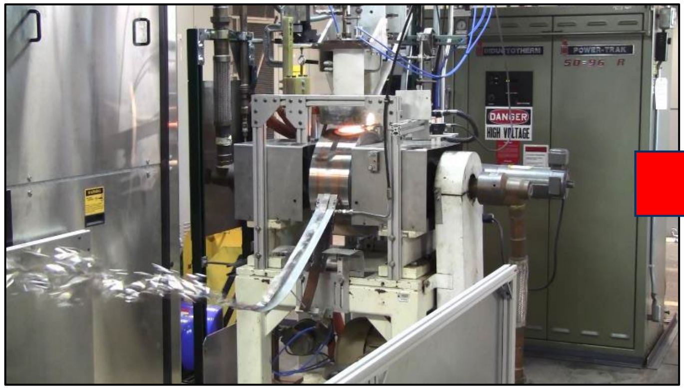
B. Cougo A. Tüysüz J. Mühlethaler J. W. Kolar, Proceedings of the 37th Annual Conference of the IEEE Industrial Electronics Society (IECON 2011).

Reliable Gap Loss Models Needed to Accurately Analyze and Design Inductors

State-of-Art Nanocomposites: Alloys + Processing

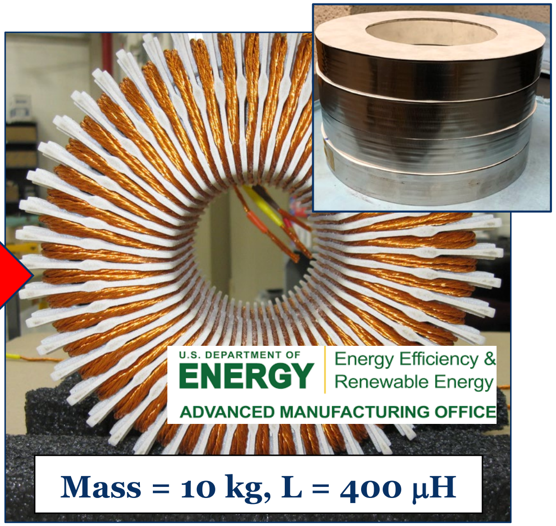
Planar Flow Casting for Amorphous Alloy Synthesis

Field and / or Strain Annealing to Optimize Properties and "Tune" Permeability in Cores



Pilot-Scale Caster (NASA GRC)

In-Line Thermal Processing (AMPED)



Mass = 10 kg, L = 400 μH

Full-scale Prototype Nanocomposite Cores

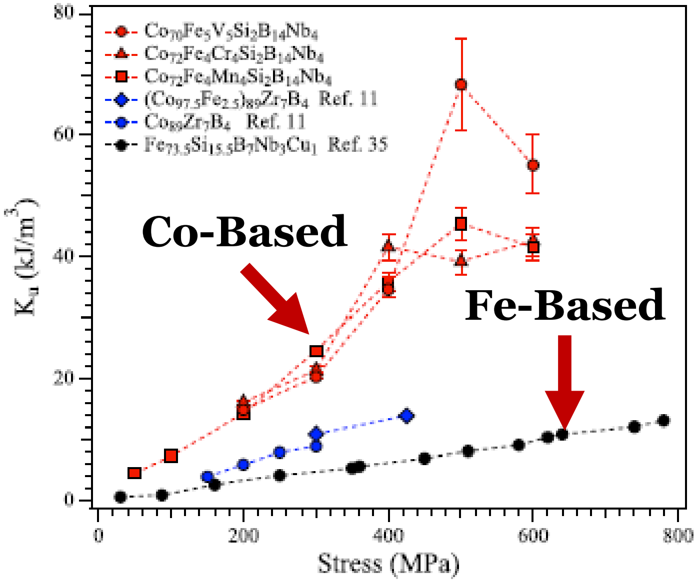
Improved Properties of New Alloys are Critical for In-Line Manufacturing Scalability

Recent Trends Pursue <u>Higher Flux Density Alloys</u> and <u>Advanced In-Line Thermal Processing</u> for Material / Core Optimization.

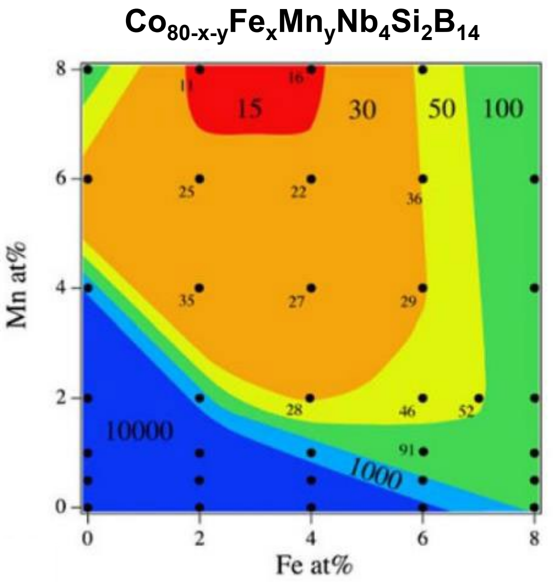
A. Leary J. Appl. Phys., 117, (2015).

Co-Based Nanocrystalline: “Permeability Engineering”

- Co-Based alloys show unprecedented induced anisotropy
- Alloy chemistry + tension enables ”engineered” permeability ~10 – 10,000, ideal for inductors

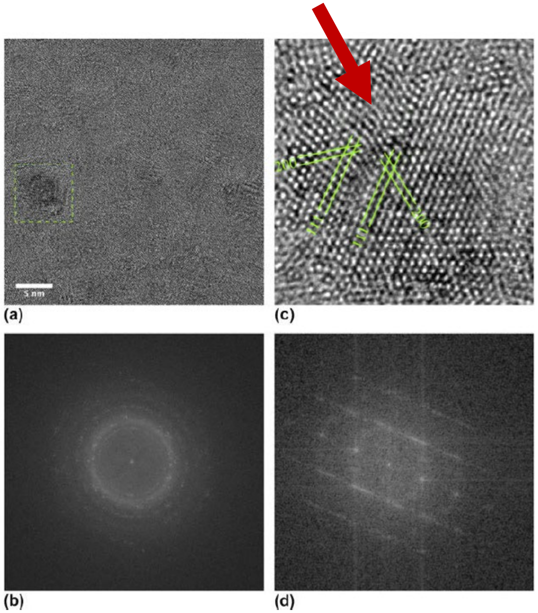


Stress Dependence for Different Compositions



Composition Dependence at 200MPa

Preferential Orientation of Planar Defects in Close Packed Crystals

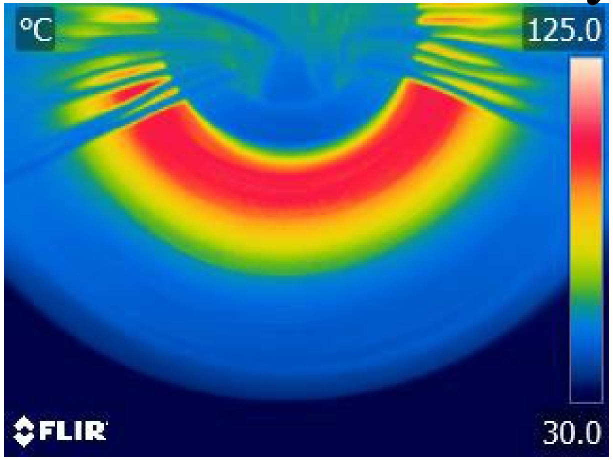


A. Leary, V. Keylin, A. Devaraj, V. DeGeorge, P. Ohodnicki, M. McHenry, J. Mater. Res., Vol. 31, No. 20 (2016).

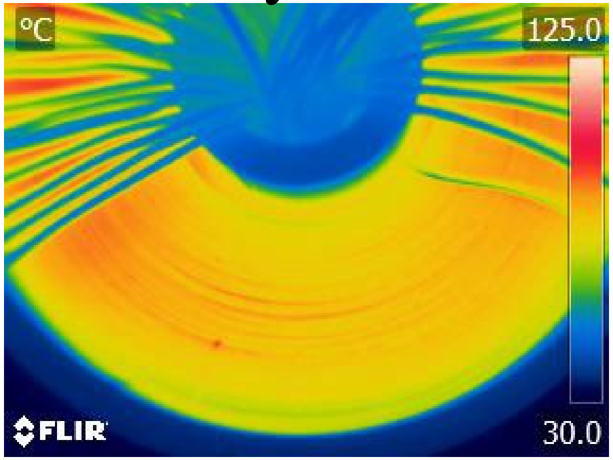
Excellent Ductility and Large Induced Anisotropy Per Unit Applied Tension Enables Manufacturability of Gapless Inductors

Co-Base Alloys : “Permeability Engineering”

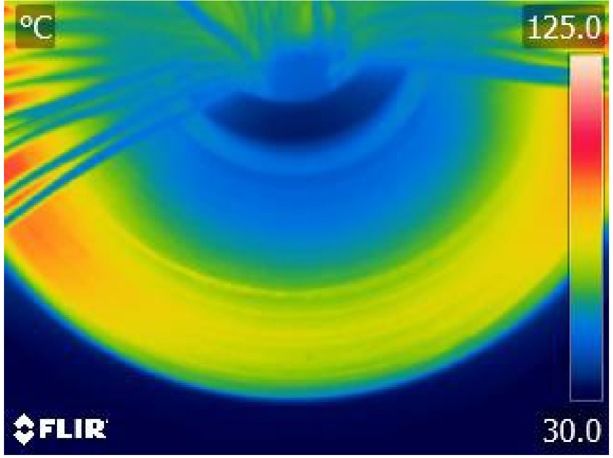
Constant Permeability



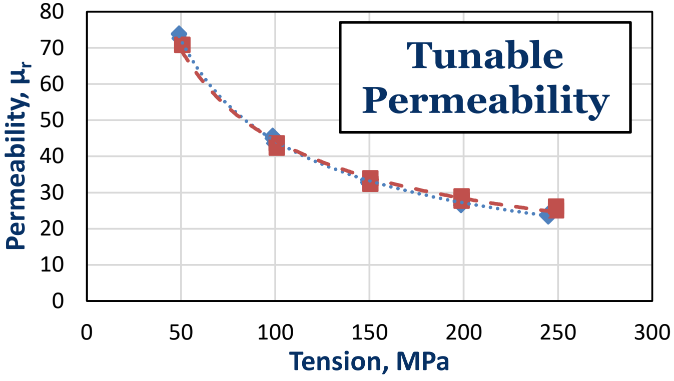
Ideally Graded



Exponentially Graded



Perm vs Tension



Tunable Permeability

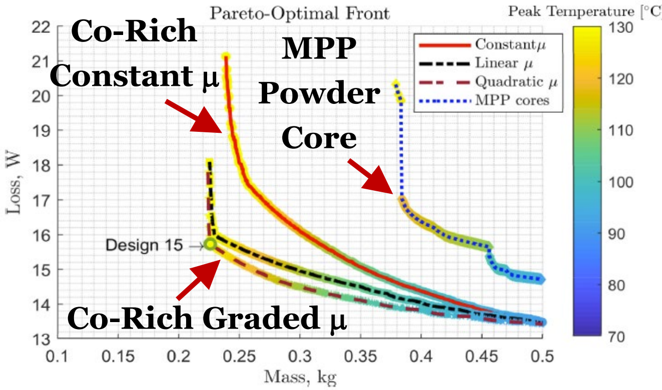
K. Byerly et al., ECCE 2021, pp. 5320–5326.

CorePower Magnetics (CPM)
Exclusive License

COREPOWER MAGNETICS

SCALEUP Seeding Critical Advances for Leading Energy technologies with Untapped Potential

V. C. Do Nascimento , P. R. Ohodnicki et al, IEEE Trans. Power Electronics, doi: 10.1109/TPEL.2020.3012911, 2020.



Co-Rich Constant μ

MPP Powder Core

Co-Rich Graded μ

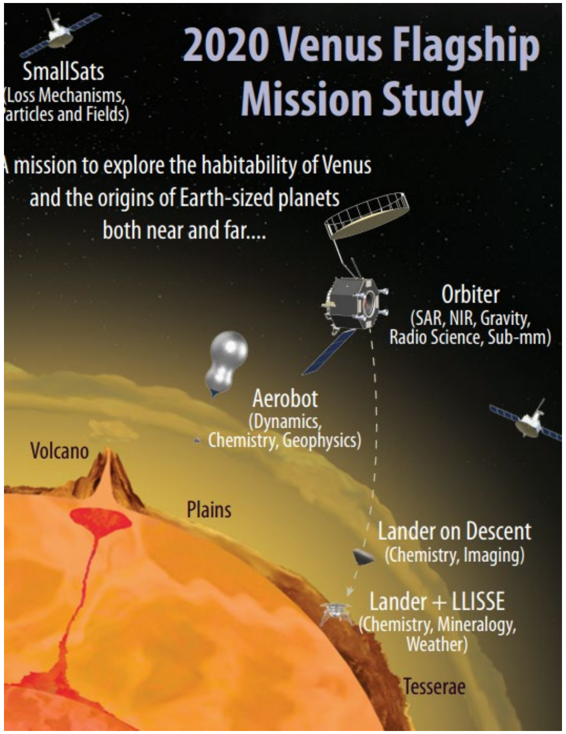
K. Byerly, P. R. Ohodnicki, et al JOM, Volume 70, Issue 6, pp 879–891 (2018).

Permeability Engineering is Possible By Exploiting Advanced Alloy Systems Combined with Optimized Tension Profiles.

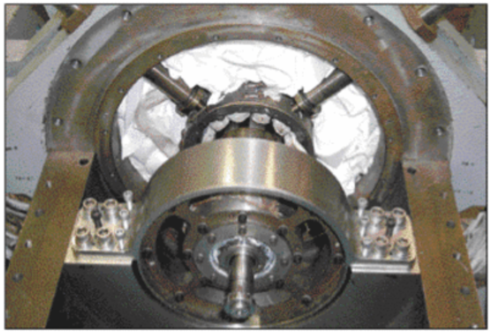
Extreme Temperature Applications (NASA)

Venus Planetary Surface Exploration

Temperature: 460 ~ 470 °C
Atmosphere pressure: 9.2 MPa

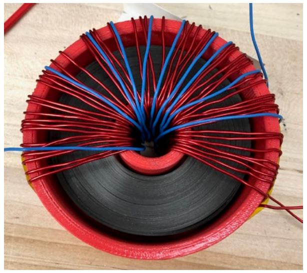


Hybrid-Electric Aviation
(Inductors, Motors, Generators)

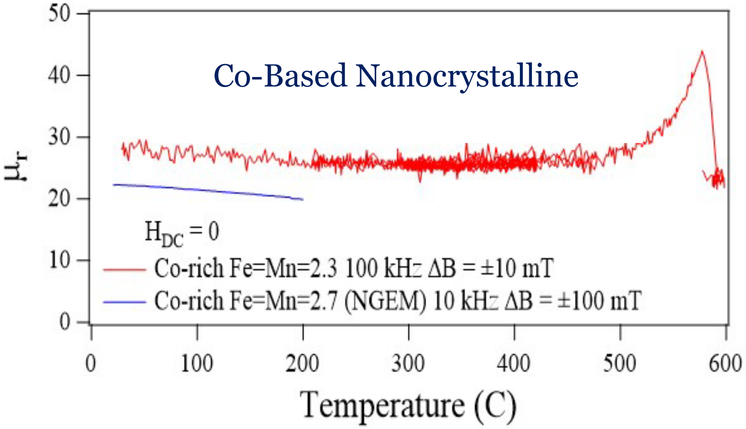


T>500C Motor / Generator
(NASA GRC)

Gapped Inductor Cores Require Impregnation Resin (Stability Limited < 400C)



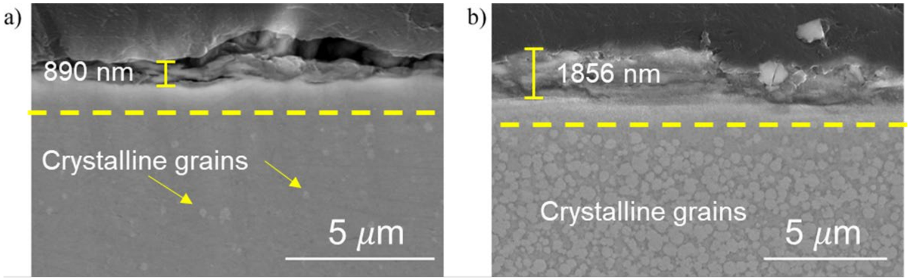
Ungapped Co-Based Nanocrystalline Potential for Operation at T=400-500C?



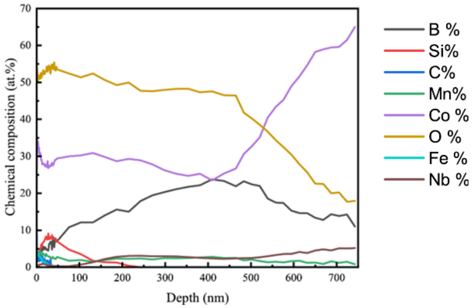
Gapless Permeability Engineered Cores Show Unique Relevance for Emerging Extreme Temperature Application Requirements

Microstructure and Environmental Stability

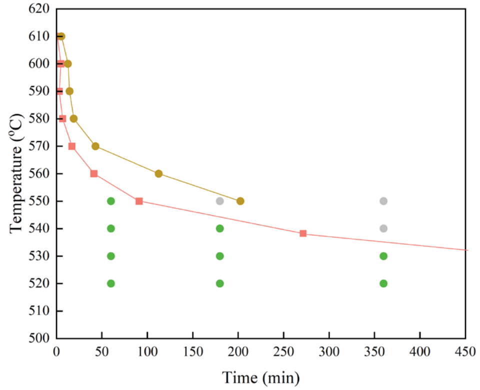
- $Co_{75.4}Fe_{2.3}Mn_{2.3}Si_{2}Nb_{4}B_{14}$
- Excellent corrosion resistance due to:
  - Amorphous structure
  - Passivation due to Boron enrichment
- Resistance to secondary crystallization
- Current limitation: abnormal grain growth



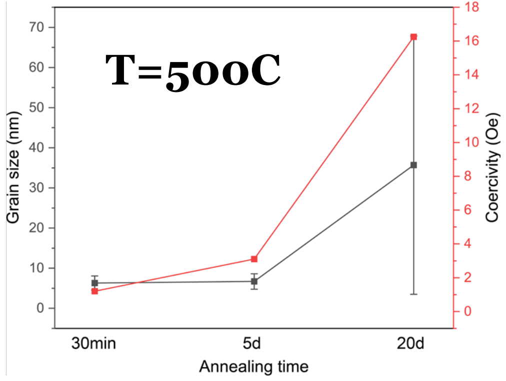
5-day oxidation **20-day oxidation**

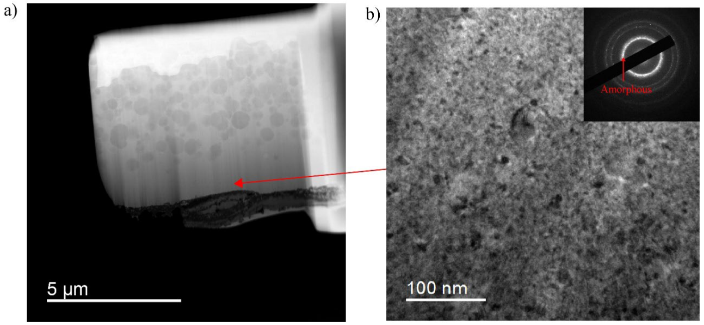


TTT Diagram



Grain size vs Coercivity

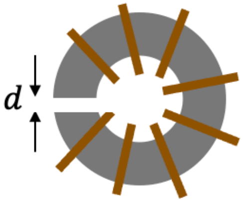




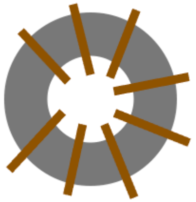
Corrosion and Oxidization Resistance is High But Abnormal Grain Growth Appears to Be a Challenge that Needs Addressed

Stability of Induced Anisotropy (i.e. Permeability)

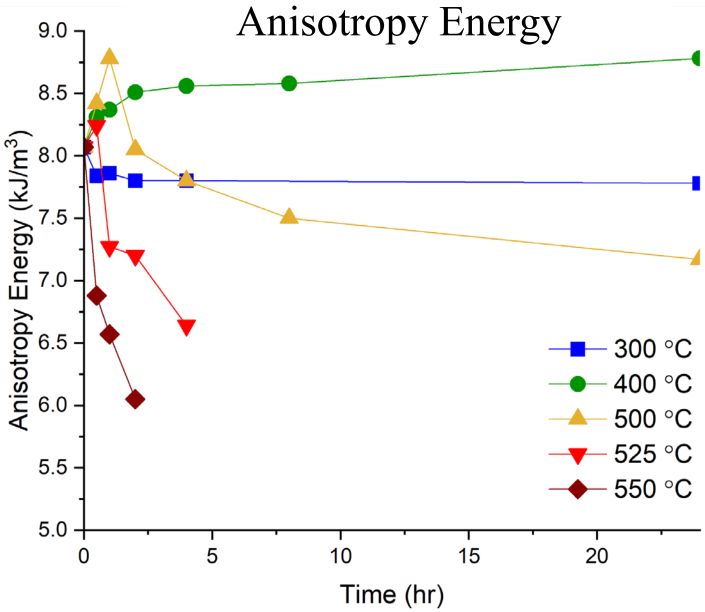
High K_u of Co-based alloys enables gapless inductors, ideal for extreme-T (> 300 °C) applications since potting resin not required

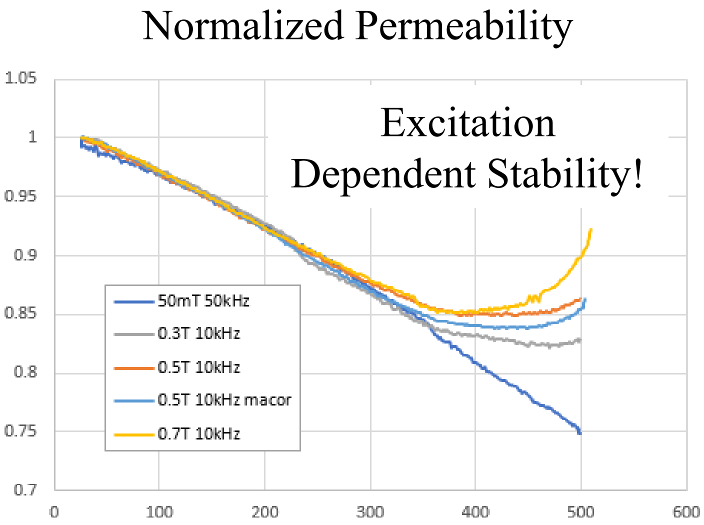


Gapped Inductor
(L controlled by d)



Ungapped Inductor
(L controlled by μ)


Anisotropy Energy


Normalized Permeability

Excitation Dependent Stability!

Courtesy: A. Leary, NASA

Leary et al. (2016) “Stress induced anisotropy in Co-rich magnetic nanocomposites for inductive applications”. *J Mat. Res.* **31**

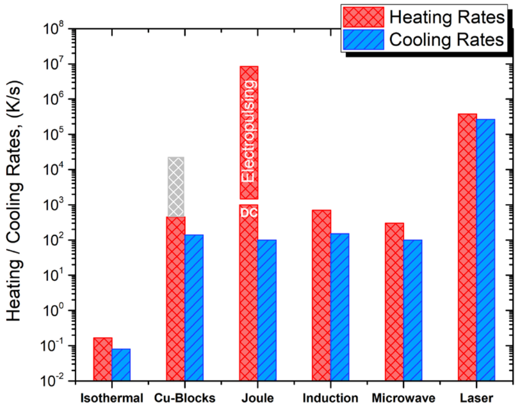
Temperature Stability of Permeability May Be the Ultimate Limiting Factor for Elevated Temperature Operation

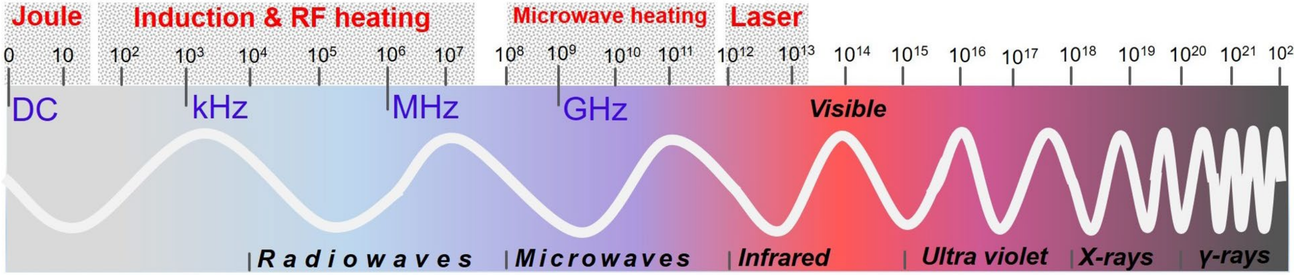
Talaat A, Ohodnicki PR et al, J Alloys Compd 2020:156480.

Alternative: Electromagnetic Field Processing

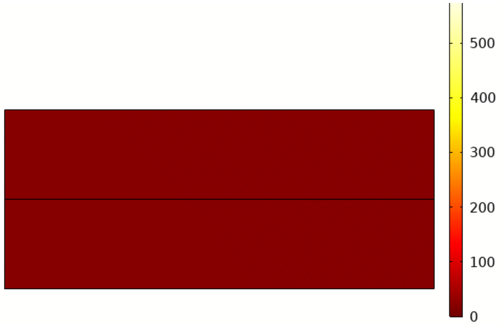
Bulk Ingot → **Rapid Solidification** → Amorphous Ribbon → **Annealing** → Nanocomposite Ribbon

Electromagnetic Field Assisted Processing





Induction Heating



Laser processing
(FEM Modeling)

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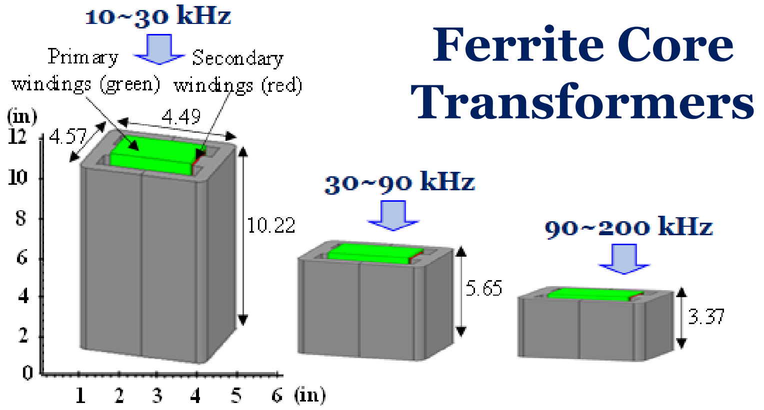
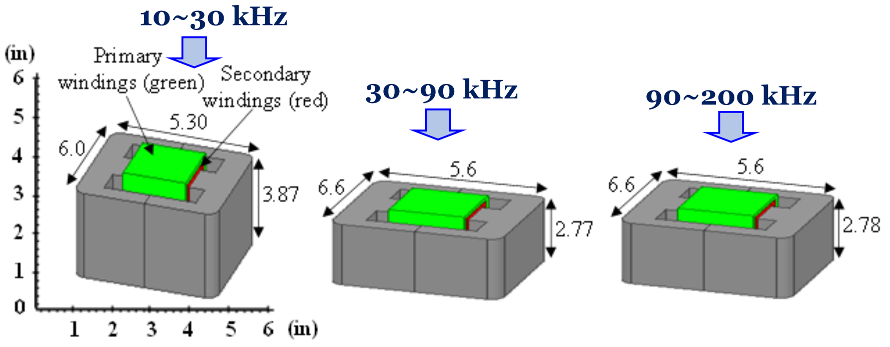
Electromagnetic Field Assisted Processing Methods are a Major Focus of our Efforts to Optimize Controlled Thermal Processing at Scale.

Ferrite and Nanocrystalline Materials Trade-Off for Medium Frequency Transformers Designs

Ferrite Core Transformers

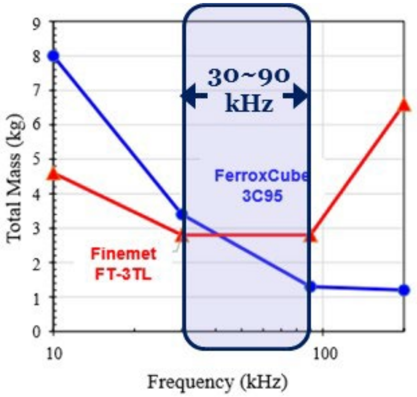


Nanocrystalline Core Transformers

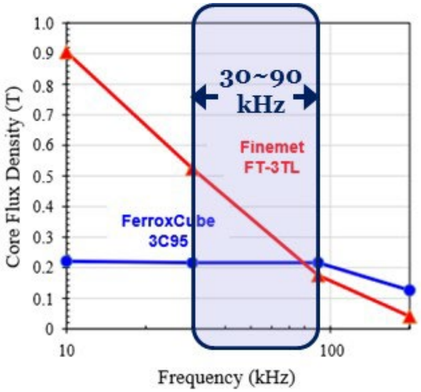


Size Reduces with Increasing f

Diminishing Returns to Size Reduction

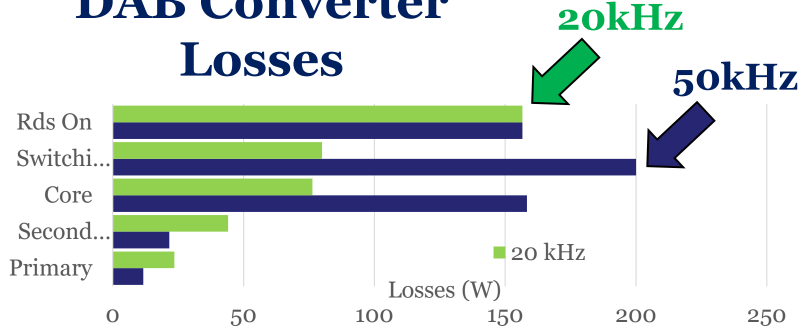


Total Mass



Flux Density

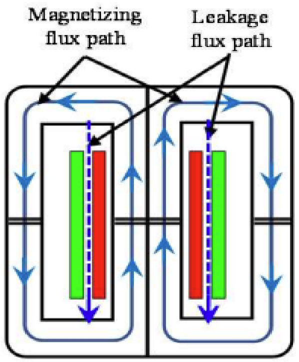
DAB Converter Losses



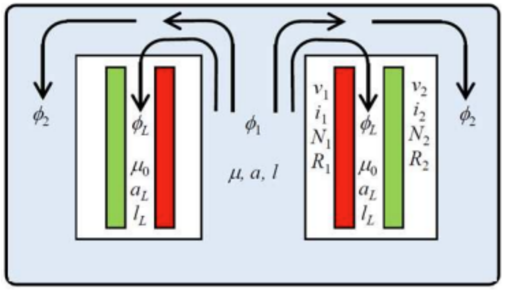
Converter Efficiency Prefers Lower f

Trade Studies Show Cross-Over Frequency of Ferrites vs. Nano

Leakage Loss Modelling using Nanocrystalline Core Design



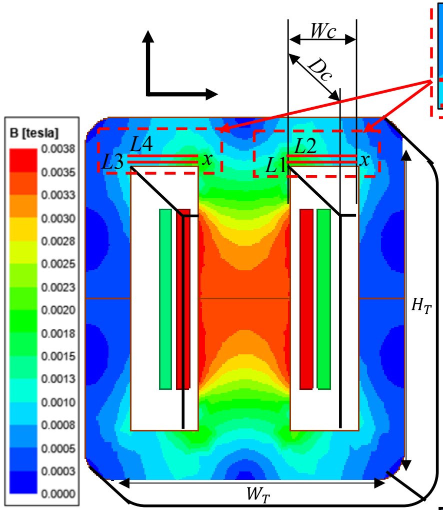
Magnetizing and Leakage Flux Path

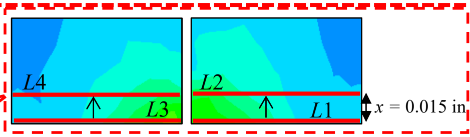


Equivalent Transformer Layout with Leakage

Design Specifications

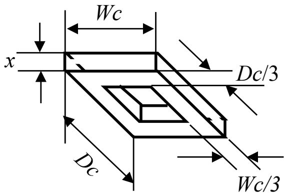
Parameters	Design Value
Base Material	Finemet FT-3TL
Frequency [kHz]	90
Flux Density (Peak) [T]	0.175
Core Density [kg/m^3]	7300
Total Mass (core + coil) [kg]	2.8
Primary Voltage [V]	1131.4 (peak), 800 (RMS)
Primary Current [A]	50.3 (peak), 35.56 (RMS)
Output Power [kW]	28
Primary Turns	10
Secondary Turns	10





Flux Distribution (with shorted sec.)

Total Height, H_T [in]	5.6
Total Width, W_T [in]	6.6



Ribbon Surface Eddy Current Path Diagram

Leakage Loss Results

Parameters	Analytical Result	Numerical Result	Δ
Leakage loss [W]	60.1	57.02	-5.1%

Leakage Loss Investigation

Flux Density [T]		A_E [in^2]	R_E [Ω]	P_E [W]
BL_1	0.0026	6.40E-04	1.08	57.02
BL_2	0.0021			
BL_3	0.0025			
BL_4	0.0021			

Calculation Method[1]

Eddy current path resistance, $R_E = \dfrac{l}{\sigma a}$ (3)

Voltage, $V_E = A_E \dfrac{d(B_p)}{dt}$ (4)

Eddy current loss, $P_E = \dfrac{1}{2}\dfrac{V_E^2}{R_E}$ (5)

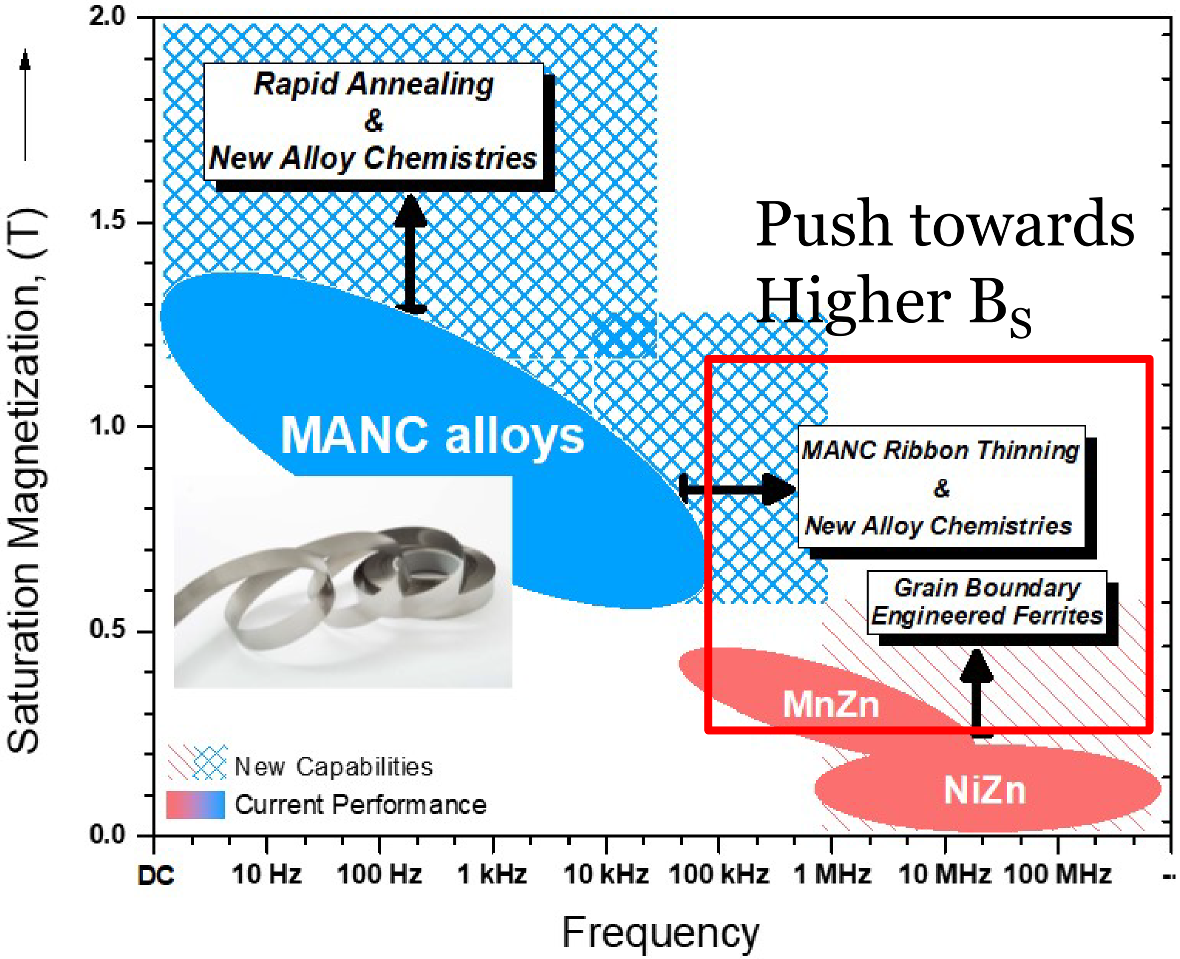
Total eddy current loss, $P_E = 4(P_{E1} + P_{E2})$ (6)

[1] M. A. Juds, “Practical Magnetic and Electromechanical Design: If I were a flux line, where would I go?,” Milwaukee, WI, USA , 2020..

Leakage Flux Losses Play a Critical Role in Cross-Over Frequency

A. Talaat, P.R. Ohodnicki, Jr et al,
Journal of Alloys and Compounds (2021).

Ferrite Based Soft Magnetics (UWBG Magnetics)



Push towards Higher B_S

Why Mn-Zn / Ni-Zn Ferrites?

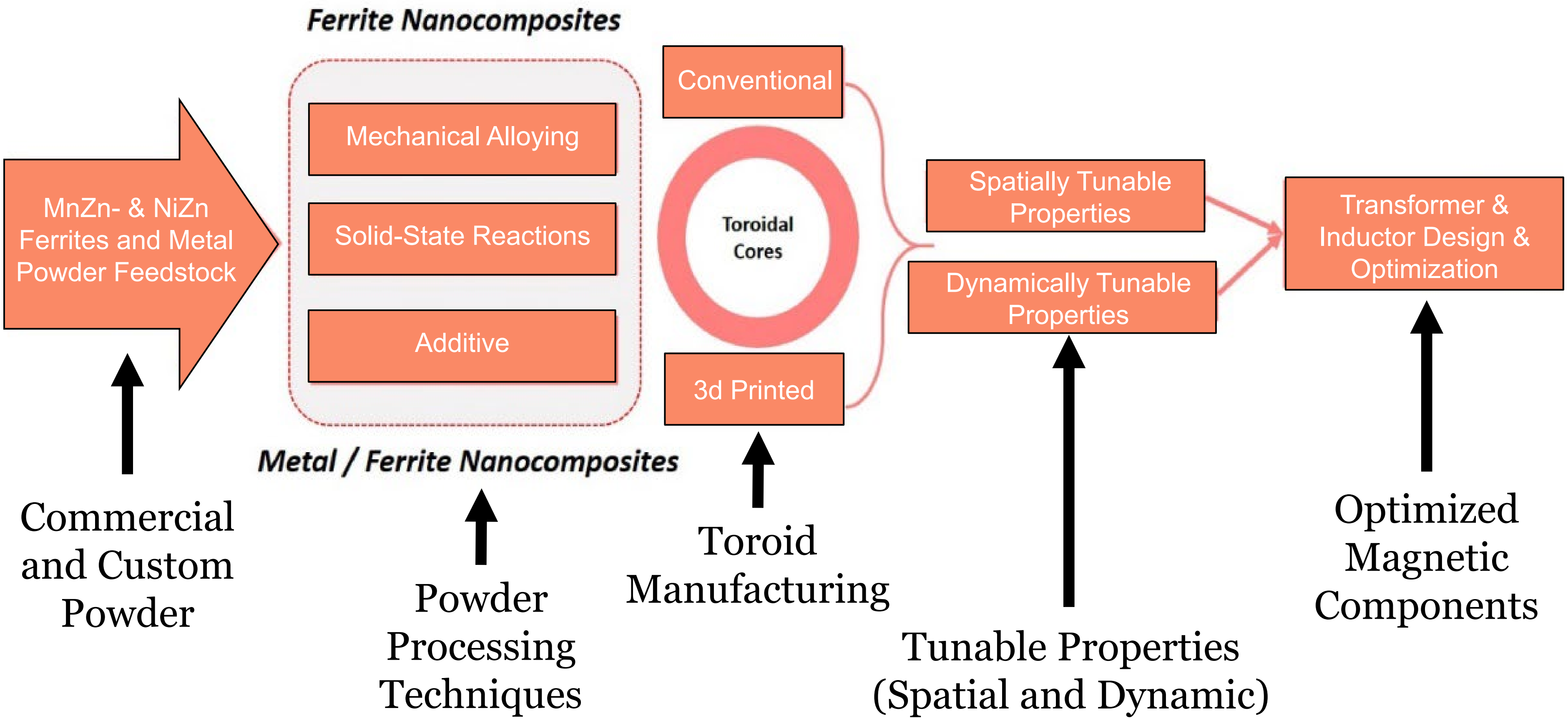
- **High resistivity**
- **Low K**
- **Low λ_s**

Ferrites Suffer Low Saturation Flux Densities

Exploring the Possibility of using Novel Ferrites and Nanocomposite Materials for Achieving Higher Flux Densities

New Ferrite Based Materials with Higher Flux Density Would Enable a New Class of Ultra-Wide Bandgap Semiconductor Devices

Ferrite Based Nanocomposites (UWBG Magnetics)



Project Work is Targeting to Combine Powder Processing and Advanced Manufacturing with Advanced Design and Optimization

Typical Processing Route of Ferrites

Mix Raw Materials (Fe_2O_3, MnO, & ZnO) → Ball Milling → Pre-Firing → Ball Milling → Pressing → Sintering 1300 C

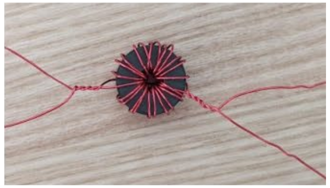
Mix
&
Ball Mill 1

Pre-Fire
&
Ball Mill 2

Die Pressing Set

Pressed
Core

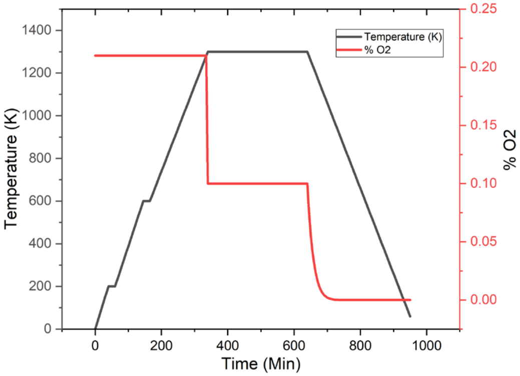
Sintered
Core



Wound Core
Ready for
Core Loss Testing

Important Sintering Parameters

1) Sintering time
2) Sintering temperature
3) PO_2 Control

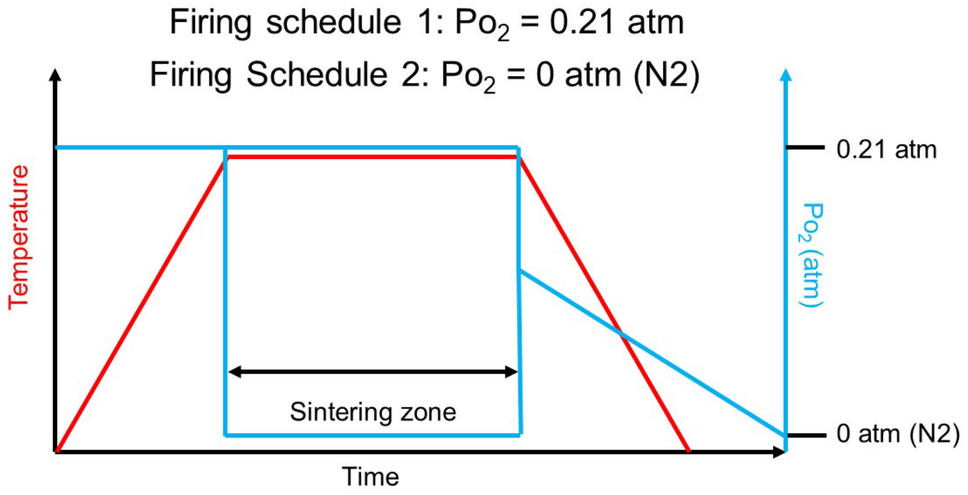


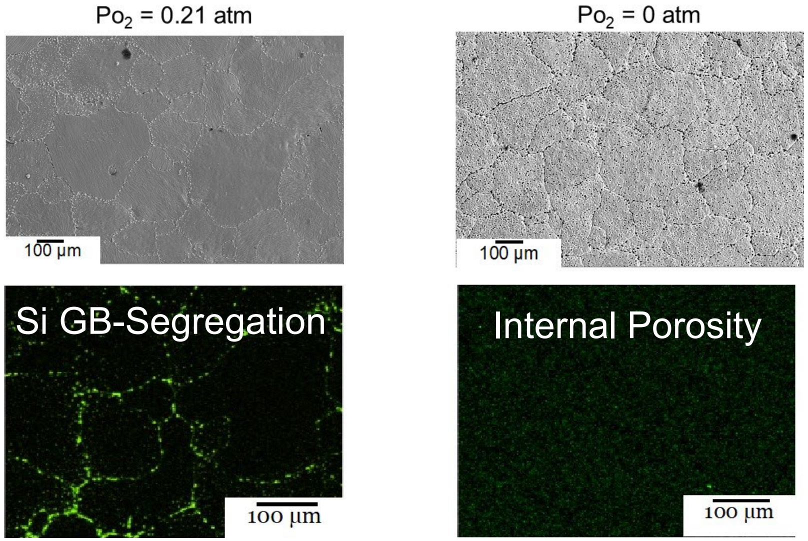
Dependent Properties

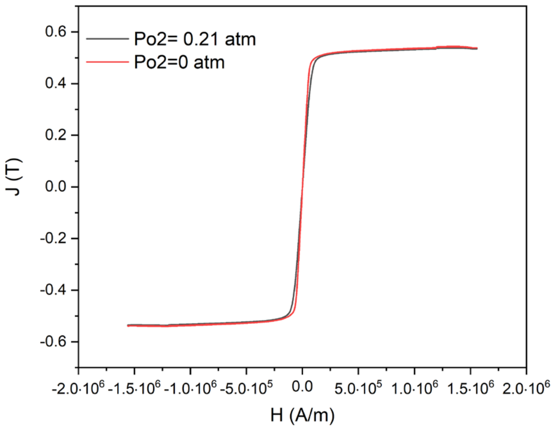
1) Grain size
2) Density
3) Zinc loss

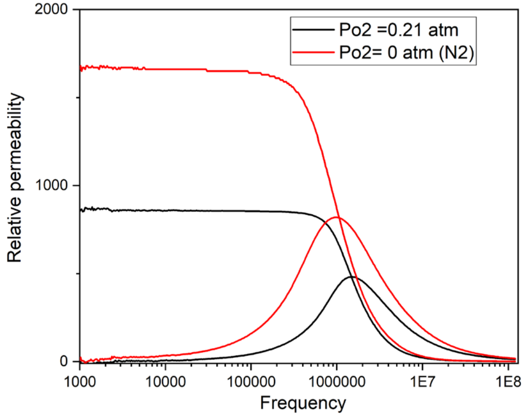
Mn-Zn ferrites are produced via powder processing routes.
Processing parameters play a major role in final properties.

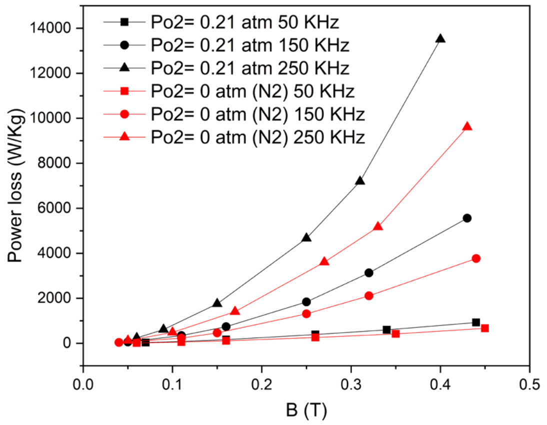
MnZn Ferrite Example : Sintering pO2 Dependence







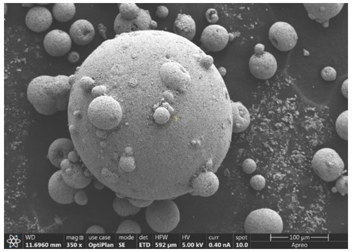




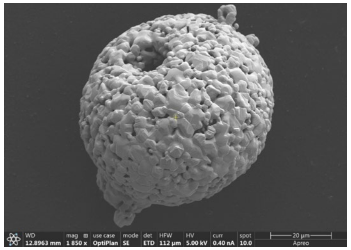
Value of pO_2 During Sintering Has Major Impacts on Permeability and Losses

Additive Manufacturing of Ferrites

Feedstock Preparation

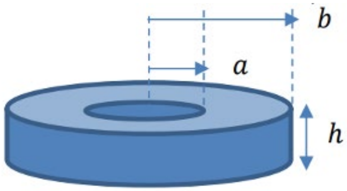


Spray dried powder



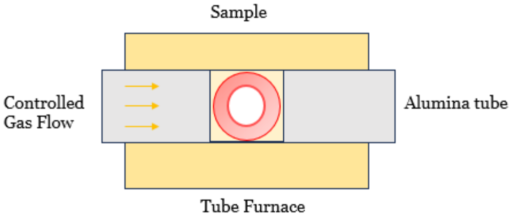
Fully Reacted powder

3D Printing

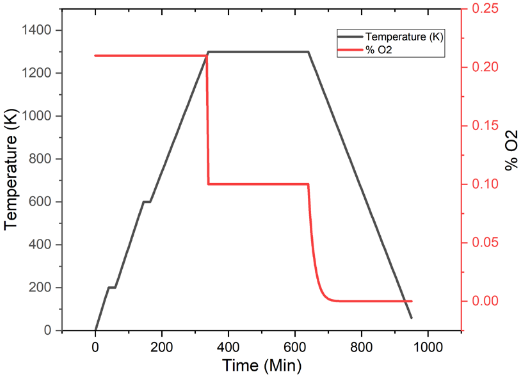


SD 53-75

Sintering in Conventional Furnace

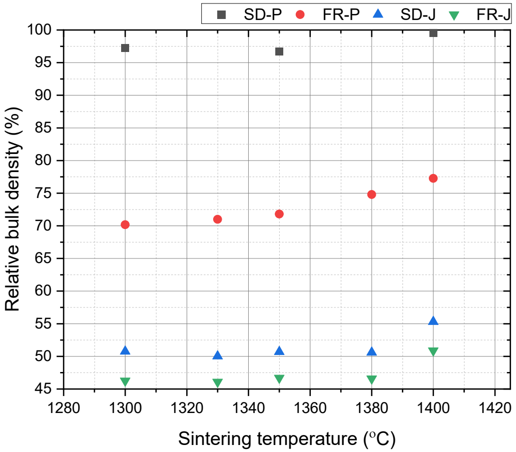


$$p_{O_2}\big|_{eq.,T} = \exp\frac{\Delta G^\circ}{RT}$$

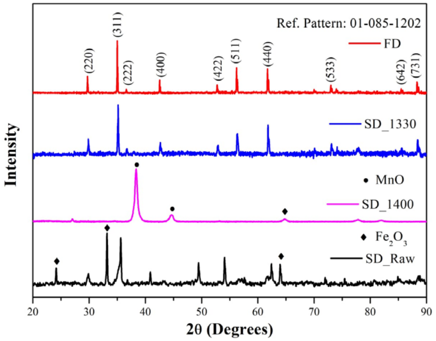


Atmosphere dictates: Microstructure & Phase purity, Properties such as permeability, resistivity and other

Initial Results



Density Vs Temperature



Peak analysis and Phase detection

Initial Efforts Have Successfully Developed Manufacturing Pathways for MnZn-based Toroidal Cores Using Additive Manufacturing Methods

Additional Design Considerations : UWBG Magnetics

High-Frequency Specific Loss/Ferrite Core Models Within MATLAB Code

Integration of Commercial Ferrite Core Properties/ Additional Losses

Magnetic Core Losses: Hysteretic, Eddy Losses

Conductor Winding Losses: Proximity and Skin Effects

Validate High Frequency Physics Assumptions Via Commercial Software

Custom, Experimental Hardware for Further Validation

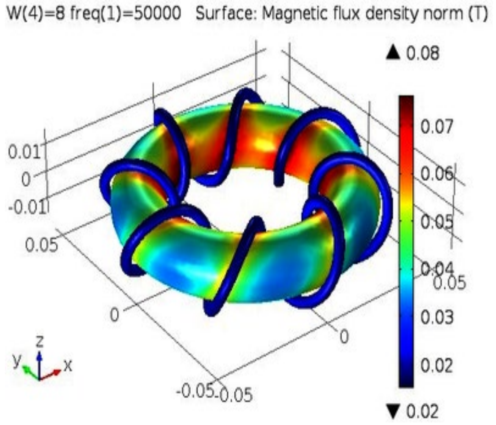


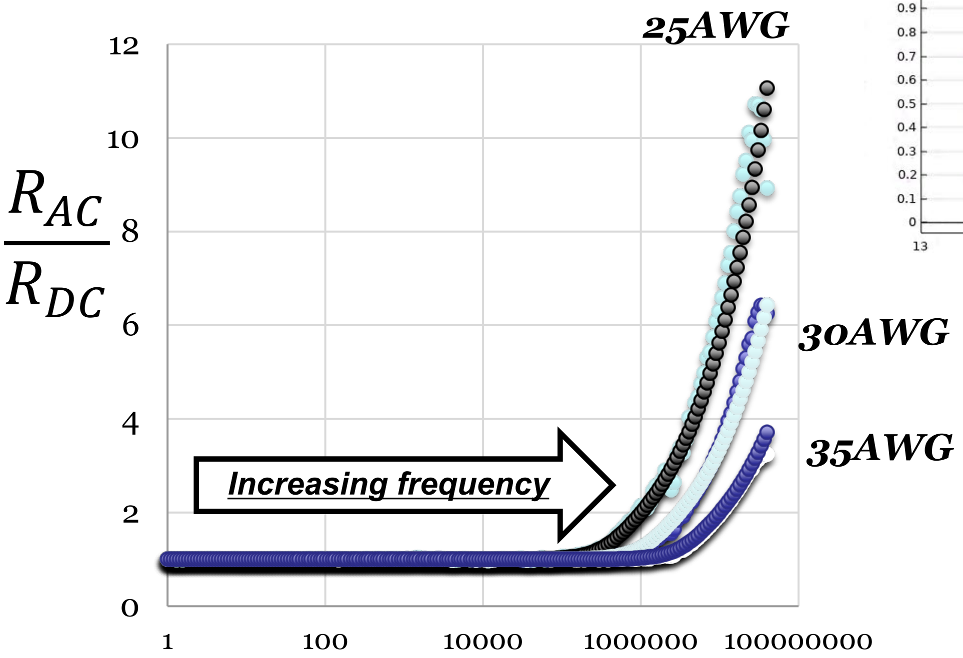
Figure: Calculation of Inductance of Sparsely Wound Toroidal Coils
https://www.comsol.com/paper/calculation-of-inductance-of-sparsely-wound-toroidal-coils-36322

A Holistic Approach to High Frequency Magnetic Component Design is Required for UWBG Applications

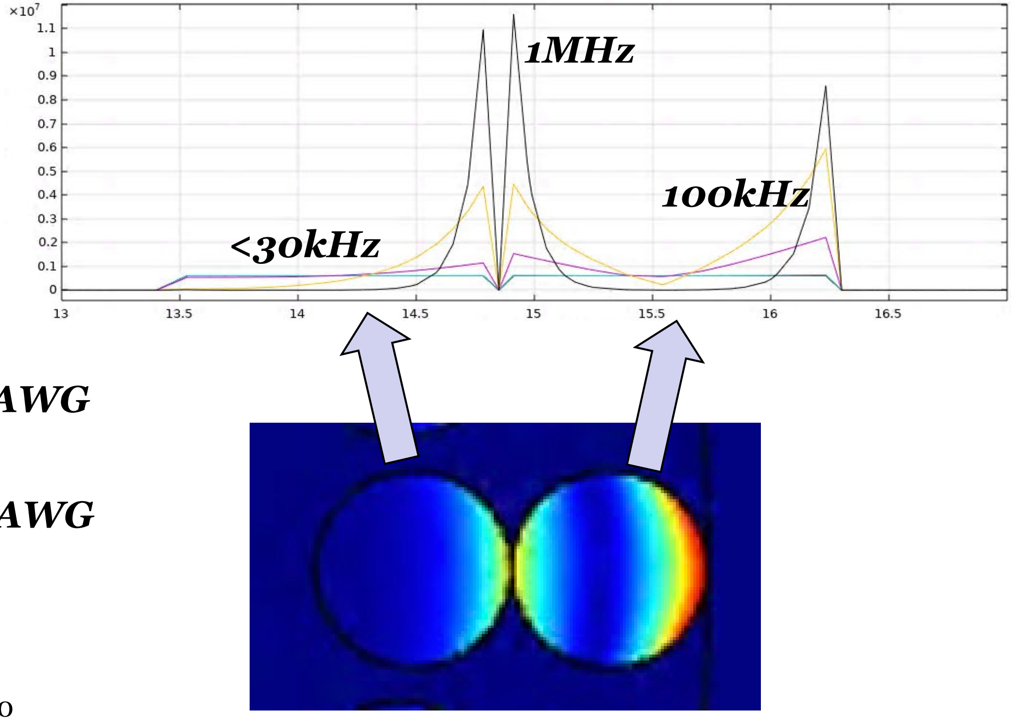
AC Winding Loss in UWBG Magnetics

- Skin Effect Modeling
- Proximity Effect Modeling

Estimating Resistance using Bessel Functions



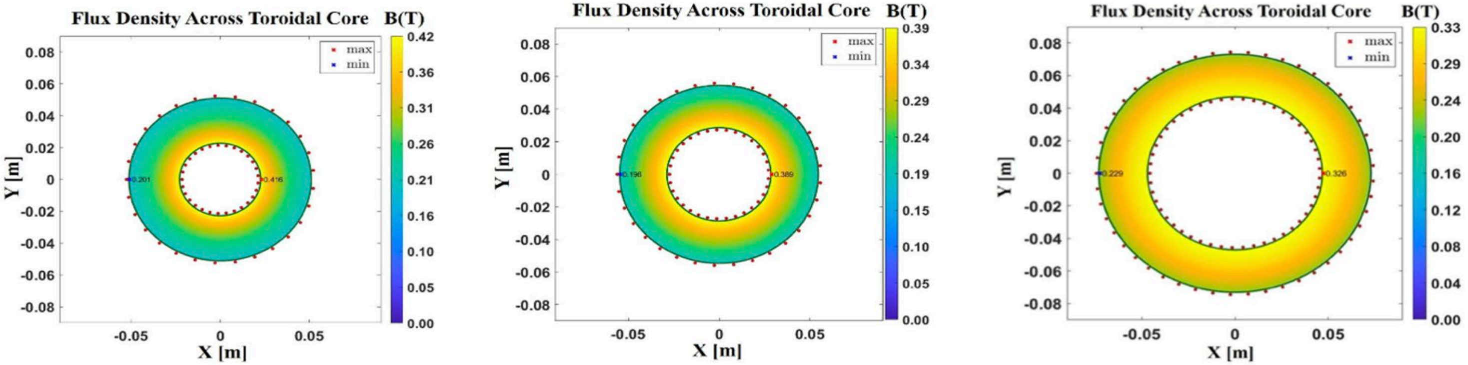
Current Density



Modeling High Frequency Winding Resistance Loss

Understanding and Improving AC Winding Loss Models

Parasitic Capacitance in UWBG Magnetics

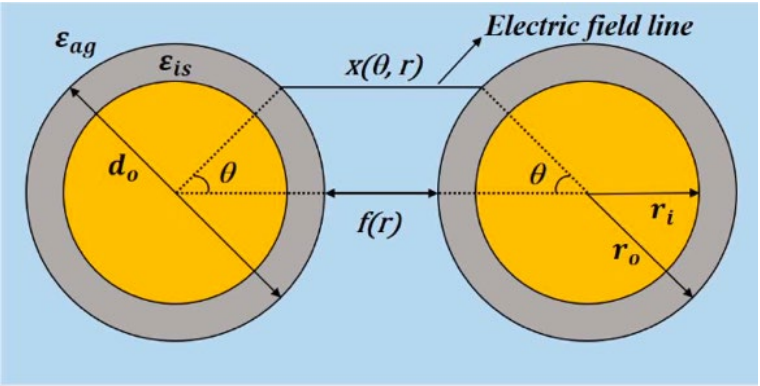


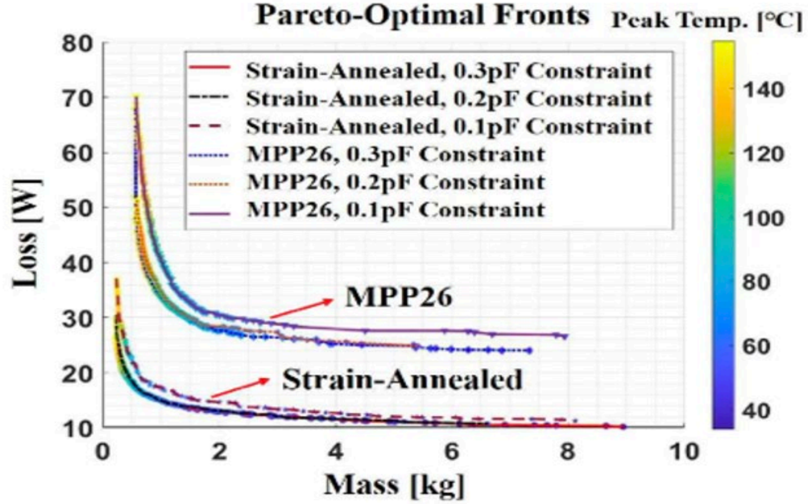
0.19 pF

0.16 pF

0.1 pF

Stricter Capacitance Constraint ***Larger Size / Mass***





Modeling Capacitance of Windings and Impacts on Component Design

Understanding and Improving AC Winding Loss Models

University of Pittsburgh

AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

Educational Initiative: AMPED Consortium

AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

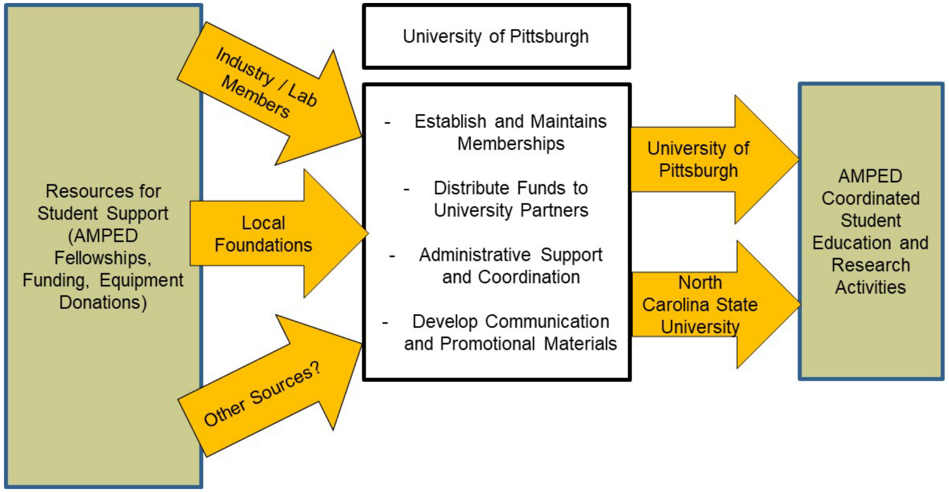
University of Pittsburgh

NC STATE UNIVERSITY

http://engineering.pitt.edu/AMPED

For Information or To Get Involved

Contact : AMPED@pitt.edu



Resources for Student Support (AMPED Fellowships, Funding, Equipment Donations)

Industry / Lab Members

Local Foundations

Other Sources?

University of Pittsburgh

- Establish and Maintains Memberships
- Distribute Funds to University Partners
- Administrative Support and Coordination
- Develop Communication and Promotional Materials

University of Pittsburgh

North Carolina State University

AMPED Coordinated Student Education and Research Activities

Charitable Contributors

Ansys

Computer Aided Technology

Keysight Technologies

Lake Shore Cryotronics

Omicron Lab

TestEquity

Brockhaus Measurements

Full Participants

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Naval Reactors

Powdermet Engineered Powder Technologies

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RCT Systems

Garrett Advancing Motion

Full Participant	Consortium Advisor	Charitable Contributors
• Participant Agreement Signed along with Participation Fee • Contribution to research road mapping and center initiatives • Project voting rights, helping to direct funds to projects of most interest • Early reports on research results • Attendance at Technical Seminars • Inclusion on AMPED Website as "Founding Participant " (https://pittamped.github.io/Founding-Participants.html)	• Attendance at Technical Seminars • Input towards research road mapping, but no voting rights • Inclusion on AMPED Website as "Consortium Advisors" (https://pittamped.github.io/Industry-Advisors.html)	• Tax Benefits • Inclusion in Promotional Materials • Attendance at Technical Seminars • Inclusion on AMPED Website as "Equipment Suppliers" (https://pittamped.github.io/Equipment-suppliers.html)

Annual Workshop August 15th, 2023

An Established Consortium Pursues Workforce Development, Research, and Industry Support in Advanced Soft Magnetic Materials and Components.

Educational Initiative: AMPED Consortium

AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

University of Pittsburgh

NC STATE UNIVERSITY

<u>August 15th, 2023</u>

Energy Innovation Center
Pittsburgh, PA

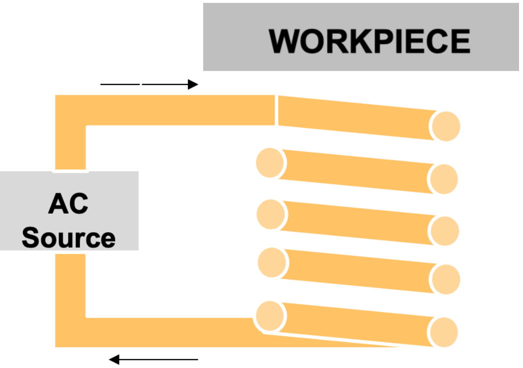
Email : AMPED@pitt.edu

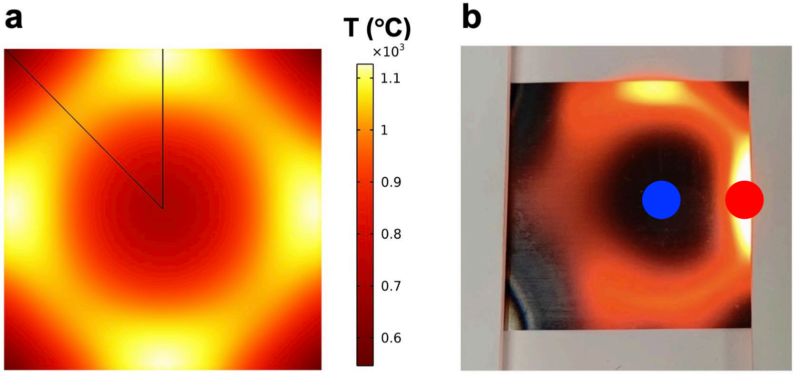
http://engineering.pitt.edu/AMPED

An Established Consortium Pursues Workforce Development, Research, and Industry Support in Advanced Soft Magnetic Materials and Components.

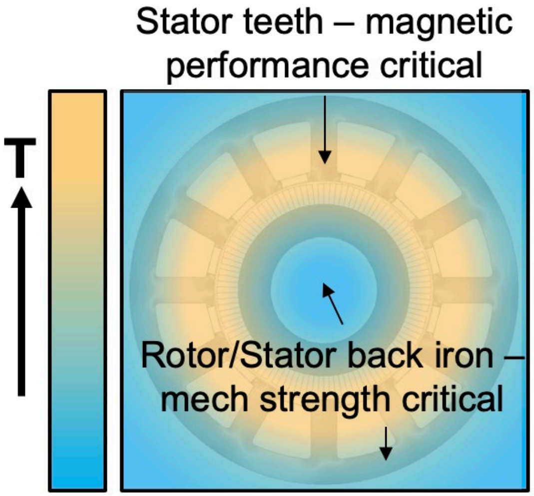
Example AMPED Research Topic: Spatially Tuned Motor Laminations w/ Induction

Transverse induction annealing can produce spatially tuned properties which overcome the tradeoff in magnetic vs. mechanical properties in bulk alloys



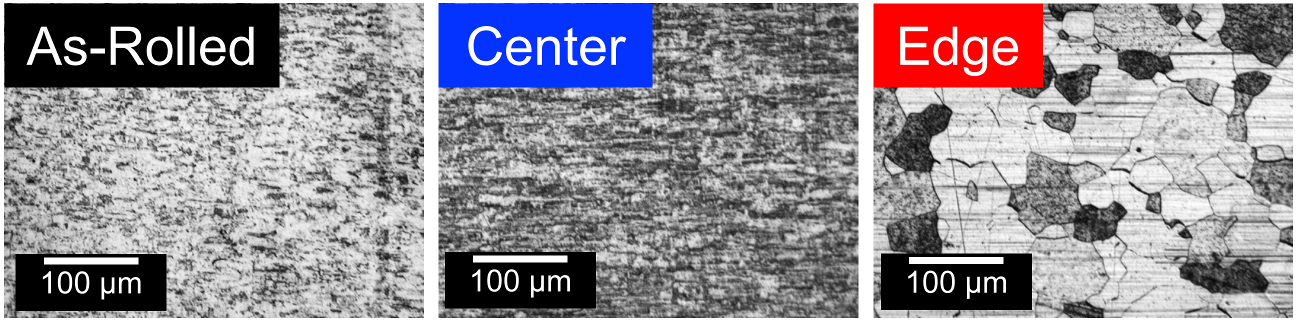


	C	E
H_c (A/m)	2130	415
HRC	52.6 ± 2.5	26.2 ± 2.9



Stator teeth – magnetic performance critical

Rotor/Stator back iron – mech strength critical



[In progress] T. Paplham et al. "Spatially tuned properties in a bulk Fe-Co alloy via transverse induction annealing and feasibility study for stator application"

Conclusions and Future Perspectives

- Emerging Applications Drive Needs in New Soft Magnetic Materials

- Nanocomposites Offer Unique Opportunity for Device Optimization

- Metallic Nanocomposite Alloys are Ideal for WBG Applications
    - Gapless Magnetics Enables Manufacturability and Mitigates Gap Losses
    - Novel Alloy Systems Enable In-Line Processing and "Permeability Engineering"
    - In-Line Processing Methods + Electromagnetic Field Processing Enables Scalability

- Novel Ferrite Based Materials are of Interest for UWBG Applications
    - High Quality Ferrite Core Manufacturing and Characterization Developed to Date
    - Several Novel Manufacturing Pathways Currently Being Explored

- AMPED Consortium Seeks to Pursue Targeted Workforce Development Efforts

Contact: 412-973-4416, pro8@pitt.edu (University of Pittsburgh)