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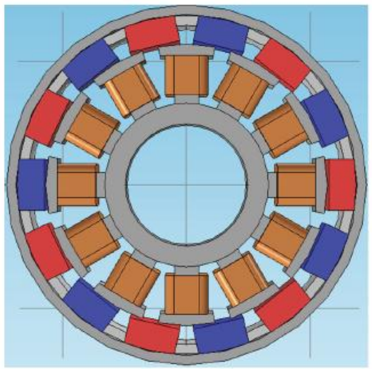
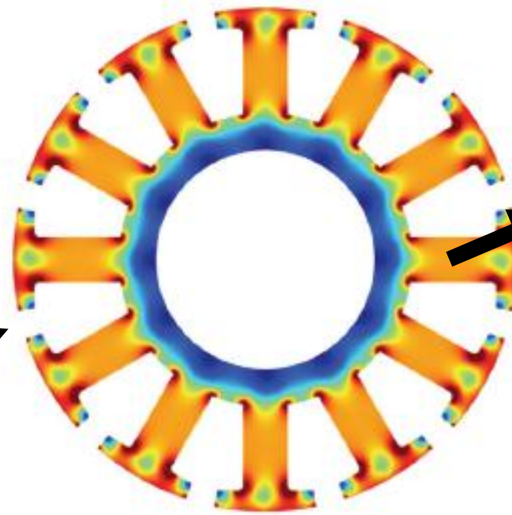


Fig. 1. Basic components of the demonstrator machine: 14-pole outer rotor and inner stator with 12 slots and distributed LRK winding.

Si steel stator



Journal of ELECTRONIC MATERIALS
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Soft Magnetic Alloys for Electrical Machine Applications: Basics, State-of-the-Art, and R&D Opportunities

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Dr. Paul Ohodnicki, Materials Scientist / Team Lead

Electrochemical and Magnetic Materials Team
Functional Materials Development Division
NETL Office of Research and Development

U.S. DEPARTMENT OF ENERGY

Overview of Presentation

- Basic of Soft Magnetic Materials for Electrical Machinery
  - Soft Magnets for Inductive Applications
  - Losses in Soft Magnets : Hysteresis and Eddy Currents
  - Interplay Between Mechanical and Magnetic Properties

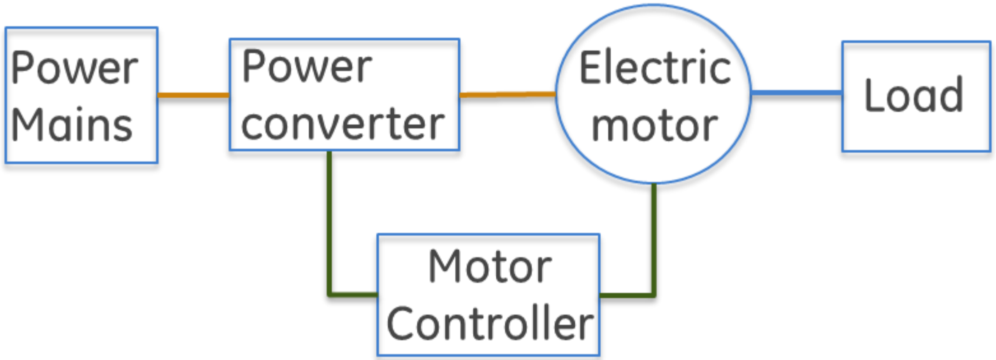
- Engineering Approaches for Soft Magnets in Electrical Machines
  - Bulk Crystalline Alloys
  - State of the Art and Emerging Materials

- Summary and Opportunities / Needs for Future Research
  - Short Term: Compatible with Existing Manufacturing
  - Intermediate Term: Requires Modifications to Manufacturing Processes
  - Long Term: Requires Major Modifications to Manufacturing Processes

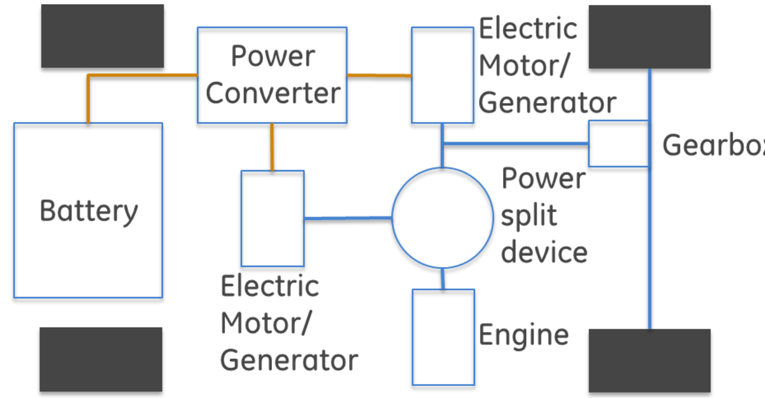
Basics of Soft Magnetic Materials for Electrical Machinery

Soft Magnetic Materials for Inductive Applications

Megawatt-scale industrial drive



10-100 kilowatt HEV traction drive



Magnetic components are critical to the performance of

- **Power converters (inductors & transformers)**
- **Electric motors and generators (laminates and permanent magnets)**

Electrical Machines:

Machine Power *= Speed x Thermal Utilization x Magnetic Utilization x Volume*

High strength rotor

Low core loss, high thermal conductivity material

High magnetic saturation/energy product material

Underlined = Soft Magnetic Materials

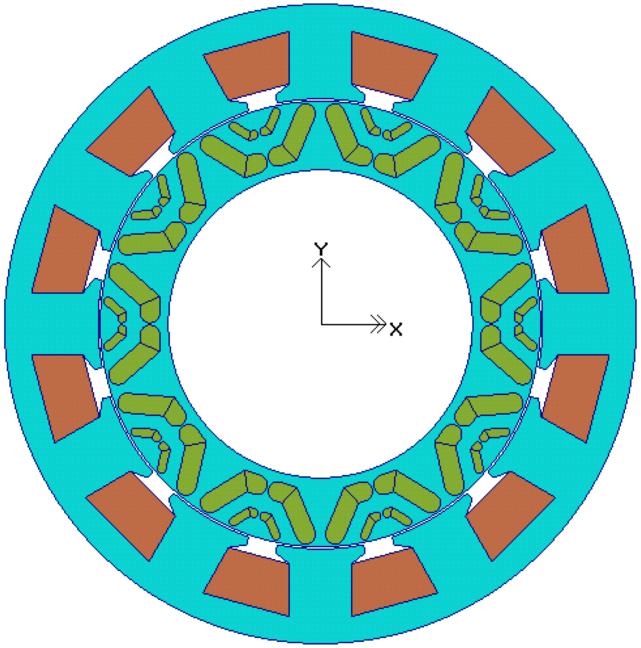
Courtesy of F. Johnson, GE Global Research

Soft Magnetic Materials for Inductive Applications

Advanced electric machines
- Higher efficiency
- High power density

Performance parameters
- Higher speeds
- Higher operating temperatures
- Lower eddy currents

Material requirements
- Higher electrical resistivity
- Higher tensile strength
- Lower power loss



Schematic of internal permanent magnet motor
- *Permanent magnets*
- *Silicon Steel laminates*
- *Copper windings*

Relevant Soft Magnetic Materials Require a Combination of :

(1) Mechanical Properties (Yield, Ductility, Creep / Fatigue Strength**)**

(2) Magnetic / Electrical Properties (Saturation Magnetization, Coercivity, Resistivity**)**

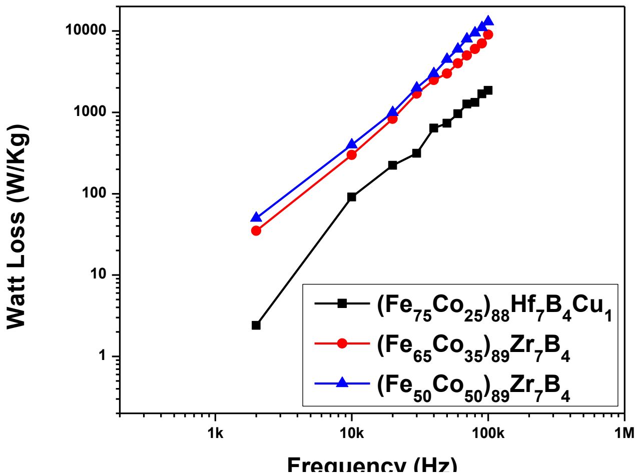
(3) Thermal Conductivity

Alternative materials must compete with M-19 3% Si steel at $2/kg

Courtesy of F. Johnson, GE Global Research

Soft Magnetic Materials for Inductive Applications

Faraday's Law of induction:



$$P_t = kf^{\alpha}B^{\beta}$$

Increased Losses at Elevated Frequency
(Rapid Switching and Eddy Currents)

$$\epsilon = -d\Phi/dt$$

ϵ ← *electromotive force*; $d\Phi$ → *time-changing magnetic flux*

$$\Phi = \mathbf{B} \cdot \mathbf{A}$$

$\mathbf{A}$ → *area*

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

flux density (induction) → $\mathbf{B}$; μ_0 ← *permeability of free space*; $\mathbf{H}$ ← *magnetic field*; $\mathbf{M}$ ← *magnetization*

<u>Power Transformers</u>

<u>Electric Motors / Generators</u>

Power = Voltage • Current or Torque • Rotation speed

Higher Frequency Magnetic Switching and Higher Flux Swings Yield a Roughly Proportion Reduction in Overall Volume for the Same Power Output.

Material / Core Losses Increase with Increasing Frequency.

Courtesy of A. Leary, Carnegie Mellon University

Key Engineering Approaches for Soft Magnetic Alloys

Emphasis on Si Steels

Other Anisotropy Sources — Induced Anisotropy by "Field" or "Stress" Annealing → Rotational vs. Wall Motion Reversal

Iron loss controlling factor

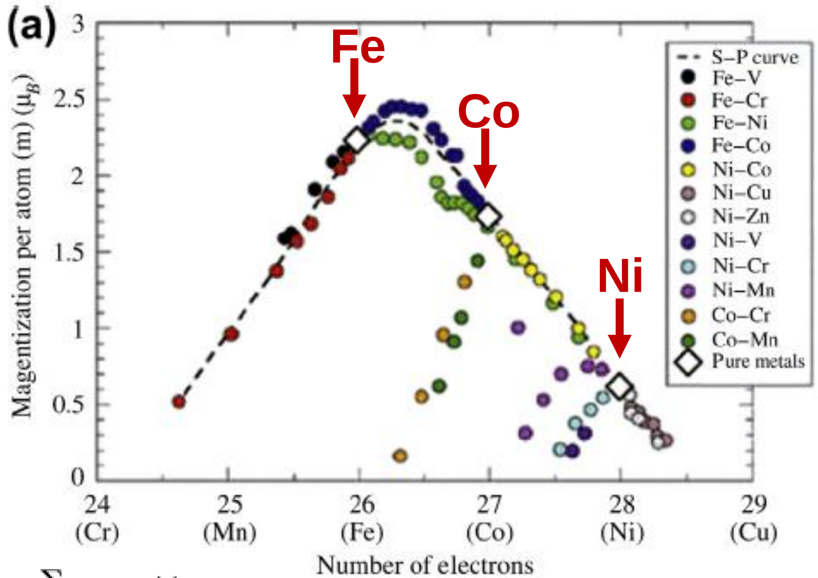
- Iron loss
  - Hysteresis loss
    - Impurities (Precipitates, inclusions): Pinning the domain wall displacement
    - Texture (Grain orientation): Desirable to have as many (100) plane as possible.
    - Grain size: The larger grain size, the smaller hysteresis loss (Larger grain size→Smaller grain boundary density →Easier domain wall displacement)
  - Eddy current loss
    - Electric resistivity (Content of Si, Al, etc.): The greater electric resistivity, the smaller eddy current loss
    - Sheet thickness: The thinner sheet thickness, the smaller eddy current loss
    - Grain size: The smaller grain size, the smaller eddy current loss

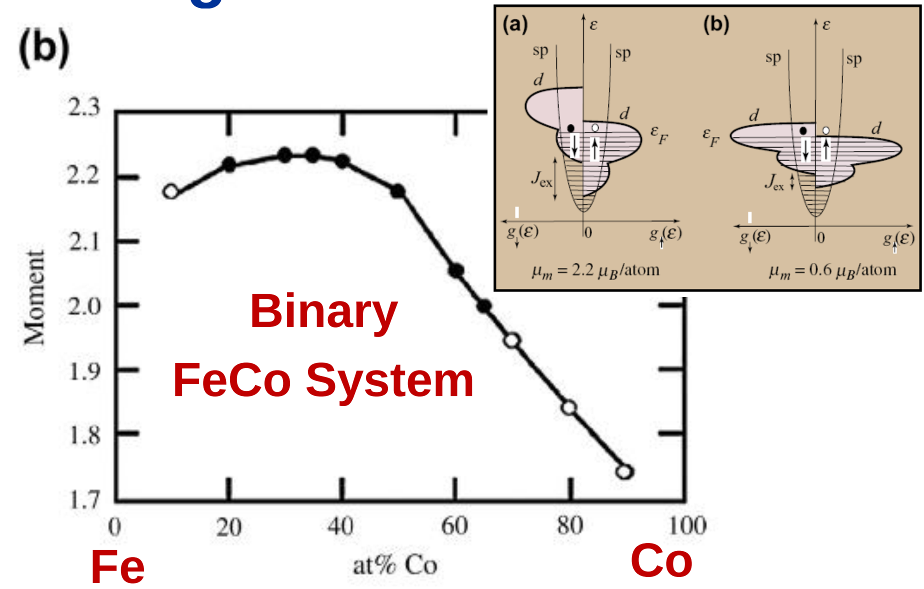
Magnetic flux density controlling factor

- Magnetic flux density
  - Compositions (Content of Si, Al, etc.): When the contents of Si or Al increases, (saturation) magnetic flux density decreases.
  - Texture (Grain orientation): Desirable to have as many (100) plane as possible.
  - **Other Anisotropy Sources**: e.g. Permeability Engineering By Induced Anisotropies Magnetoelastic Anisotropies (Magnetostriction)

Hiroaki Toda
Electrical Steel Research Dept., Steel Research Laboratory, JFE Steel Corporation
December 4. 2013 JMAG User's Conference 2013

Saturation Induction in Soft Magnetic Materials





$$M = \frac{\Sigma_{atoms} \times \mu_{atom}}{V}$$

$M_{Fe} > M_{Co} > M_{Ni}$

$M_{FeCo} > M_{Fe\text{-}C,Fe\text{-}Si} > M_{NiFe}$

Curie Temperature Also Important in Some Applications

Table 3 Structures, room temperature and 0 K saturation magnetizations and Curie temperatures for elemental ferromagnets (O'Handley, 1987)

Element	*Structure*	M_s *(290 K) (emu/cm³)*	M_s *(0 K) (emu/cm³)*	n_B *(μB)*	T_c *(K)*
Fe	bcc	1707	1740	2.22	1043
Co	hcp, fcc	1440	1446	1.72	1388
Ni	fcc	485	510	1.72	627
Gd	hcp	–	2060	7.63	292
Dy	hcp	–	2920	10.2	88

Saturation Inductions of Magnetic Materials are Primarily Dictated by Electronic Structure and Elemental / Alloy Chemistry. Available Soft Magnetic Alloys are Grouped According to Several Archetypal Composition Ranges.

M. E. McHenry and D. E. Laughlin, Magnetic Properties of Metals and Alloys, 2014

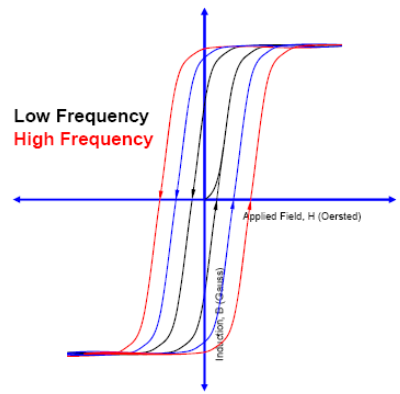
Losses in Soft Magnetic Materials

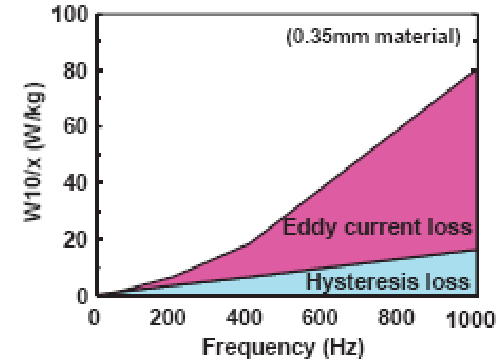
Steinmetz Expression for Core Losses

$$P_{\text{tot}} = C f^{\alpha} B_m^{\beta}$$

Hysteretic Losses — *Eddy Current Losses* — *Anomalous Eddy Current Losses*

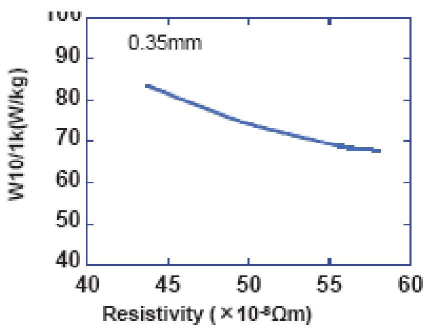
$$P_{\text{tot}} = P_h + P_{ec} + P_{an}$$



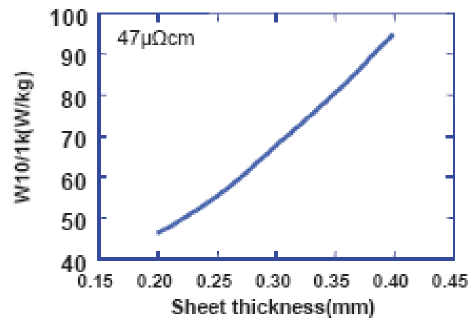


$$P_t = k_h f B_m^{\alpha} K(B_m) + (\sigma/12)(d^2 f/\delta)\int_{1/f}(dB/dt)^2 dt + k_e f \int_{1/f}|dB/dt|^{1.5} dt$$

B_m : peak flux density、 f : frequency, σ : material electrical conductivity
δ : material mass density, d : lamination thickness



Effect of resistivity on iron loss



Effect of sheet thickness on iron loss

Eddy current loss is dominant in the high frequency range.

Theoretical formula of eddy current loss (classical theory)

$$\text{Eddy current loss} = \frac{\pi^2 B^2 f^2 t^2}{6\rho}$$

B: Magnetic flux density
f: Frequency
t: Sheet thickness
ρ: Electric resistivity

Improving method: ① Decreasing the thickness
② Increasing the resistivity

☆ Effect of thickness on iron loss at high frequency is higher than that of resistivity

Losses in Magnetic Materials Can Be Separated into Different Sources:

1) Hysteretic Losses (Microstructure + Magnetic Anisotropy)
2) Classical Eddy Current Losses (Resistivity + Thickness / Geometry)
3) Anomalous Eddy Current Losses (All Above + "Magnetic Structure")

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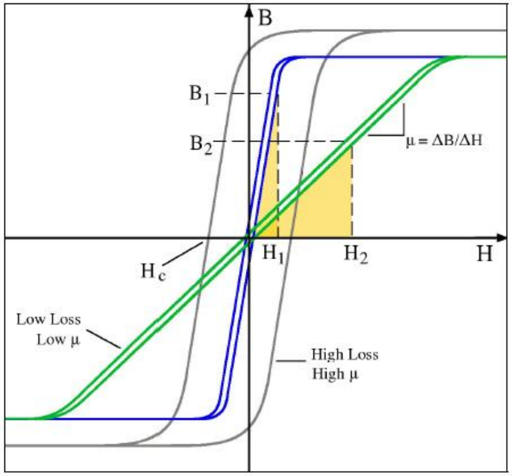
December 4, 2013 JMAG User's Conference 2013

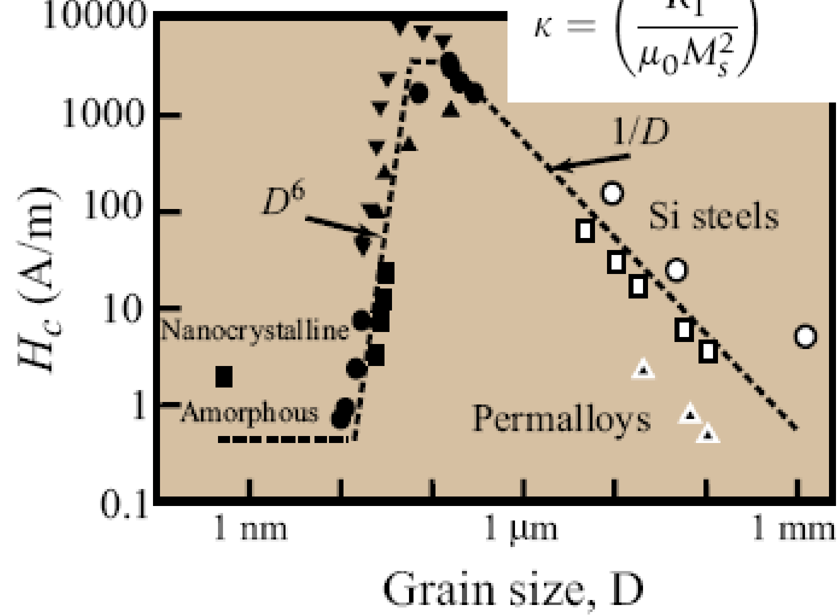
Permeability and Losses in Soft Magnetic Materials



For Bulk Alloys Grain Boundaries and Precipitates Act as Pinning Sites Increasing Losses

"Hardness" Parameter

$$\kappa = \left(\frac{K_1}{\mu_0 M_s^2}\right)^{1/2}$$



Review: M. A. Willard and M. Daniil, Nanocrystalline Soft Magnetic Alloys Two Decades of Progress, Handbook of Magnetic Materials Vol. 21., Elsevier B.V., 2013.

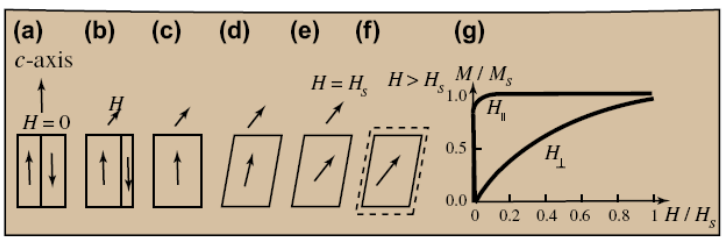


Figure 23 Steps in the magnetization process (a) virgin state, (b) wall motion, (c) monodomain, (d) rotation, (e) saturation and application of a field exceeding that required to saturate. (For color version of this figure, the reader is referred to the online version of this book.)

Hysteretic Losses are Dictated by a Combination of Magnetic Anisotropy / Microstructure and Depend on Reversal Mechanism (Domain Wall Motion vs. Rotation)

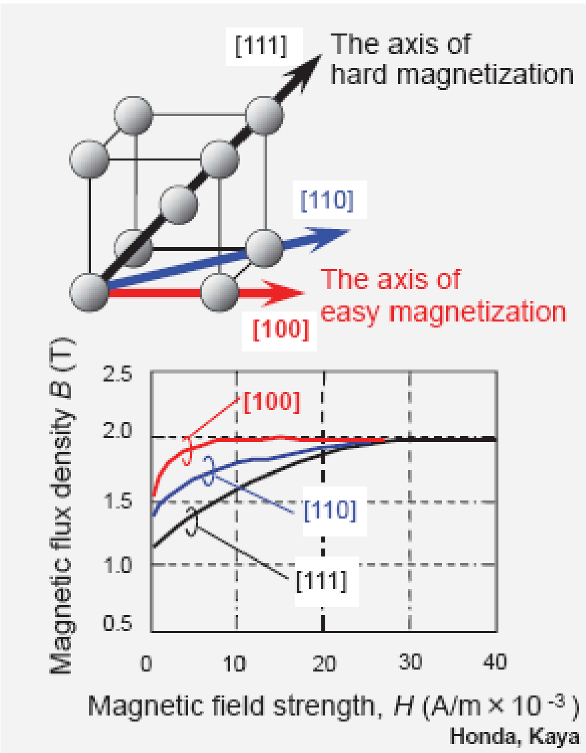
M. E. McHenry and D. E. Laughlin, Magnetic Properties of Metals and Alloys, 2014

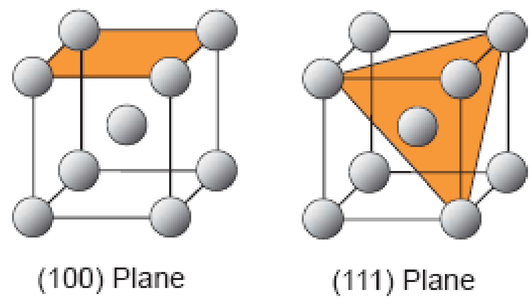
Permeability and Losses in Soft Magnetic Alloys

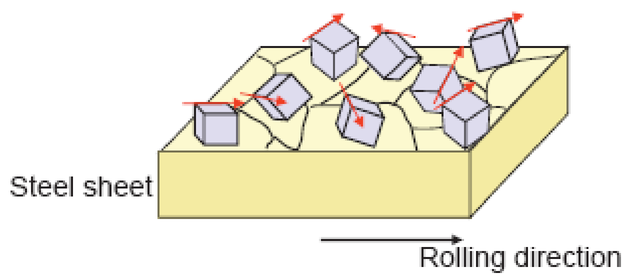
Crystallographic Texturing is a Key Engineering Approach to Minimize Losses and Maximize Permeability

Magnetocrystalline Anisotropy (BCC Fe)

[100] Easy Direction, (100) Easy Plane
[111] Hard Direction, (111) Hard Plane

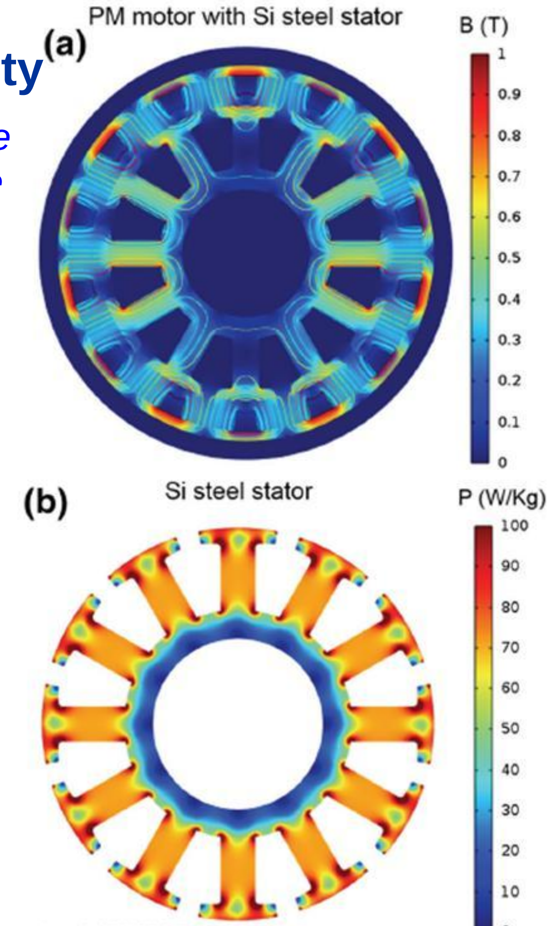






It's desirable to have as many (100) plane as possible, including the axis of easy magnetization. It's vital to minimize (111) plane.

Finite Element Simulations



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Laminates are Not Driven to Saturation in Most Regions, and So "Magnetic Induction" in Electrical Machines is Also Impacted By Permeabilities Which are Highly Sensitive to Microstructure and Processing

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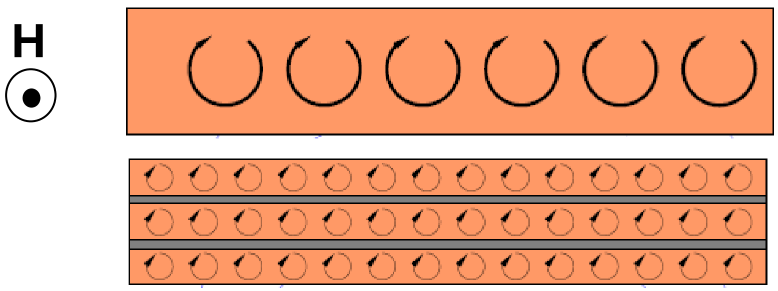
December 4. 2013 JMAG User's Conference 2013

Eddy Current Losses in Soft Magnetic Materials

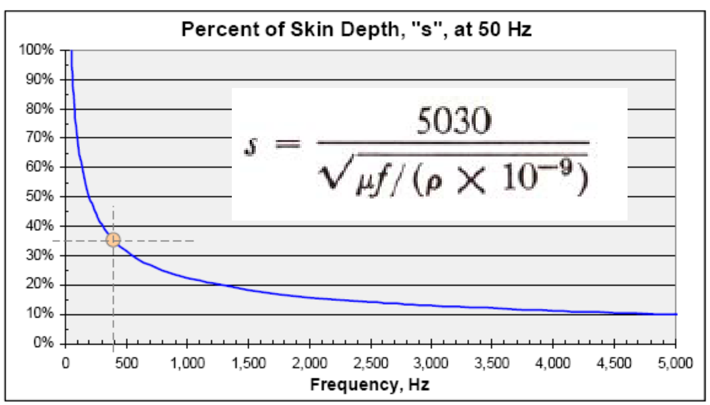
Hysteretic Losses — *Eddy Current Losses* — *Anomalous Eddy Current Losses*

$$P_{tot} = P_h + P_{ec} + P_{an}$$

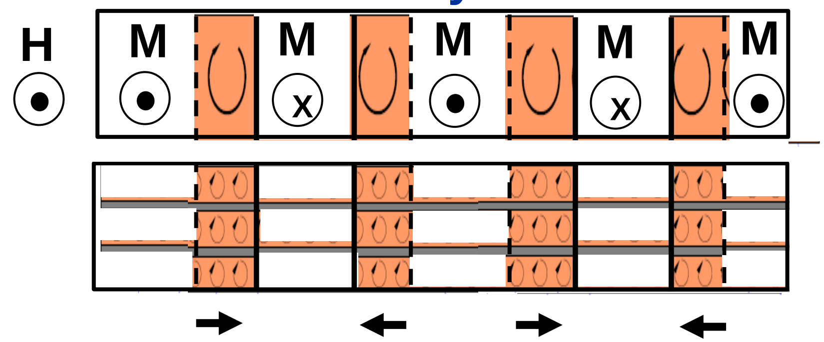
Classical Eddy Current Losses



Laminate Structure with Reduced Thickness and Select High Resistivity Materials



Anomalous Eddy Current Losses



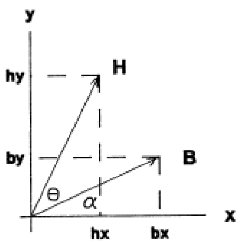
Increase Domain Wall Density to Minimize Wall Velocity and Reduce Localized Losses

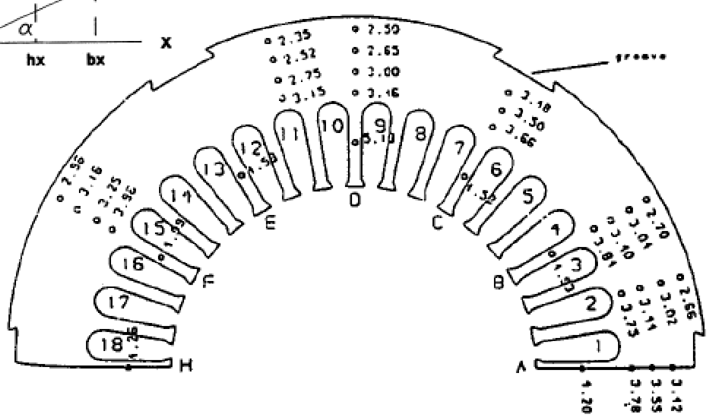
Domain Structure Engineering can Be Accomplished Through Laser / Mechanical Scribing

Classical Eddy Current Losses are Controlled by Geometry / Resistivity.
Anomalous Eddy Current Losses are Highly Sensitive to Details of Magnetization Process Including Magnetic Domain Structure.

S. Constantinides, Arnold Magnetic Technologies, 2009

Rotational Magnetization Processes





Localized loss (W/kg) at various points in the annealed core at 1.0T in stress free condition.

Table 1 Alternating and Rotational Power Loss in Various Materials and Their Ratios

Samples	Alternating power loss (P_{AC}), W/kg	Rotational power loss (P_R), W/kg	P_R/P_{AC}
Nonoriented 2.7% silicon iron	1.40	3.50	2.50
Nonoriented 1.2% silicon iron	1.23	4.00	3.25
Semiprocessed low-silicon iron	1.93	5.53	2.86
Four square 3.0% silicon iron (0.03 mm)	0.70	1.40	2.00
3.2% Goss-oriented silicon iron	0.46	1.84	3.90
Metglas 2605S-2	0.11	0.21	1.90
Powercore strip	0.12	0.130	1.05

Note: All values obtained at 1.0 T and 50 Hz.

Table 3 Estimate of Rotational Losses and the Effect of Reducing the Rotational Loss by 50%

	Volume, %	Mean iron loss, W/kg	Proportion of total loss %	Proportion of total loss W	Proportion of total loss when rotational loss is halved %	Proportion of total loss when rotational loss is halved W
Core back carrying ac flux	28.3	2.63	22	17.6	30	17.6
Core back region carrying partial rotating flux	25.6	2.98	25.9	20.7	19.2	10.4
Core back region carrying rotation flux	27.6	3.64	29.5	23.6	19.8	11.7
Teeth	18.5	4.72	22.6	18.1	31	18.1
Total	100	3.37	100	80	100	58

Note: Three-phase 3-kW star-connected induction motor. Peak stator core back flux density = 1.0 T.

Non-Uniform Field Distributions, Stray Fields, and Rotational Hysteresis Effects Are Particularly Important in Electrical Machine Applications. Rotational Losses Tend to Be Significantly Higher than Alternating.

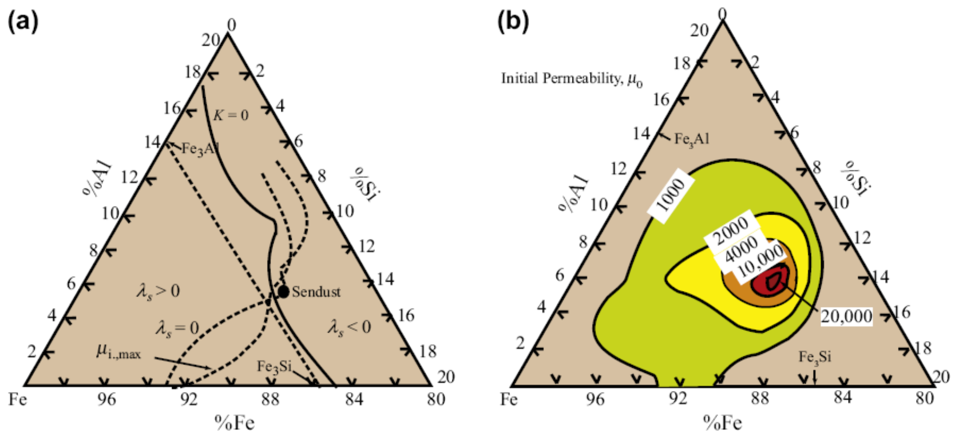
A.J. Moses JMEPEG (1992) 1:235-244

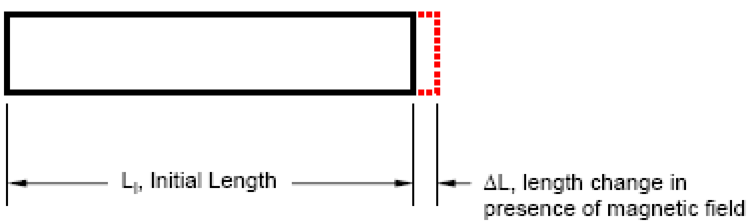
Interplay Between Mechanical and Magnetic Properties

Magnetostrictive Alloys:

-Higher Losses and Lower Permeabilities

-More Sensitive to Stamping / Processing





N. Volbers, J. Gerster: High Saturation, High Strength Iron-Cobalt Alloy for Electrical Machines Proceedings of the INDUCTICA, CWIEME Berlin 2012.

Engineering Mechanical Properties

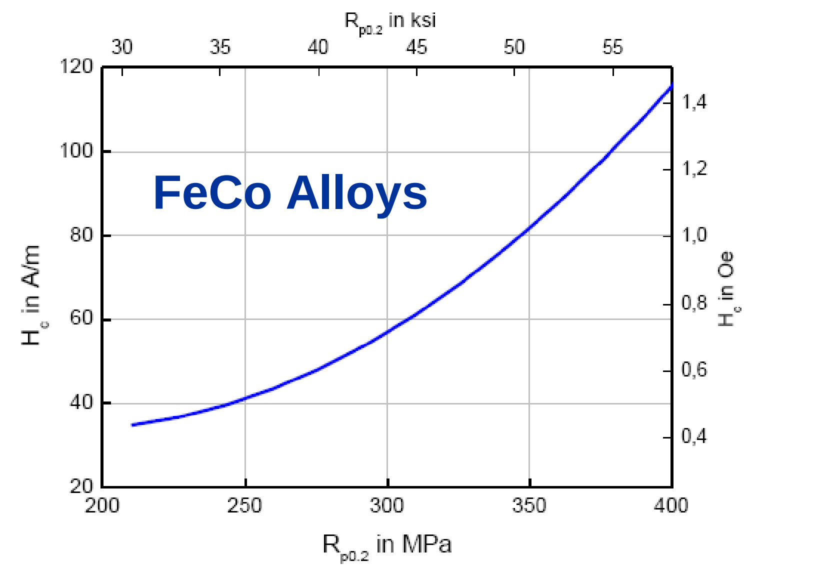


Figure 2: Possible combinations of coercivity H_c and yield strength $R_{p0.2}$ for VACODUR® 49.

Selection of Alloy / Heat Treatment Temperature (Grain Size) for Magnetic vs. Mechanical Properties

Mechanical Properties are Critical for Consideration as Well

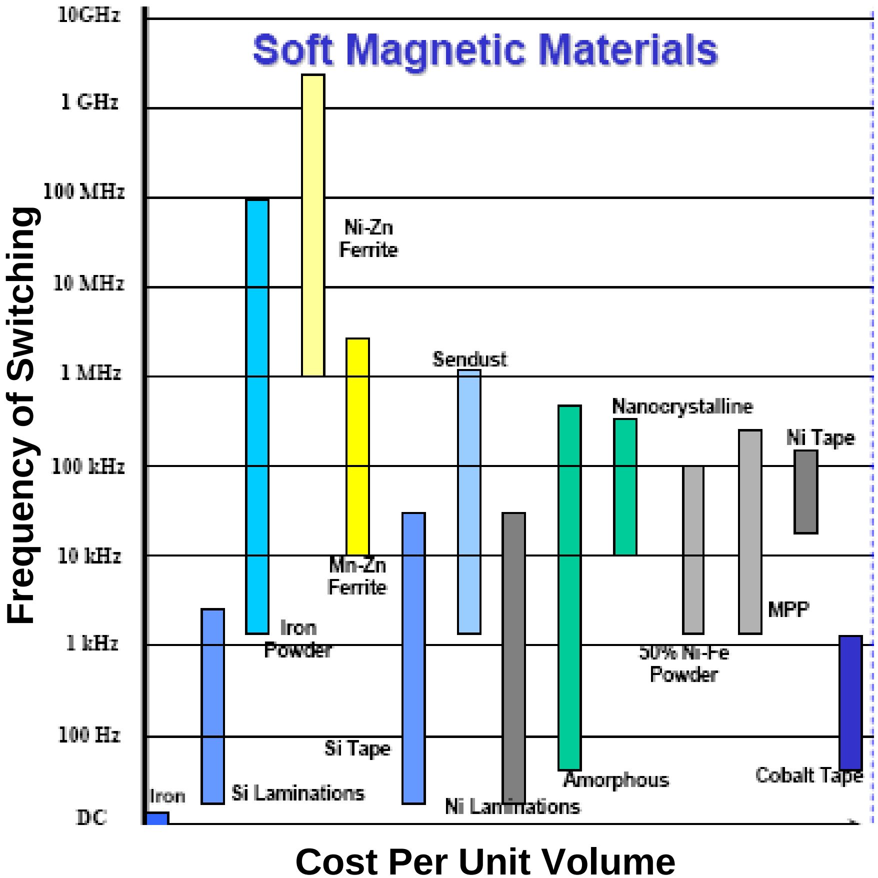
Direct Interplay : Magnetic Properties via Magnetostriction

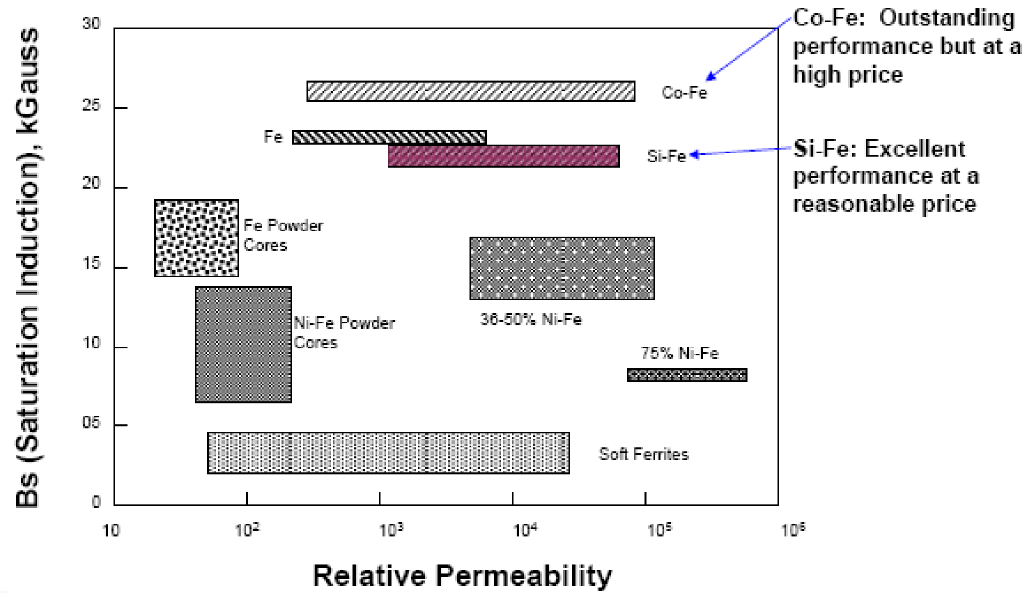
Indirect Interplay: Tendency for “Trade-offs” in Magnetic vs. Mechanical

M. E. McHenry and D. E. Laughlin, Magnetic Properties of Metals and Alloys, 2014

Engineering Approaches for Soft Magnets in Electrical Machines

Bulk Crystalline Alloys



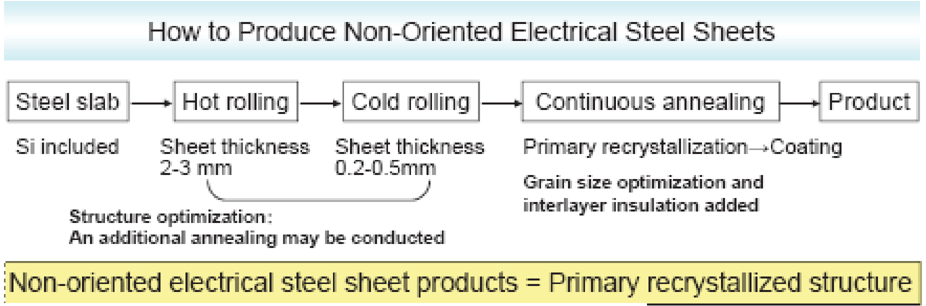


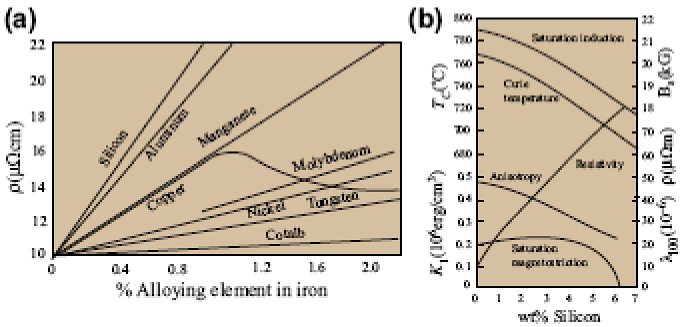
Materials Selection for Electrical Machine Applications is Carefully Sensitive to Price in Addition to Performance.

Silicon Steels Offer an Excellent Combination of Price / Performance for Large-Scale Industrial Applications.

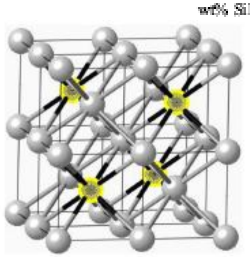
S. Constantinides, Arnold Magnetic Technologies, 2009

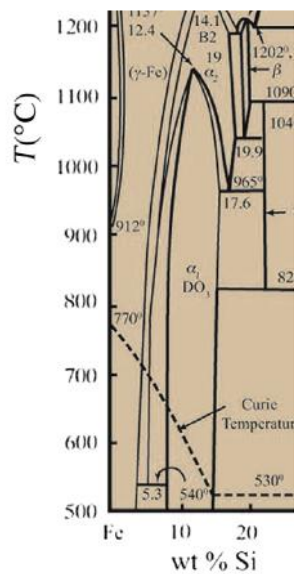
Conventional Silicon Steels





Fe_3Si (DO3)





M. E. McHenry and D. E. Laughlin

Magnetic Properties of Metals and Alloys, 2014

1) Texture Engineering to Promote (100) In Plane (NOES vs. GOES vs. GOES Hi-B)

2) Si-Content Adjustment

3) Controlling Impurities and Undesired 2nd Phases

4) For Grain Oriented Steels, Intentional 2nd Phase Precipitates Enable Abnormal Grain Growth of Textured Grains

5) Domain Refining Using Laser / Mechanical Scribing

Materials Selection for Electrical Machine Applications is Carefully Sensitive to Price in Addition to Performance.

Silicon Steels Offer an Excellent Combination of Price / Performance for Large-Scale Industrial Applications.

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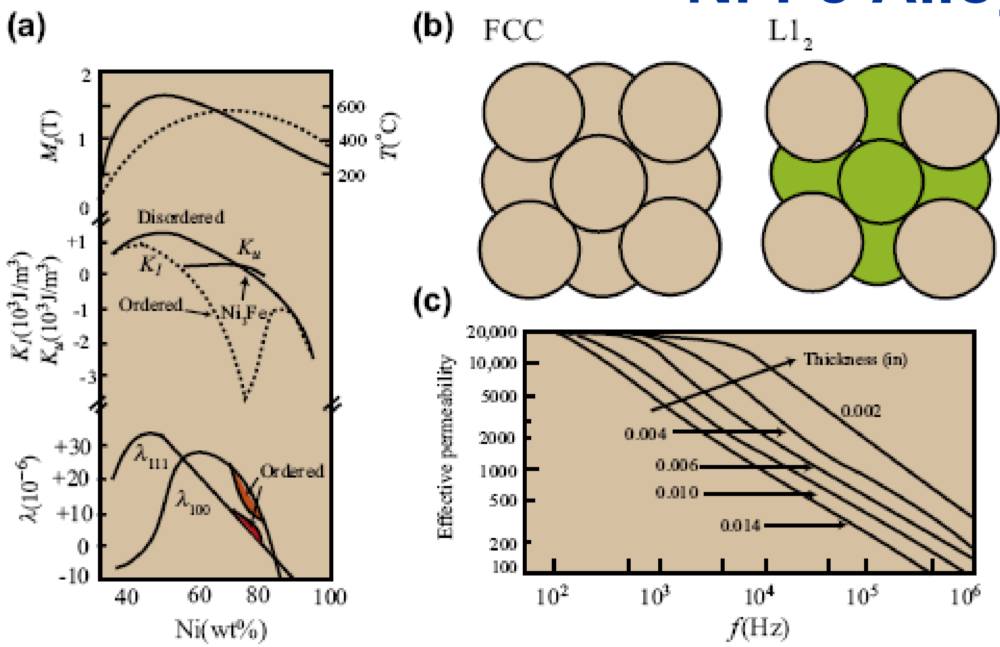
Ni-Fe Alloys



1) Selection of Ni_xFe_y Ratio (Balance of Elements <1%)

2) Controlling Impurities and Undesired 2nd Phases During Annealing Treatments

3) Final Anneal Temperature Dictates Performance for Relatively High Frequencies (Low Temperatures) or Relatively Low Frequencies (High Temperatures)

Carpenter HyMu "800"

Carbon	0.01 %	Manganese	0.50 %
Silicon	0.15 %	Nickel	80.00 %
Molybdenum	5.00 %	Iron	Balance

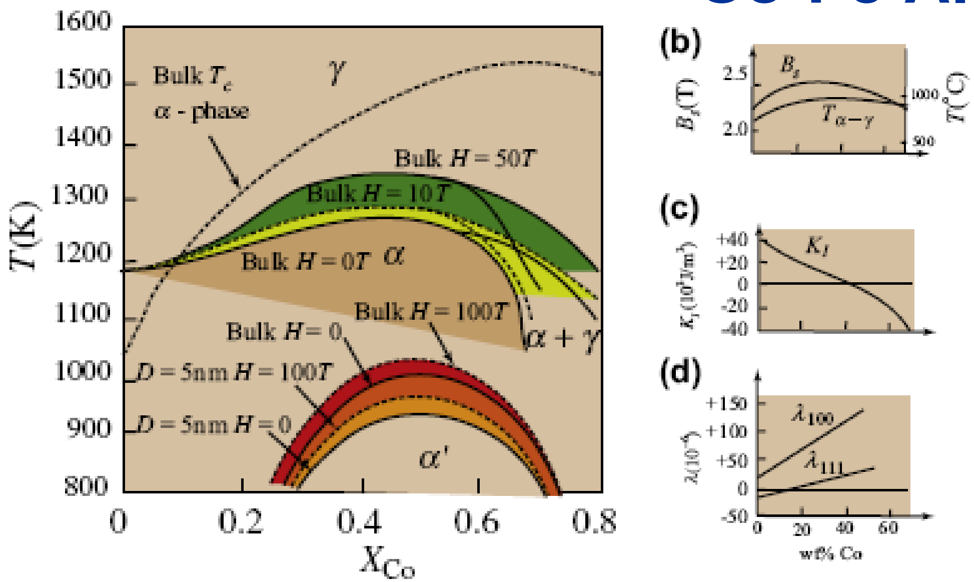
Carpenter High Permeability "49"® Alloy

Carbon	0.02 %	Manganese	0.50 %
Silicon	0.35 %	Nickel	48.00 %
Iron	Balance		

NiFe-Alloys are Well Known to Have Superior Soft Magnetic Properties in Terms of Losses, Permeability, and Field Annealing Response. Saturation Induction is Reduced and Costs are Higher Compared to Si-Steels Making them Useful Primarily for Specialty Applications.

Courtesy of S. Kernion, Carpenter Technology

Co-Fe Alloys



Hiperco® 27 Alloy

Carbon	0.01 %	Manganese	0.25 %
Silicon	0.25 %	Chromium	0.60 %
Nickel	0.60 %	Cobalt	27.00 %
Iron	Balance		

Hiperco® 50 Alloy

Carbon	0.01 %	Manganese	0.05 %
Silicon	0.05 %	Cobalt	48.75 %
Columbium/Niobium	0.05 %	Vanadium	1.90 %
Iron	Balance		

1) Selection of Co_xFe_y Ratio (Balance of Elements <~2.5%)

2) Controlling Impurities and Undesired 2nd Phases

3) Ternary Alloying Elements Can Be Used to Optimize Magnetic Properties, Corrosion, or Mechanical Properties (e.g. V for Suppressing Ordering)

4) Final Anneal Temperature Dictates Both Magnetic Properties and Mechanical Properties

FeCo Alloys are Unsurpassed in Terms of High Moment and High Temperature Applications But are Significantly More Costly.

Primary Applications for FeCo Alloys Fall within High Temperature and Volume Constrained Applications Such as Aerospace.

Courtesy of S. Kernion, Carpenter Technology

Conventional and Emerging Materials Comparison

		Low Frequency <(~400Hz) Losses	High Frequency >(~400Hz) Losses	Temperature Stability	Cost	Mechanical Properties	Thermal Conductivity	Bs	Initial Permeability	Resistivity	Material TRL	System TRL
Conventional	Low C Steels				Very Low Cost						Commercial	Commercial
	Si Steels										Commercial	Commercial
	NiFe Alloys	Very Low Loss							Very Soft Alloys		Commercial	Commercial
	CoFe Alloys			Highest T_{Curie}				Highest Bs			Commercial	Commercial
Emerging	Amorphous Alloys	Very Low Loss			Higher $ / kg, But Smaller Volume				Very Soft Alloys	Amorphous	Commercial	20kW Demo
	Fe-Based Nanocomposite Alloys (Conventional)	Very Low Loss			Higher $ / kg, But Smaller Volume	Brittle			Very Soft Alloys	Amorphous Matrix	Very Soft Alloys	No Significant Demo
	Fe-Based Nanocomposite Alloys (Partially Crystallized)	Very Low Loss			Higher $ / kg, But Smaller Volume				Very Soft Alloys	Amorphous Matrix	Very Soft Alloys	No Significant Demo
	Co-Based Nanocomposite Alloys				Higher $ / kg, But Smaller Volume					Amorphous Matrix		No Significant Demo
	Soft Magnetic Composites									Insulating Binder / Matrix		Insulating Binder / Matrix
	Ferrites							Lowest Bs			Commercial	Insufficient Bs

Unacceptable	(red)
Not Ideal	(yellow)
Suitable	(pale green)
Good	(green)
Best in Class	(dark green)

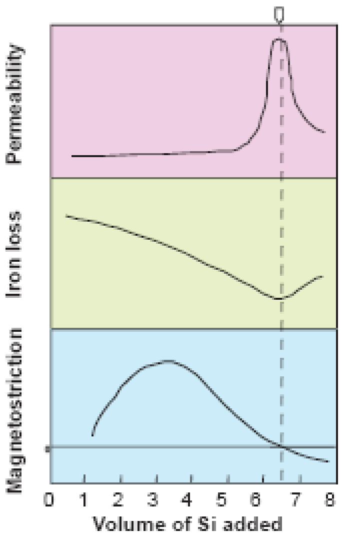
Standard Si-Steels : High Performance and Inexpensive for High MW.

Adoption of Alternative Material Systems Must Be Driven By:

1) **Policies on Energy Efficiency**
2) **Technical Needs of Specialty Applications (e.g. Aerospace)**
3) **Full Optimization at the System Level (Alternative Machine Designs)**

Higher Si-Steel Containing Alloys

6.5% Silicon steel



6.5% Silicon steel

High permeability

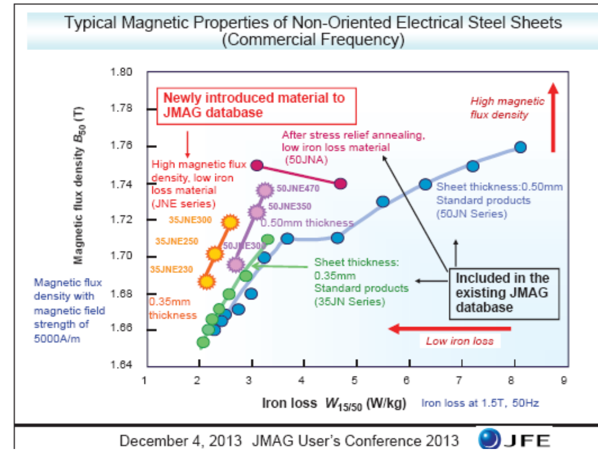
Low iron loss

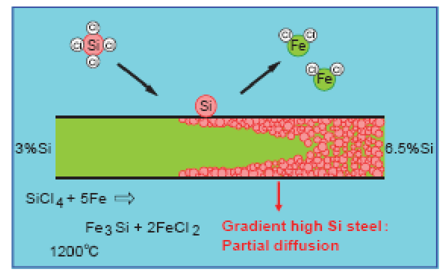
Zero magnetostriction

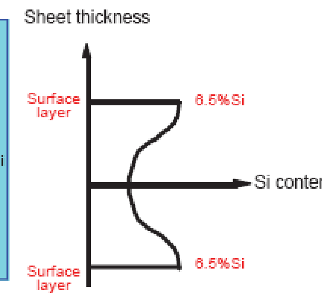
Suitable for high frequency transformers, reactors and high-speed motors

Impossible to produce 6.5% Si steel sheet by cold rolling method due to its embrittlement.

Industrial production of 6.5% Si steel sheet using CVD method (@JFE Steel Corporation) [Used for core material for high frequency power reactors and transformers]







Material	Thickness (mm)	Saturation magnetization (T)	Iron loss (W/kg)					Magnetostriction at 400 Hz, 1.0T(x10-6)
			$W_{10/50}$	$W_{10/400}$	$W_{5/2k}$	$W_{1/10k}$	$W_{0.5/20k}$	
6.5% Si Steel (10JNEX)	0.10	1.8	0.5	5.7	11.3	8.3	6.9	0.1
Ultrathin oriented Electromagnetic Steel sheet	0.10	2.0	0.7	6.4	20.0	18.0	14.0	-0.8
Ferrous amorphous	0.025	1.5	0.1	1.5	8.1	3.0	3.3	27.0

◇ Characteristics of Gradient High Si Steel (JNHF) :

(1) Low iron loss; Low iron loss at high frequency of 10 kHz or higher

(2) High workability; punching, interlocking and bending

(3) High saturation magnetization; 1.84 -1.94T (6.5%Si Steel 1.80T)

Higher Efficiency Silicon Steel Technologies Exist and are the Subject of Additional Development, Currently No US-Based Producer :

Economics Must Make Sense to the Materials and Laminate Purchaser or Energy Efficiencies Must Be Mandated

Hiroaki Toda

Electrical Steel Research Dept., Steel Research Laboratory, JFE Steel Corporation

Fe-Based Amorphous Alloys (And Partially Crystallized)

Loss coefficients	Amorphous (W/m^3)	M19 Steel (W/m^3)
Hysteretic k_h	125.167	178.478
Classical k_c	0.00235968	1.41304
Anomalous k_e	0.534436	1.79322

Highest Relative Gains for High Speed (Frequency) Operation

ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 18, NO. 9, 2012

Tapered design: 300W 7000 rpm
stator core power density: 0.3 W/g
2006 → 2015

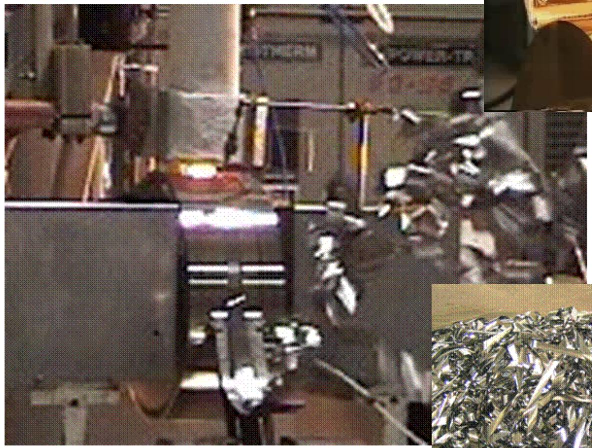

Radial design: 2200W

N. Ertugrul, R. Hasegawa, W. Soong, J. Gayler, S. Kloeden, and S. Kahourzade, IEEE Trans. Magn., vol.. 51, no. 7, 2015.

M. Dems, K. Komeza, IEEE Trans. Ind. Elec., vol. 61, no. 6, pp. 3046, 2014.

Hysteretic Losses · *Eddy Current Losses* · *Anomalous Eddy Current Losses*

$$P_{\text{tot}} = P_h + P_{\text{ec}} + P_{\text{an}}$$

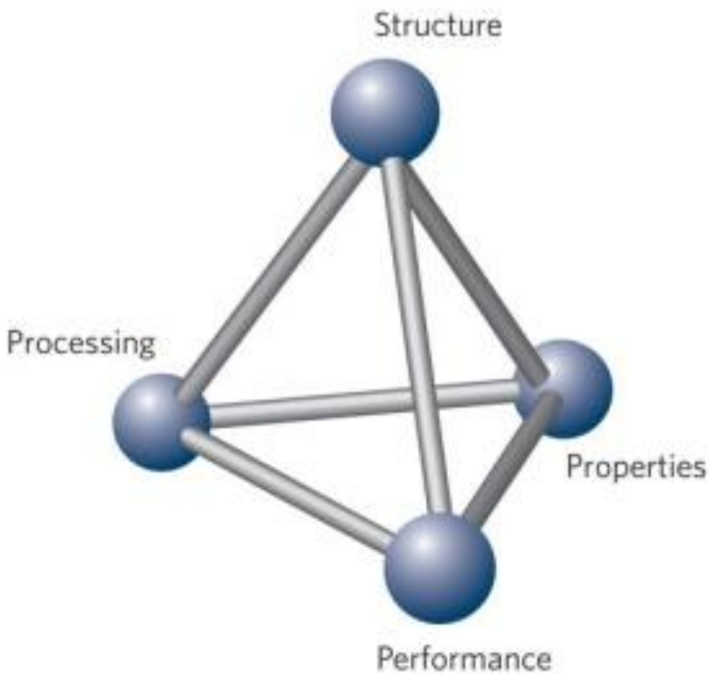

Fe-Based Amorphous Alloys are Emerging as Potential Substitutes for Si-Steels with Higher Efficiencies in Many Cases But Require:

1) **Wide Ribbon Rapid Solidification Processing**
2) **Stamping and/or Laser Cutting Processing**
3) **Alloy Development for High Bs, Low Loss, Mechanical Properties**
4) **Opportunities for Advances in <u>"Permeability Engineering"</u>**

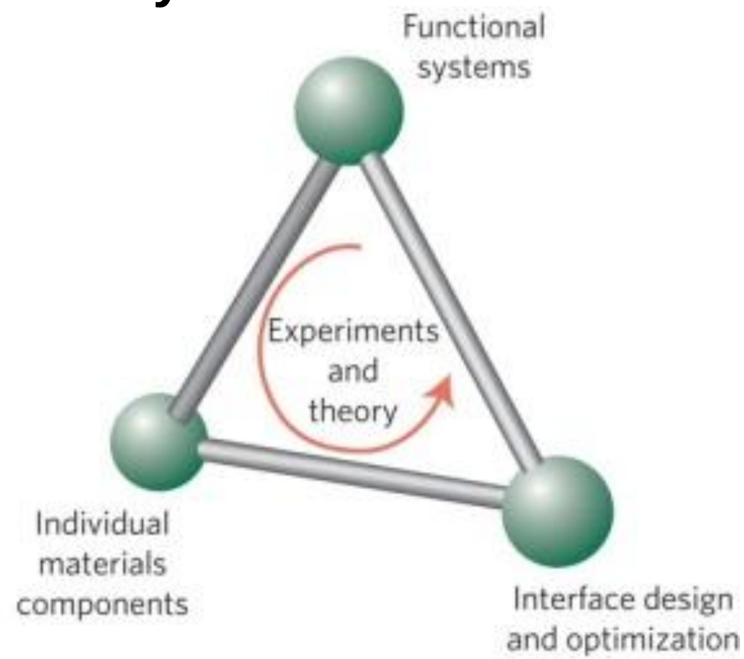
Courtesy of A. Leary, Carnegie Mellon University

Global System Optimization Perspective

Classic Materials Science Paradigm



Emerging Paradigm Materials Interface with Functional Systems and Devices



Alternative Motor and Generator Designs, Higher Rotational Speeds, and Controllable Permeability Engineering of Materials are Novel Concepts that Can Justify Higher Cost Materials with Improved Functionality.

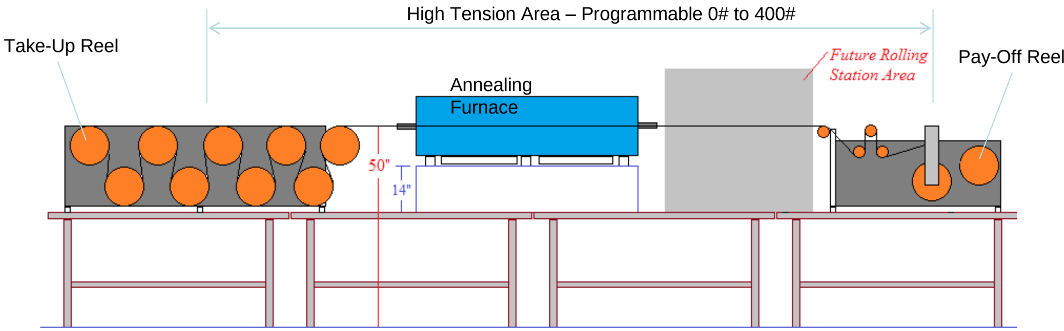
e.g. Uniaxial Flux-Based Electrical Machines Could Leverage GOES

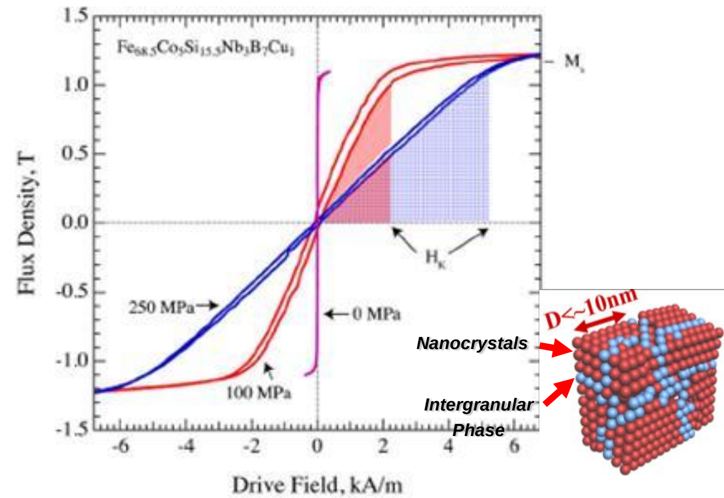
Nanocomposite Amorphous / Nanocrystalline Alloys

Alloy / Ribbon Processing

- Thermal
- Thermal + Magnetic
- Thermal + Mechanical
- e.g. Field or Stress Annealing

Commercial Scale Processing / Core Fabrication Facilities





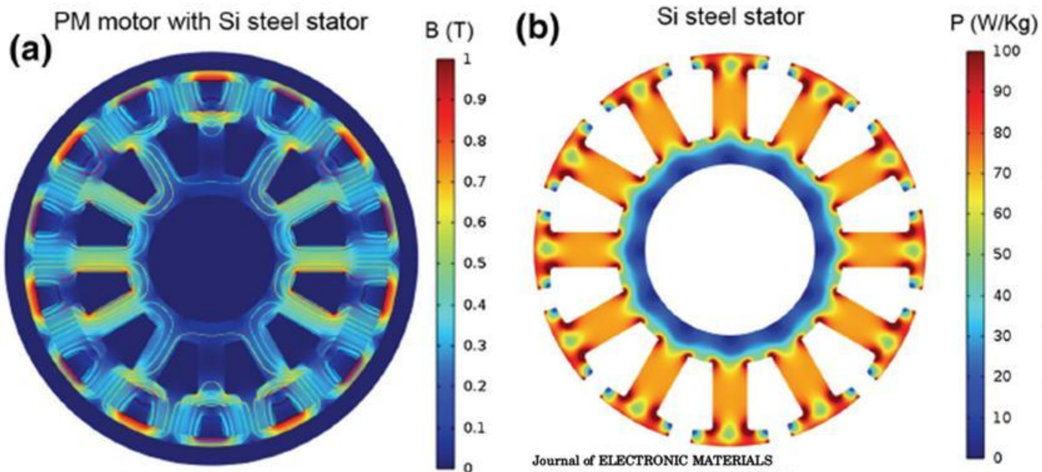
In Addition to Alloy Composition Design, Thermal Processing Design is Required.

High Performance Nanocomposite Alloys Can Yield a Combination of Bs, High Freq. Losses, and Temp. Stability Surpassing Amorphous Alloys.

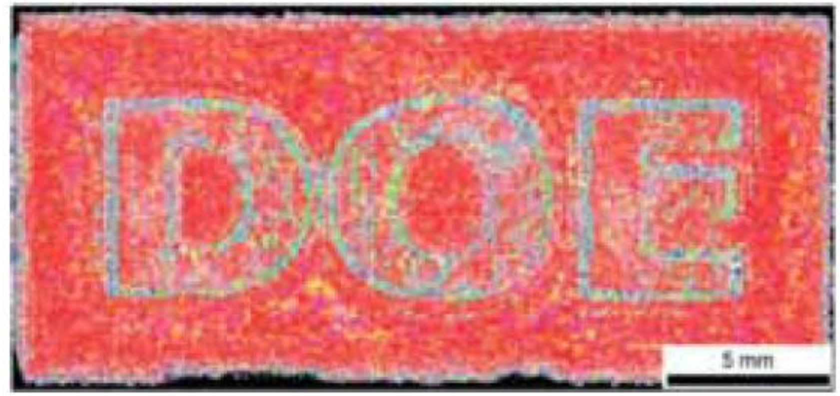
Nanocomposites Also Allow for Possibility of "Permeability Engineering".

Laminate Manufacturing / Alloy Mechanical Properties Must Be Addressed.

Spatially Engineered Permeability Alloys



Journal of ELECTRONIC MATERIALS
DOI: 10.1007/s11664-015-3968-1



M. Johnson, OE Workshop on Materials for Grid, 8/2015

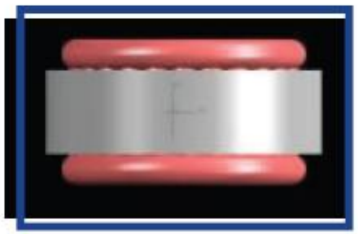
Non-Uniform Flux Densities and Rotational Magnetization Processes Offer Opportunities for "Advanced Permeability Engineering"

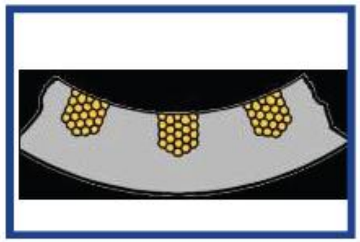
Potential Examples:

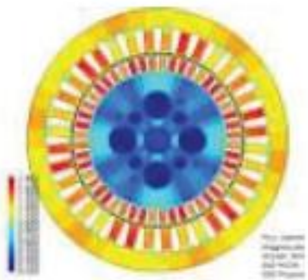
1) Locally Controlled Crystallographic Texture
2) Masking and In-Line Processing of Strip Alloys
3) Strain, Field, or Rolling Induced Anisotropy

Coupling of Advanced Electrical Machine Design with Tunable Permeabilities as a Function of Position Could Enable Revolutionary Advances in Electrical Machine Design.

Soft Magnetic Composites (i.e. 3-D Micro/Nanostructured)







Soft magnetic composites are pressed Fe powder parts suitable for some motor designs

- **Enables 3-D flux paths**
- **Substantial size and weight reduction**
- **Suitable for claw-pole and linear brushless DC motors**
- **High speed motors**

Products include Somaloy from Höganäs:

Somaloy Material	ρ (μΩ-cm)	B/10,000 A/m (T)	μ_{max}	$W_{1.0/100}$ (W/kg)
130i	8000	1.4	290	12
700	400	1.56	540	10
700 HR	1000	1.53	440	10

IMFINE sintered lamellar SMC:
W 1.0/60 < 2 W/kg, μ > 2,000, B_{max} 1.7 T

P. Lemieux, JOM, Vol. 64, 2012, pp. 374-387

3-Dimensional Micro/Nanostructuring through Alternative Processing With Sufficient Compositional and Microstructural Control Could Eliminate Laminate Geometry and Enable New Machine Designs. Existing Soft Magnetic Composites Have Permeability / Temp. Limitations.

Courtesy of F. Johnson, GE Global Research

Capabilities and Facilities for Large-Scale Alloy Discovery, Development, and Deployment at NETL

NETL Metallurgical Discovery and Deployment

NETL Capabilities and Research Spans from Discovery (Including Thermo / Ab-Initio) to Full-Scale Casting and Prototyping of 100kg Casts.

Courtesy of P. Jablonski, National Energy Technology Laboratory

NETL Large-Scale Alloy Development Facility

Button Furnace – Up to 500 grams
Vacuum Induction Melting – Up to 200 lb
Vacuum Arc Remelting - Up to 400 lb
Electroslag Remelting - Up to 400 lb
Air Induction Melting – Up to 300 lb
Directional Solidification - Up to 200 lb
Induction Skull Melting - Up to 50 lb
Vacuum Heat Treating – Up to 1650C

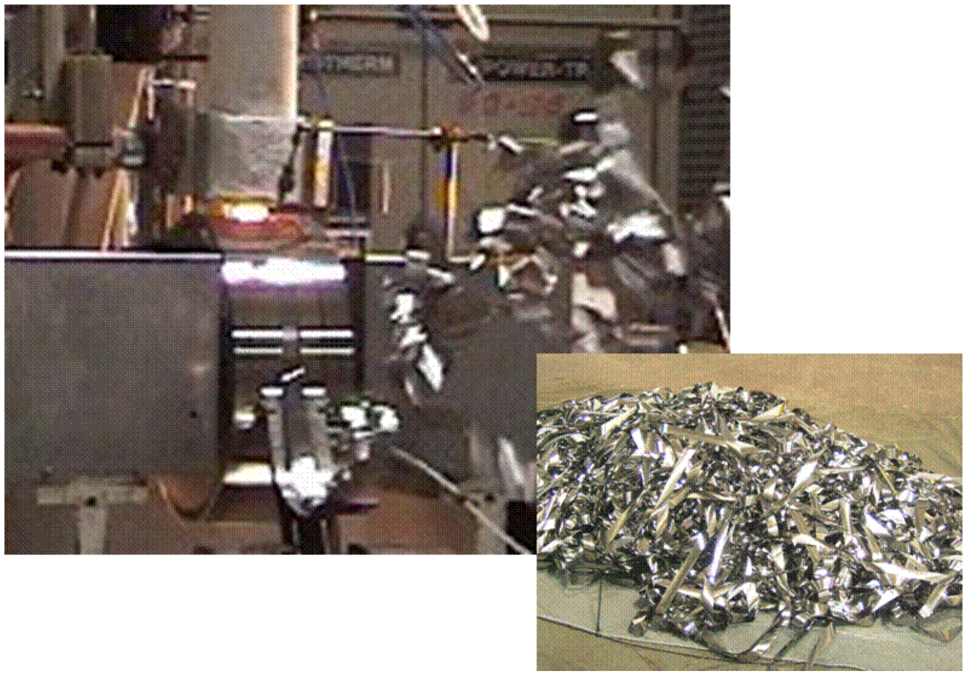
Preheat – Up to 1500C, 3x3x6 ft^3
Press Forge (500 Ton)
Hot Rolling (420 Ton)
Cold Rolling (750 Ton)

NETL is Well-Equipped for Large-Scale Metallurgical Process Development and Research with Major Recent Commercial Successes.

Courtesy of P. Jablonski, National Energy Technology Laboratory

NETL Expertise and Collaborations in Large-Scale PFC

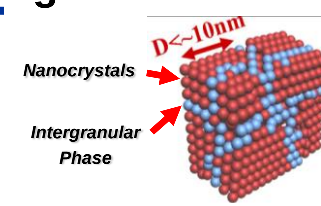
NETL Carnegie Mellon University NASA



Commercial Scale Processing / Core Fabrication

Alloy / Ribbon Processing

Thermal
Thermal + Magnetic
Thermal + Mechanical
e.g. Field or Stress Annealing



NETL Has Expertise and Collaborations in Large-Scale Planar Flow Casting, Core Fabrication / Processing, and Magnetic Property Measurements for Amorphous and Nanocrystalline / Amorphous Alloy Development.

Suggestions for High Potential Impact R&D

Short Term (“Plug and Play” Solutions if Successful):

- New Fe-Based Metallic Alloy R&D
- Large-Scale Processing for High Si-Steel Content Alloys
- Fe-Based Amorphous Alloy Development R&D
- Low Crystal Volume Fraction Fe-Based Nanocomposite Alloy Development R&D
- Large-Area Rapid Solidification and Amorphous Alloy Laminate Manufacturing

Intermediate Term (Require Manufacturing Process Modifications if Successful):

- “Permeability Engineering” in Fe-Based Strip, Amorphous, and Nanocomposite Alloys Leveraging In-Line Processing
- High Crystal Volume Fraction Fe-Based Nanocomposite Alloy Development R&D
- Nanocomposite Alloy Laminate Manufacturing
- “Global Systems Level Optimization” with Collaboration Between Materials Developers, Laminate Manufacturers, and Electrical Machine Manufacturers (Higher Speed Designs, Unidirectional Flux Designs, etc.)

Long Term (Major Manufacturing Process Modifications):

- Soft Magnetic (Nano/Micro) Composites with Highly Engineered Microstructure for 3-D Magnetics
- Spatially Tunable “Permeability Engineering”

NETL Has Significant Capabilities / Expertise to Leverage Here and is Highly Interested in Partnering and Collaborating with Others in this Technical Area

Thank You to NIST and DOE AMO for the Opportunity to Attend and Present!

Please Contact Me if Interested in Discussing Potential Collaborations, Technical Support to Program Planning, or Further Details Regarding this Presentation.

Dr. Paul Ohodnicki, 412-386-7389, paul.ohodnicki@netl.doe.gov