Amorphous and Nanocomposite Magnets for

Energy-efficient Electric Motors

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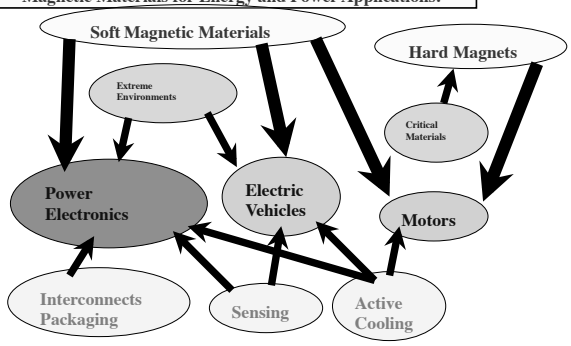
1

Outline

- Motivation: Electric motors, energy, hard magnets
- Soft magnets: steel vs amorphous and nanocomposites
- Parallel Path Magnetic Technology
- Brushless permanent magnet motors
- Conclusions & Future work

2

Magnetic Materials for Energy and Power Applications.



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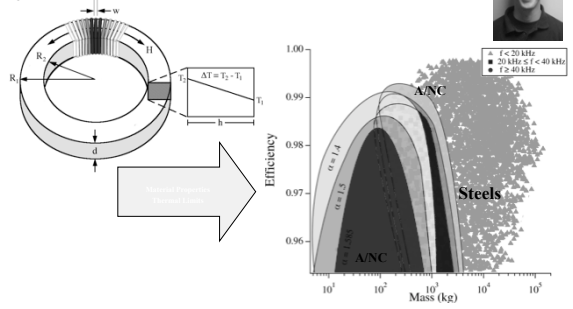
Scaling

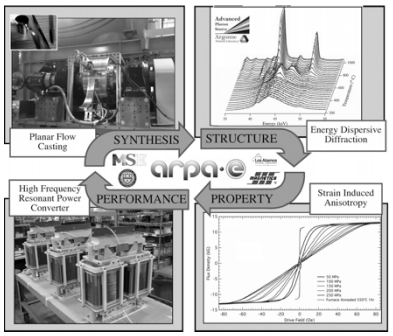
Material properties necessary for high-f operation?

A., Leary, P. Ohodnicki, M. E. McHenry, Soft Magnetic Materials in High Frequency, High Power Conversion Applications; JOM, 2012.



Converter applications: Controlling Losses Allow 100-fold or more reduction in size/ mass. Materials must have robust properties in extreme environments; P, T, stress, corrosive.

Materials Paradigm for Magnetic Materials

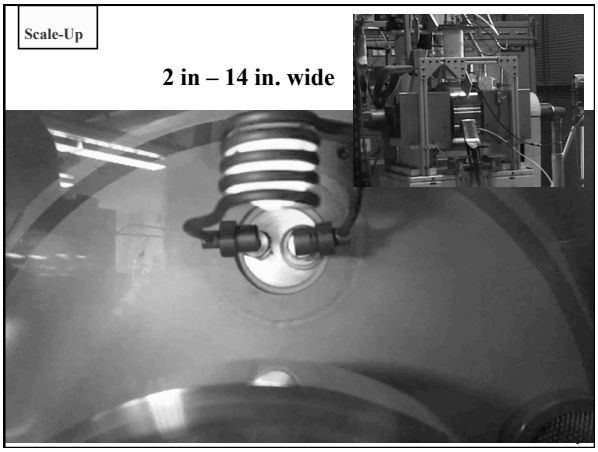


Power Converters
Electric Vehicles
Motors
Sensors

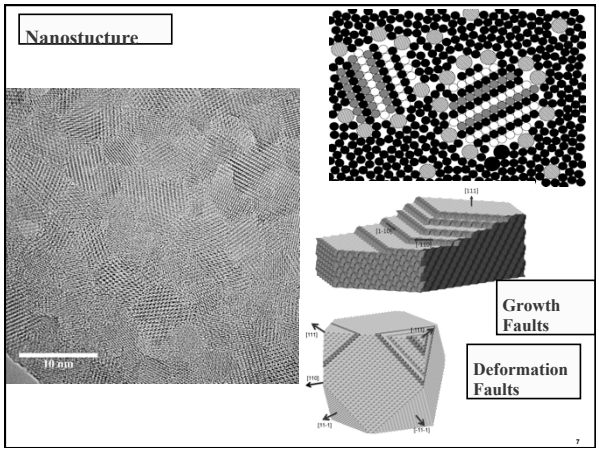
Collaborations (funding):
NETL, ANL, PNNL
WPAFB, ARL
NASA Glenn
NSF
Industry

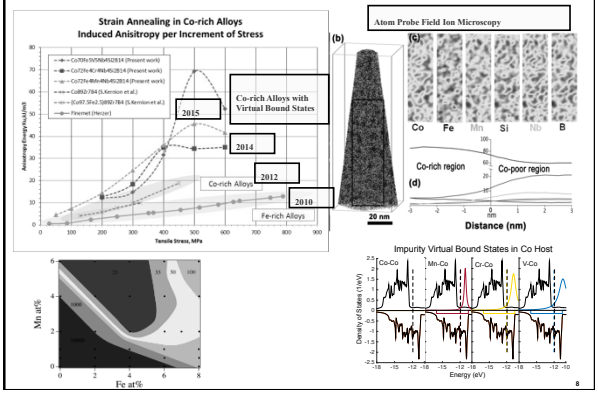
Scale-Up

2 in – 14 in. wide



Nanostucture

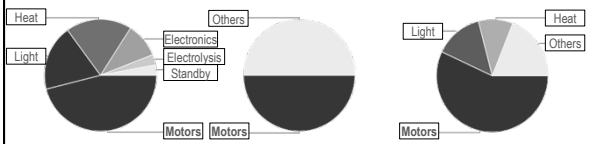




Electric Motors & Energy

- **Motors usually comprise ferromagnets, either to produce or to direct magnetic flux, which varies temporally/spatially**

Global (2006) **Electric Energy Consumption USA (2010)** **Japan (2005)**



Source: A+B International, 2009. From the 2011 report "Energy-Efficient Policy Opportunities for Electric Motor-Driven Systems". International Energy Agency.

Source: Moyer, University of Chicago, 2010

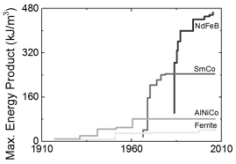
Source: Fuji-Keizai Report.

Even small efficiency improvements from the ferromagnet's field would lead to large energy savings

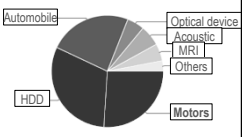
9

Electric motors & Hard magnets

- **The advent of modern electronics and high-energy hard magnets (SmCo, NdFeB) have promoted the use of permanent magnet (PM) motors in the past years.**



Applications of Nd-magnets



Source: Shin Etsu, 5th Int. Rare Earths Conf. (2009)

- **PM motors have high performance, high power density, high robustness, and high reliability.**

10

Electric motors & Hard magnets

- **China controls about 80% of the world's rare earths.**
- **PM are sensitive to high temperature.**

NdFeB type	Maximum Operating Temp	Curie Temp
N	176 °F (80 °C)	590 °F (310 °C)
NM	212 °F (100 °C)	644 °F (340 °C)
NH	248 °F (120 °C)	644 °F (340 °C)
NSH	302 °F (150 °C)	644 °F (340 °C)
NUH	356 °F (180 °C)	662 °F (350 °C)
NEH	392 °F (200 °C)	662 °F (350 °C)

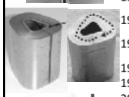
11

Advantages of amorphous & nanocomposite soft magnets

- **The reduction in core losses allows to excite the motor at higher frequencies without incurring unacceptable heating.**
- **The motor can therefore operate at higher rotational speeds.**
- **An increase in speed proportionally increases the output power for an equivalent torque level, or smaller and lighter machines for the same output power.**
- **Motor size reduction leads to less amount of rare-earth hard magnets.**

12

Amorphous Alloys in Motors: Previous Efforts



RADAM
RADIAL ANISOTROPIC MOTORS

1981 Test Results On a Low Loss Amorphous Iron Induction Motor, Mischler W. et al, IEEE Transactions on Po... ...00 pp 2907-2911 No. 6 June 1981

1982 Application of Low Loss Amorphous Metals in Motors and transformers, Johnson L. et al, IEEE Transactions on Power Apparatus and Systems, Vol PAS-101 pp 2109-2114 No. 7 July 1982

1983 Utilization of Amorphous Metals In Electric Motors, Johnson L., Prepared by General Electric Company, Corporate Research and development for the Oak ridge National Laboratory operated by Union Carbide Corporation for the DOE Contract No. W-7405-eng-26, October 1983

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1992 A Low-Loss Permanent-magnet brushless dc Motor Utilizing Tape Wound Amorphous Iron, Jensen C. et al, IEEE Transactions on Industry Applications, Vol. 28 No 3, pp 646-651 May/Jun 1992

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2008 Test Results of an SRM Made From a Layered Block of Heat-Treated Amorphous Alloys, Chiba A. et al, IEEE Transactions on Industry Applications, Vol. 44, No. 3 pp 699-706 May/Jun 2008

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2011 Application of amorphous alloy in the new energy-efficient electrical motor, Wang L. et al, Applied Mechanics and Materials, Vols 48-49 (2011) pp246-248

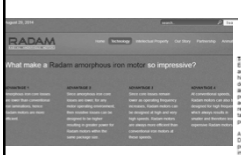
2011 Stator Used In An Electrical Motor or Generator With Low Loss Magnetic Material And Method Of Manufacturing A Stator, PCT/US11/64535, December 13, 2011

2014

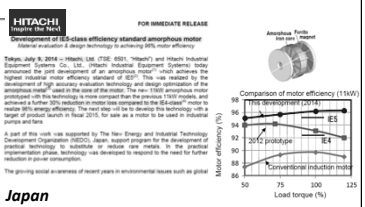
13

Fe-based and Co-rich alloys

- **Recent efforts in replacing Si-Steel by Fe-based amorphous components to develop highly-efficient low-rare-earth-PM motors:**



USA



Japan

14

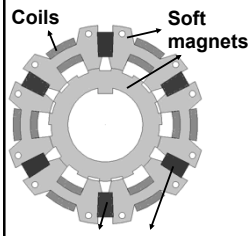
Fe-based and Co-rich alloys

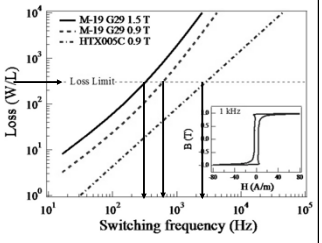
- **But Fe-based alloys are very brittle, especially nanocomposites.**

Co-rich alloys (HiTperms) have robust mechanical properties, better tunable anisotropies, can have ~zero magnetostriction, and can operate at higher temperatures (>300°C) *CMU Patent pending*

15

Parallel Path Magnetic Technology





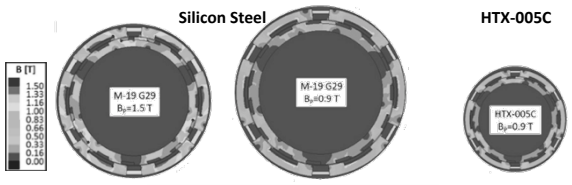
Power = Torque x Speed

16

Parallel Path Magnetic Technology

Silicon Steel

HTX-005C



JOURNAL OF APPLIED PHYSICS 115, 17A319 (2014)

High speed electric motors based on high performance novel soft magnets

J. M. Silveyra,[1] A. M. Leary,[2,a)] V. DeGeorge,[3] S. Simizu,[3] and M. E. McHenry[3]

machines. Here, we present a finite element analysis of Parallel Path Magnetic Technology rotating motors constructed with both silicon steel and Co-based nanocomposite. The later achieved a 70% size reduction and an 83% reduction on NdFeB magnet volume with respect to a similar Si-steel design. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4864247]

17

Common Permanent Magnet Brushless Motors

Radial flux machine

Axial flux machine

Stacking

Winding

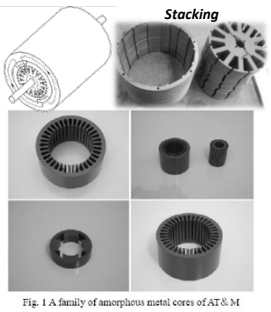


Fig. 1 A family of amorphous metal cores of AT & M

18

Radial Permanent Magnet Brushless Motor

We built a small outrunner (i.e. outer rotor) with custom-made ferrite hard magnets and soft magnetic stators: from Si-steel or nanocomposite

19

Laser cutting

IEEE TRANSACTIONS ON MAGNETICS, VOL. 50, NO. 4, APRIL 2014

Application of Rapidly Quenched Soft Magnetic Materials in Energy-Saving Electric Equipment

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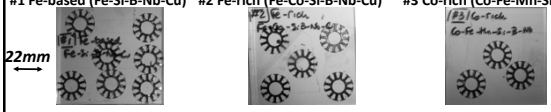
Department of Functional Materials, Institute of Non-Ferrous Metals, Gliwice 44-100, Poland

- **Made out of Metglas amorphous Fe-based stacked cut sheets**
- **Failed attempt to use Finemet nanocomposite material due to its brittleness**
- **Holy Grail → Thermoplastic deforation processing.**

Cadcam FB750 machine
50-watt laser
40-50mm/sec
Possibility of adding a automatic roll feed system

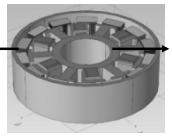
Radian Laser Systems
2320 E. Orangethorpe Avenue, Suite B
Anaheim, CA 92806
Attn: Manoj Bakshi
mbakshi@radianlaser.com

#1 Fe-based (Fe-Si-B-Nb-Cu) **#2 Fe-rich (Fe-Co-Si-B-Nb-Cu)** **#3 Co-rich (Co-Fe-Mn-Si-B-Nb)**



20

Modeling Radial PM Brushless Motors

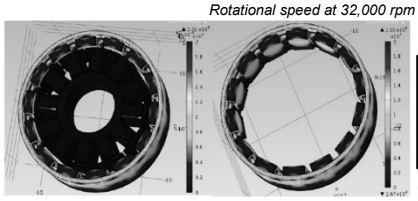


Outer rotor
- Silicon steel ring
- Custom-made Ferrite (C-8) magnets

Inner stator
- Silicon steel OR Co-rich alloy laminated core
- Coils

Stress distribution on the motor

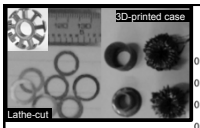
Rotational speed at 32,000 rpm



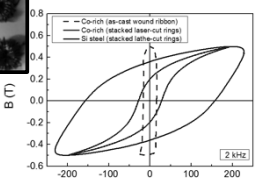
Simulations prove rotor to be mechanically stable at 32,000 rpm (validated with experiments)

Left: Full motor. Right: Rotor.

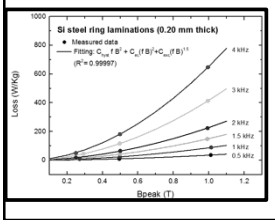
21

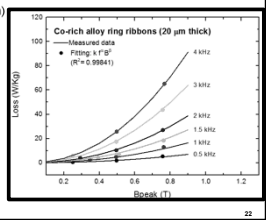


Core losses



Si steel | **Co-rich alloy**





22

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Amorphous and Nanocomposite Materials for Energy-Efficient Electric Motors

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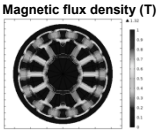
We explore amorphous soft-magnetic alloys as candidates for electric motor applications. The Co-rich system combines the benefits of low hysteretic and eddy-current losses while exhibiting negligible magnetostriction and robust mechanical properties. The amorphous precursors can be devitrified to form nanocomposite magnets. The superior characteristics of these materials offer the advantages of ease of handling in the manufacturing processing and low iron losses during motor operation. Co-rich amorphous ribbons were laser-cut to build a stator for a small demonstrator permanent-magnet machine. The motor was tested up to ~30,000 rpm. Finite-element analyses proved that the iron losses of the Co-rich amorphous stator were ~80% smaller than for a Si steel stator in the same motor, at 18,000 rpm (equivalent to an electric frequency of 2.1 kHz). These low-loss soft magnets have great potential for application in highly efficient high-speed electric machines, leading to size reduction as well as reduction or replacement of rare earths in permanent-magnet motors. More studies evaluating further processing techniques for amorphous and nanocomposite materials are needed.

Key words: Soft-magnetic materials, amorphous, nanocomposites, iron loss, electric motor, finite-element analysis

23

Modeling Radial PM Brushless Motors

Magnetic flux density (T)

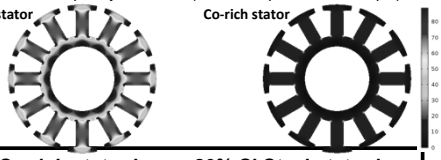


We computed the iron loss in the stator from the previous iron loss models and the flux density distribution obtained through finite element analysis

Loss density distribution (W/kg) on the stator

Electric frequency at 2.1 kHz (rotational speed at 18,000 rpm)

Si Steel stator | **Co-rich stator**



Co-rich stator loss ≈ 20% Si Steel stator loss

24

Conclusions

- Electric motors still seem to be a good niche for amorphous and nanocomposite materials, especially for Co-based alloys
- Energy efficiency improvement, size reduction and rare-earths reduction may be achieved with these materials in electric motors

25

POSCO Steel

POSCO TMC: Transformer, Motor Core Company

"Under the motto of becoming a global leader in green energy parts, POSCO TMC is preparing for new changes to achieve Vision 2020. First, with the development of Fe Amorphous, an eco-friendly high efficiency new material, which can significantly reduce the no-load loss to transformers, we will build up the full line-up for transformers to provide a solution for increased energy demand."

26