AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

Review of Current and Emerging Alloys for Electrical Motor Applications

Prof. Paul R. Ohodnicki
Tyler Paplham

Contact Email: pro8@pitt.edu

Soft Magnetic Materials for High-Speed Electric Motors

Existing State of Art Nanocrystalline

Material Classes	B_s (T)	ρ_r (μΩ-cm)	Mechanical Ductility	Upper Temp. Limit (°C)	Upper Freq. Lim. (Hz)	High Speed Application
Ferrites	0.2-0.4	>1000	Brittle	100-300	10^6-10^9	No, B_s too low
Fe-Si	2	~10	Ductile	800	10^2	<~1kHz frequency
Fe-Co	2.3-2.4	~40	Semi-brittle	900-1000	10^2	<~1kHz frequency
Commercial Fe-based Amorphous	1-1.6	~100	Ductile	150	10^5	<~5kHz frequency
Commercial Fe-based NC	1.3	~100	Brittle	150	10^5	No, too brittle
New FeCo-based NC (CMU)	1.5	~120	Ductile	~500	10^5	<~10kHz frequency
New Co-based NC (CMU)	1	~100	Ductile	~500	10^5	<~10kHz frequency
New FeNi-based NC (CMU)	~1.3-1.5	~100	Ductile	300+	10^5	<~10kHz frequency

Emerging Nanocrystalline Alloys

Materials for High-Speed Electrical Motor Applications

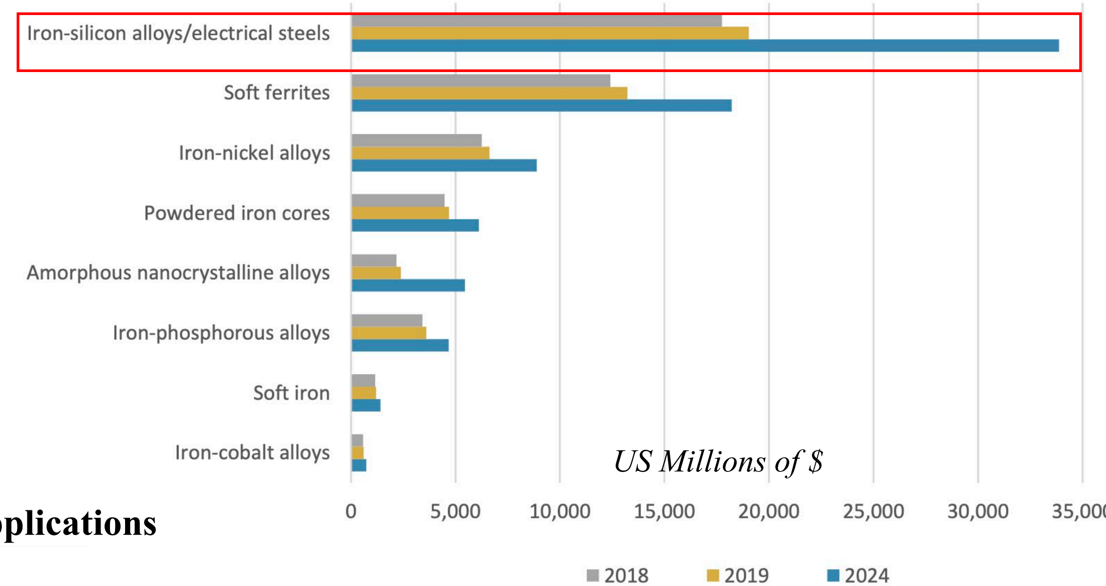
PITT SWANSON ENGINEERING
OHODNICKI GROUP
MAGNETIC , ELECTRONIC, AND PHOTONIC MATERIALS AND DEVICES

Bulk crystalline alloys for motor applications

PITT | SWANSON ENGINEERING

Electrical Steels

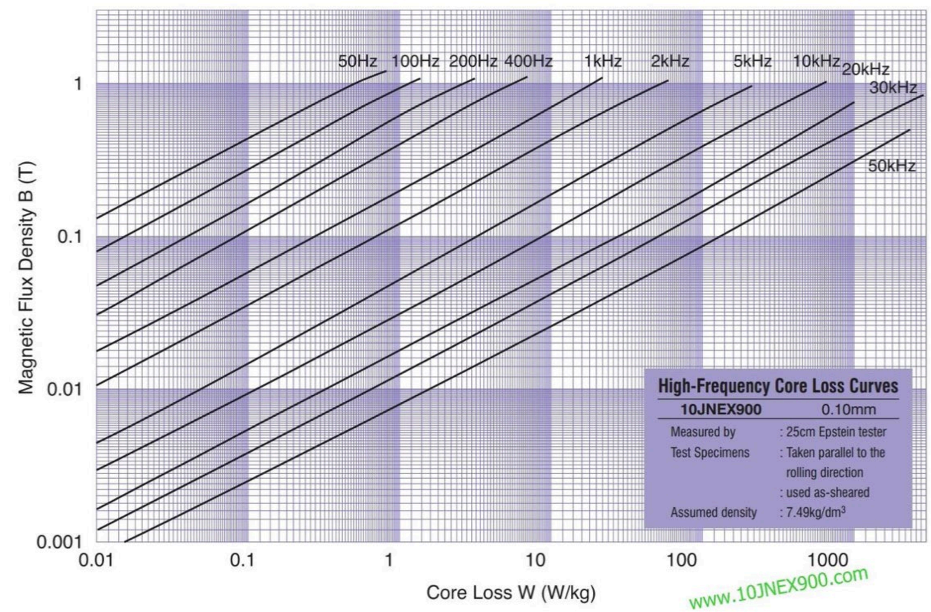
Most commonly Fe-Si (with small addition of Al), but low carbon steels sometimes used in low-demand applications



BCC Research, LLC. *Soft Magnetic Materials: Applications and Markets*

Conventional Grades (~3.2 wt.% Si) and Applications

Type of steel	Thickness (mm)	Power loss	Conventional density (g cm^{-3})	Relative permeability	Usage
Non-oriented motor grade requiring customer anneal	0.65	7.0 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.85	3000 at 1.5 T	Small
Non-oriented superior motor grade, requiring customer anneal	0.5	3.8 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.85	3000 at 1.5 T	Small/medium motors
Non-oriented fully annealed	0.5	5.3 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.75	1620 at 1.5 T	Larger rotating machines small transformers
Non-oriented fully annealed	0.35	2.25 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.60	660 at 1.5 T	Large rotating machines
Grain oriented steel (CGO)	0.27	0.78 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.65	1.83 T at 800 Am^{-1} Rel μ1830 at 1.83 T	Transformers
High permeability grain oriented steel	0.27	0.98 W kg$^{-1}\hat{B}$ 1.7 T, 50 Hz	7.65	1.93 T at 800 Am^{-1} Rel μ1930 at 1.93 T	Transformers
Relay soft steel	1.0	–	7.85	Coercive field strength	56–80 A m^{-1}

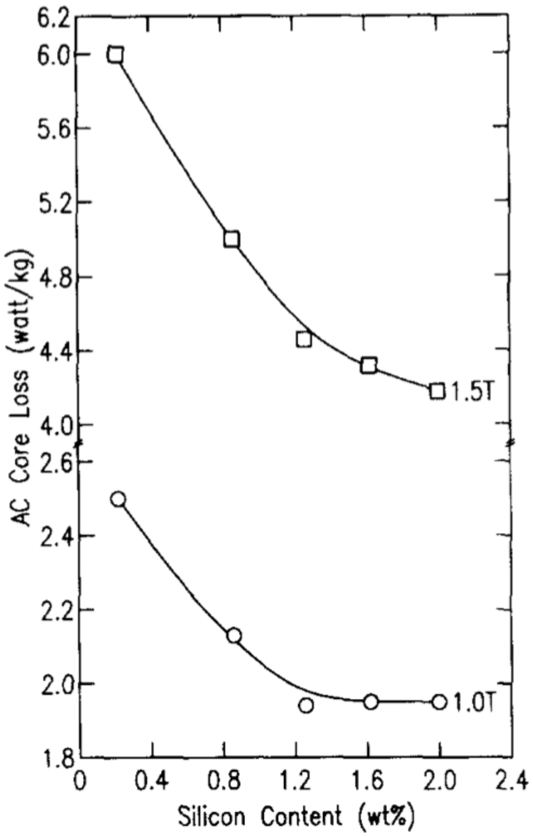


High-frequency Core Loss of Hi-Si (~6.5 wt.% Si) Steels

Beckley & Sujan (2016) "Steels, Silicon Iron-based: Magnetic Properties" in *Reference Module in Materials Science and Engineering*

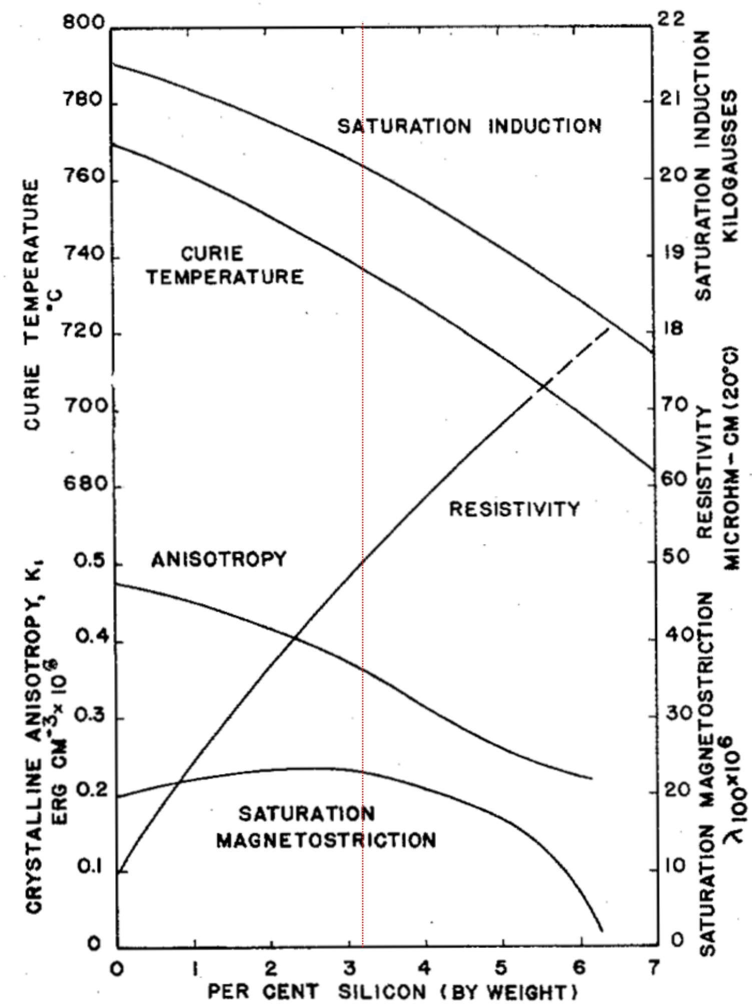
Electrical Steels (Fe-Si)

Greatly reduced eddy current and hysteresis losses relative to Fe…also cheap to produce



Hou (1996) *MMM* **162**

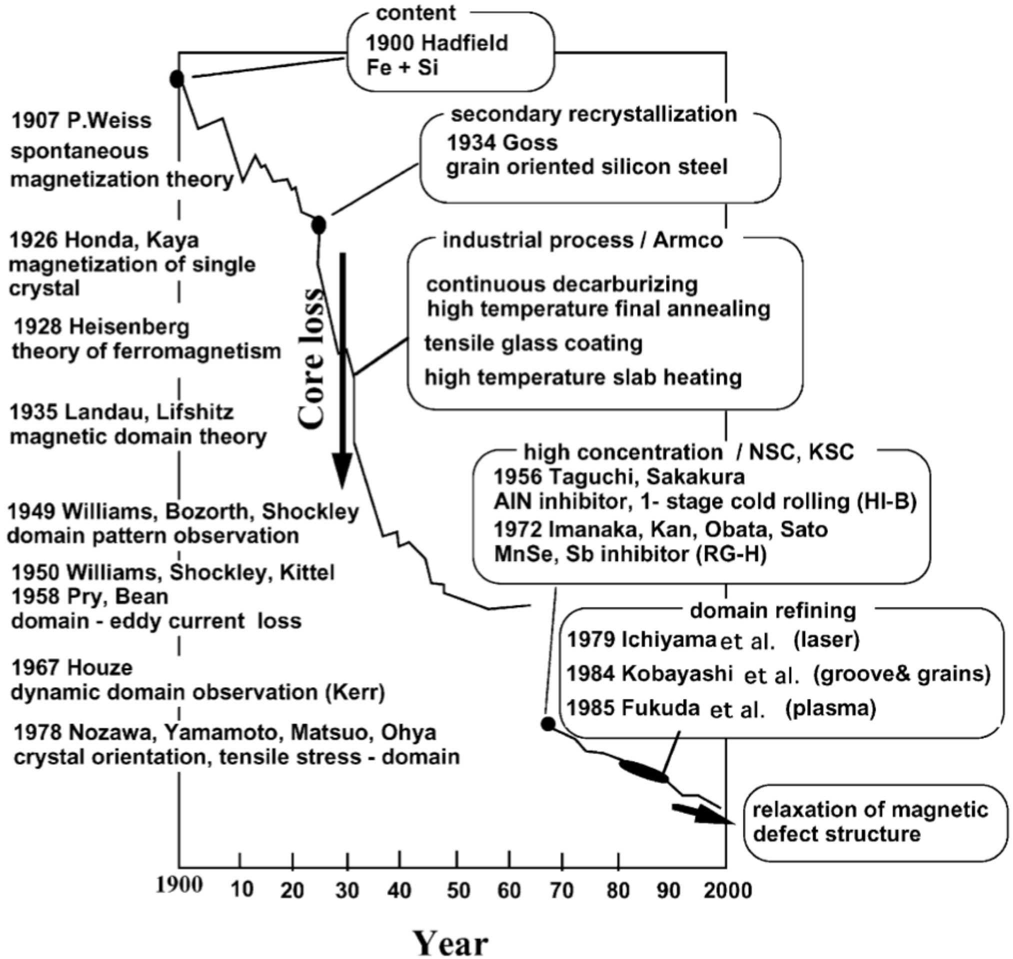
10 million tons/year produced, 80% of market share for soft magnetic materials (as of 2019)



Littmann (1971) *IEEE Trans. Mag*. **7**

Standard composition Fe-3.2wt% Si → compromise between optimal electromagnetic properties and workability (becomes brittle above this composition)

Electrical Steels (Fe-Si)



Ushigami et al. (2003) *MMM* **254**

Can be grain-oriented or non-oriented

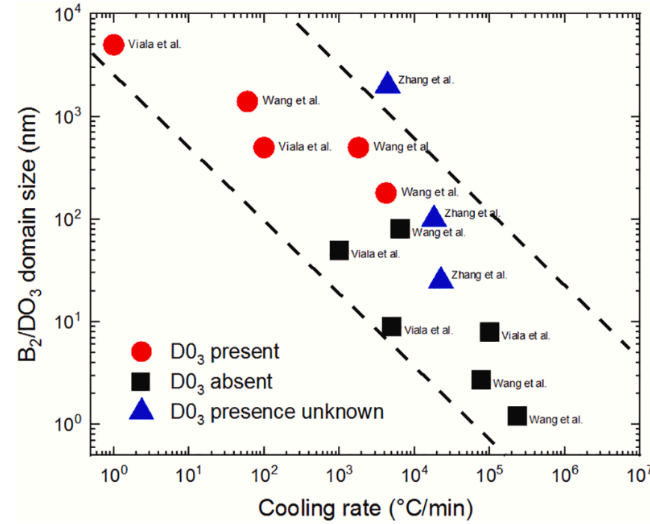
Non-oriented: More common, used when magnetization changes direction

Grain-oriented: {110}<001> takes advantage of Fe easy axis, used mainly for transformers

Goss technique produces thin-gauge GO steel by first hot rolling Fe-Si strip, then alternating cold working and heat treatment

PITT | SWANSON ENGINEERING AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

Fig from Ouyang et al. (2019) *MMM* ***481***. Data from Zhang et al. (2011) *Mat Sci Eng A* **530**, Viala et al. (1996) *Mat Sci Eng A* **212**, and Wang et al. (2015) *IEEE Trans Mag* **51**

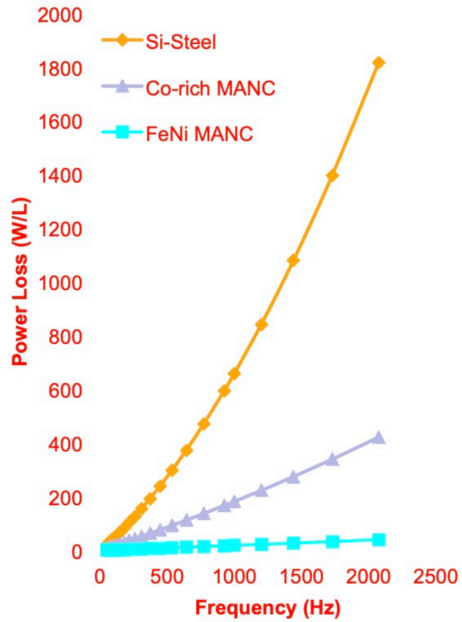


Electrical Steels (Fe-Si)

High-Si steels (6.5wt%):

-high saturation magnetization
-high resistivity
-near-minimal losses
-near-zero magnetostriction

Ideal electrical and magnetic properties, but brittle due to $D0_3$ ordering above 6 wt%*



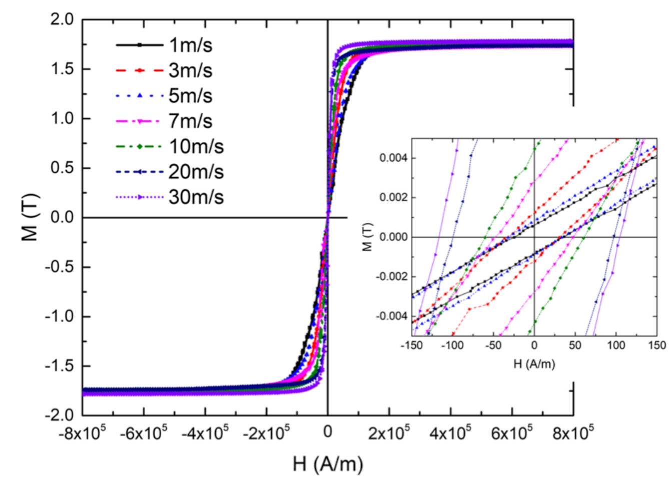


Table 3.6 Typical properties of modern commercial high silicon steels compared to a thin grade GO steel and Fe-based amorphous ribbon [21]

Material	Thickness (mm)	Resistivity (μΩm)	Saturation magnetisation (T)	Core loss (Wkg^{-1}) 50 Hz/1.0 T	400 Hz/1.0 T	5 kHz/0.2 T	20 kHz/0.05 T	Magnetostriction at 400 Hz/1.0 T (με)
10JNEX900	0.1	0.82	1.8	0.5	5.7	11.3	6.9	0.1
10JNHF600	0.1	–	1.9	1.1	10.1	11.2	5.0	–
GO SiFe	0.1	0.48	2.0	0.7	6.4	20.0	14	−0.8
Fe-based amorphous ribbon	0.025	1.30	1.5	0.1	1.5	8.1	3.3	27.0

Can be hot rolled as slabs at high temperatures (1150-1250 °C), but melt spinning of Fe-Si ribbon becoming more common

Ouyang et al. (2017) *AIP Advances* **8**

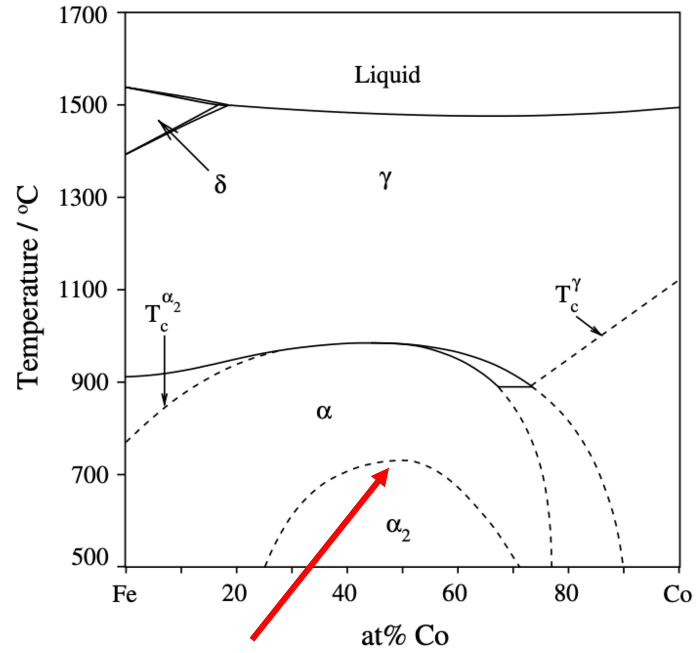
Nishizawa & Ishida (1990)

Permendur/Hiperco (Fe-Co)

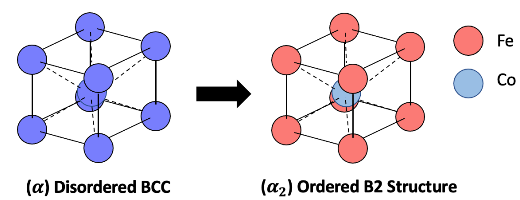
Extremely high saturation magnetization (2.3-2.4 T)

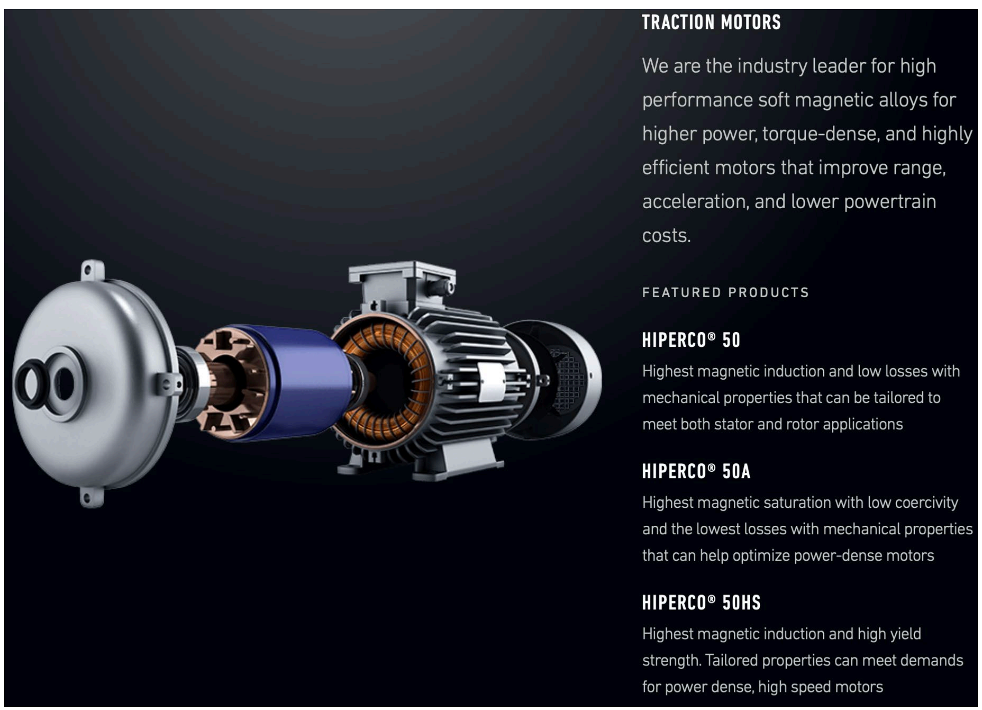
High Curie temperature (T_C~920 °C)

Typically at near equiatomic compositions, with small amounts of V and Nb added to increase ductility. Ideal for **high temperature, high torque** motor applications, more costly due to Co content



Exceptional magnetic properties due to ordering reaction ~700 °C





For Carpenter Hiperco® 50HS ($Fe_{49.05}Co_{48.75}V_{1.9}Nb_{0.3}$)

Commercially Available

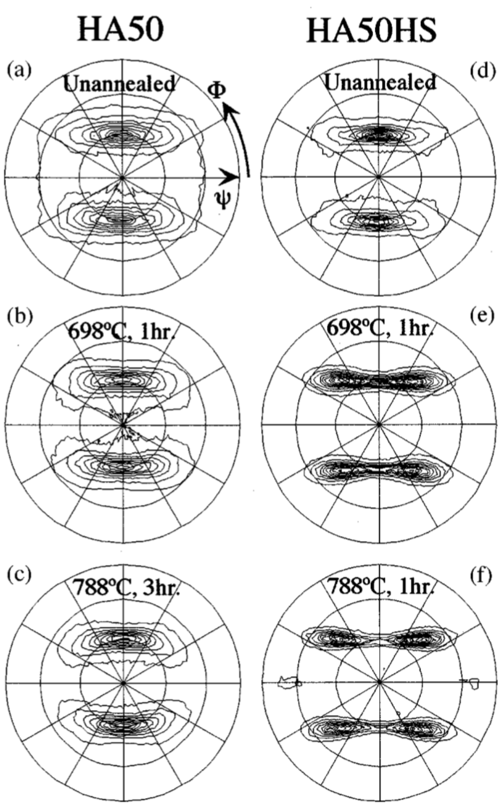
Annealing conditions		Grain size	Saturation
Temp (°F)	Time (h)	(μm)	induction (T)
1300	1	1.13	2.37
1328	1	1.68	2.40
1328	2	2.80	2.43
1350	1	2.33	2.40

Fingers & Kozlowski (1997) *J Appl Phys* **81**

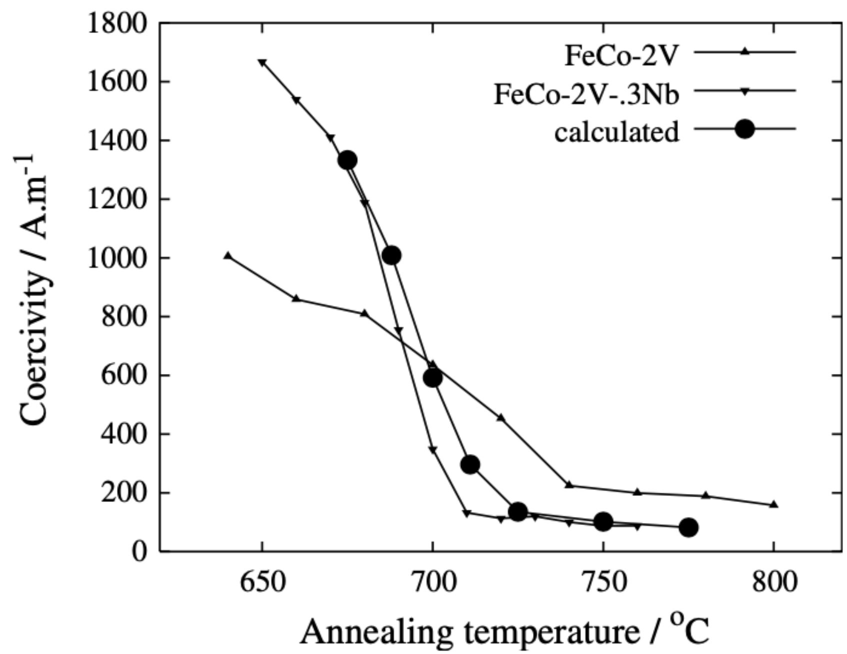
Permendur/Hiperco (Fe-Co)

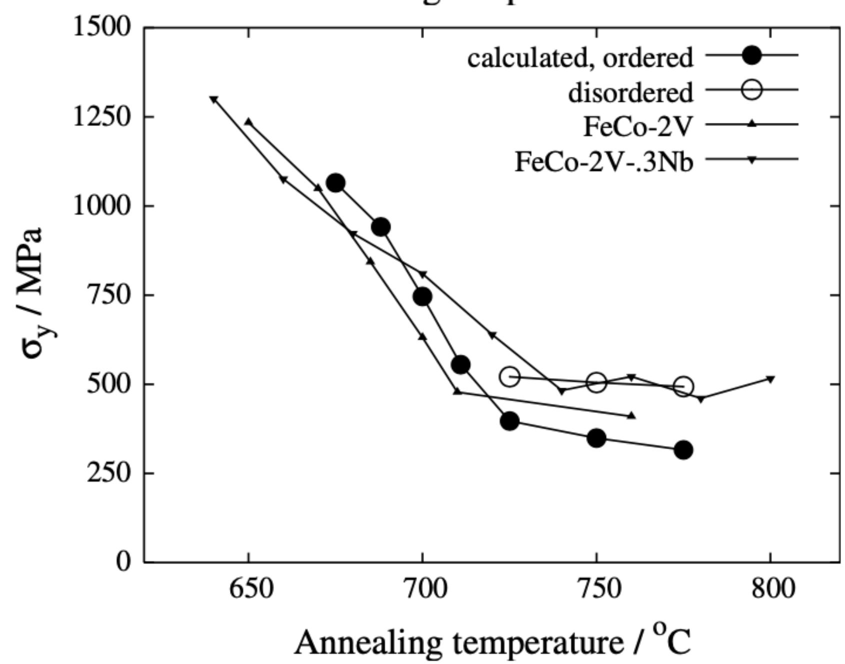
Magnetic/mechanical properties vary greatly with annealing temperature

Typically cold-rolled, develops significant rolling texture



Shang et al. (2000) *J Appl Phys* **87**

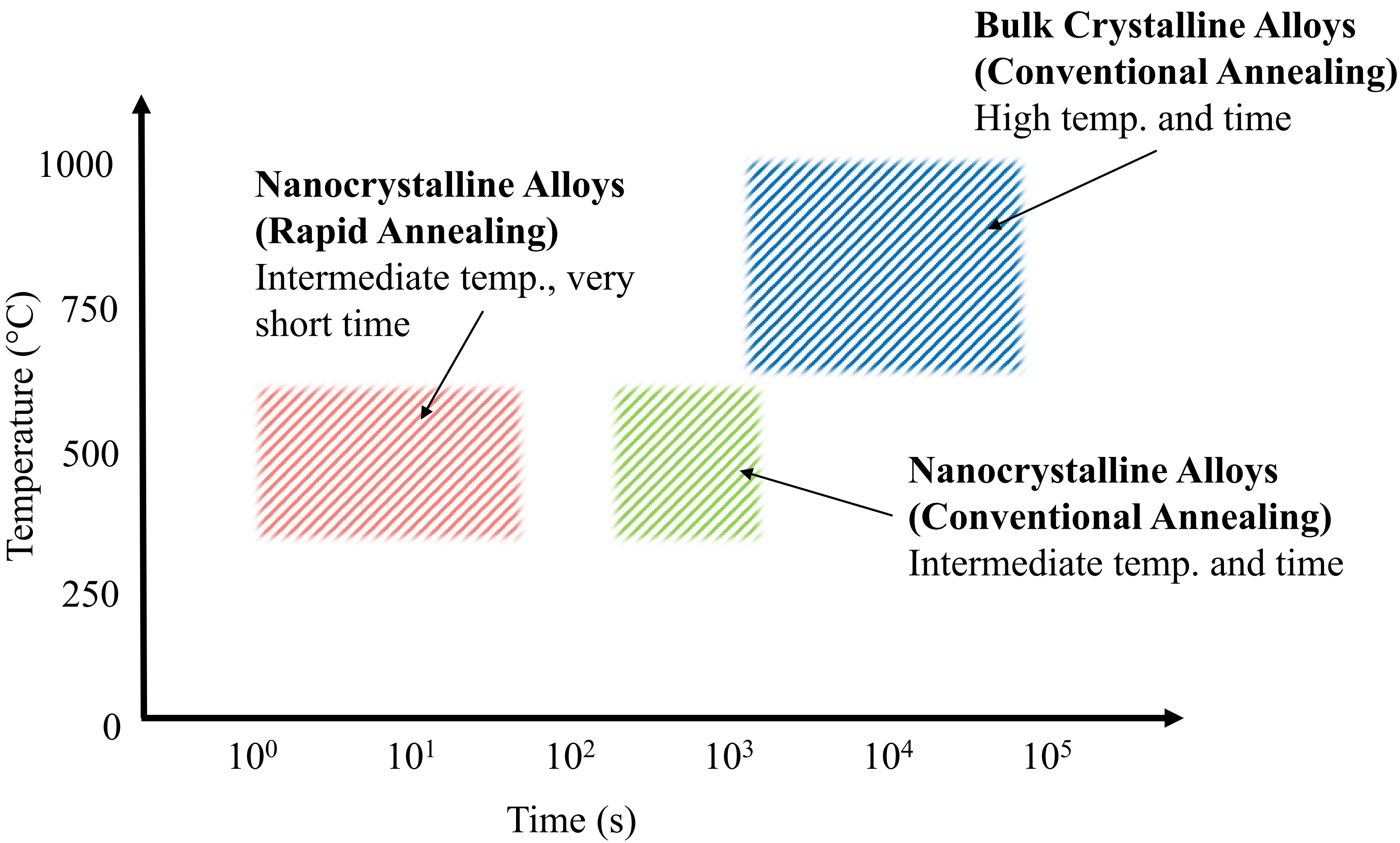




Figs. reproduced from Sourmail (2005) *Prog. Mat. Sci.* **50**. Data from Thornburg (1969) *J Appl Phys* **40**, Hailer (2001) *Master's Thesis* Stoloff & Davies (1966) *Trans Met Soc* **236**

Amorphous and nanocrystalline alloys for motor applications

Processing Comparison of Bulk and Nanocrystalline Alloys



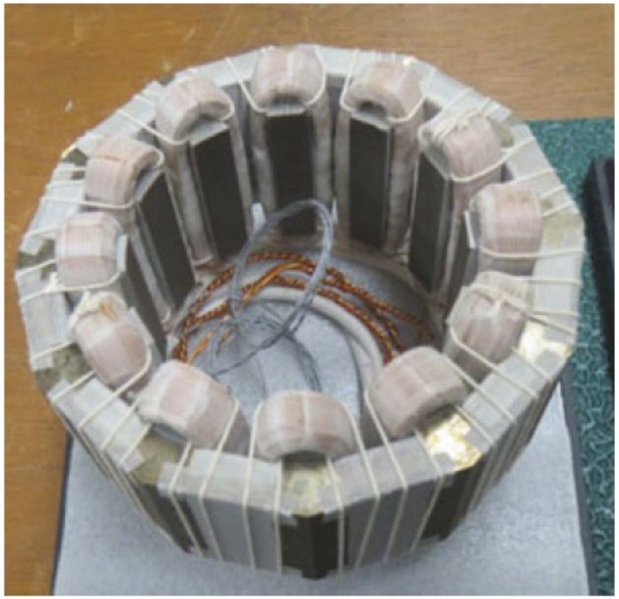
PITT | SWANSON ENGINEERING AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

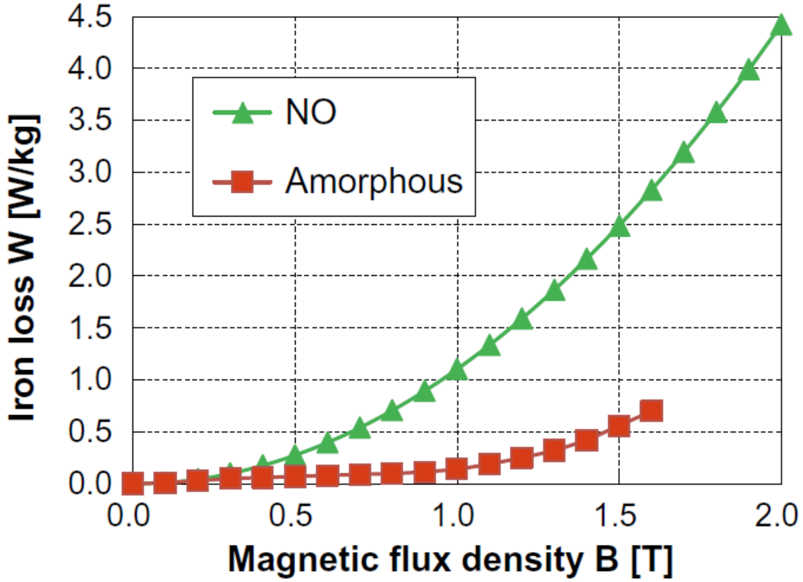
Fe-Based Amorphous (Metglas 2605HB1M)

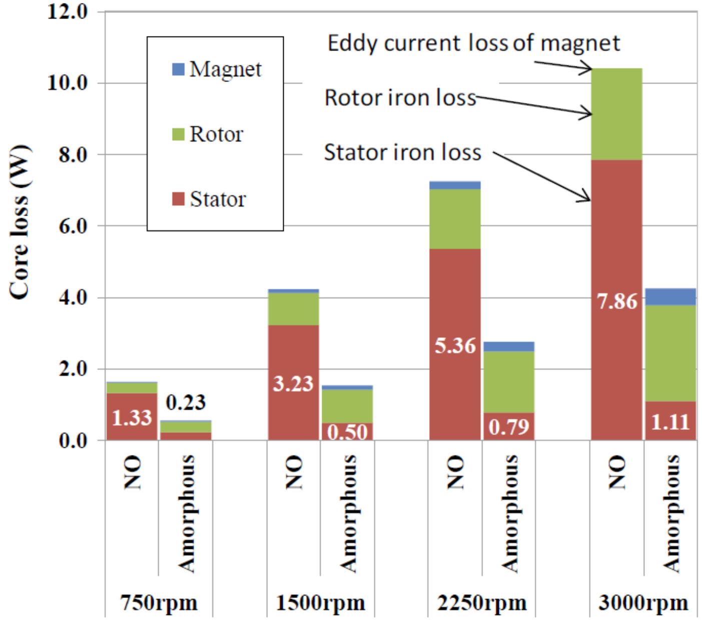
Attractive properties for high-speed applications with electrical switching frequency f>1kHz.

Substantial reductions in iron loss are possible when compared with non-oriented electrical steels.

Limitations include (1) reduced saturation flux densities, (2) magnetostriction, and (3) laminate manufacturing (hardness wears standard dies rapidly).



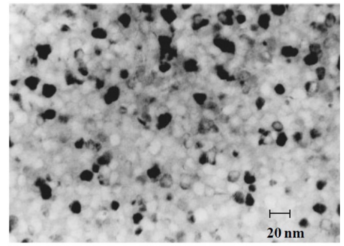


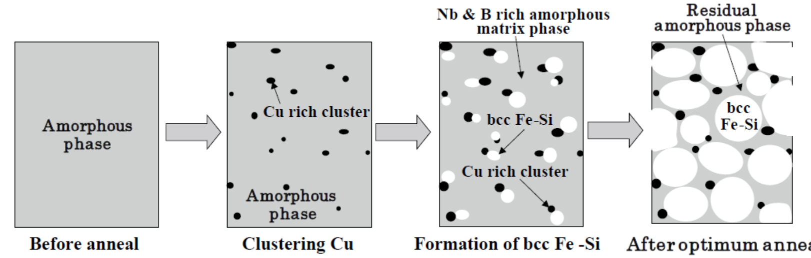


Figs. reproduced from “Magnetic materials for motor drives systems”, K. Fujisake editor, Springer 2019.

PITT | SWANSON ENGINEERING

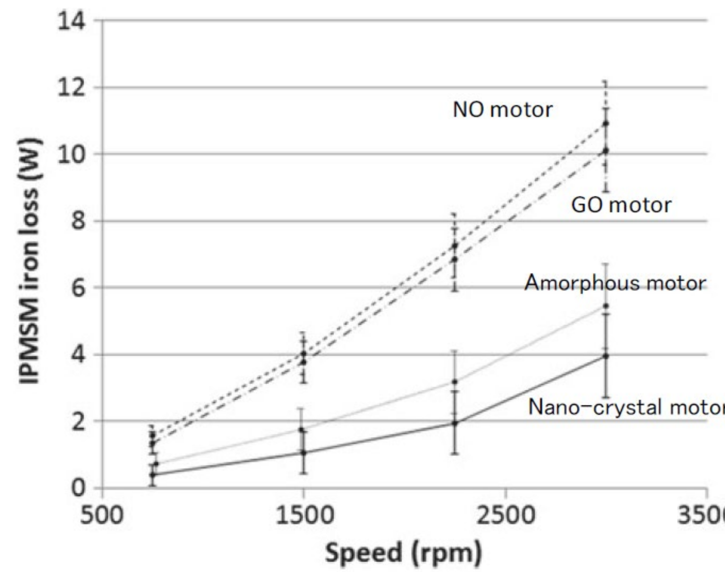
Fe-Based Nanocrystalline (Finemet Hitachi)

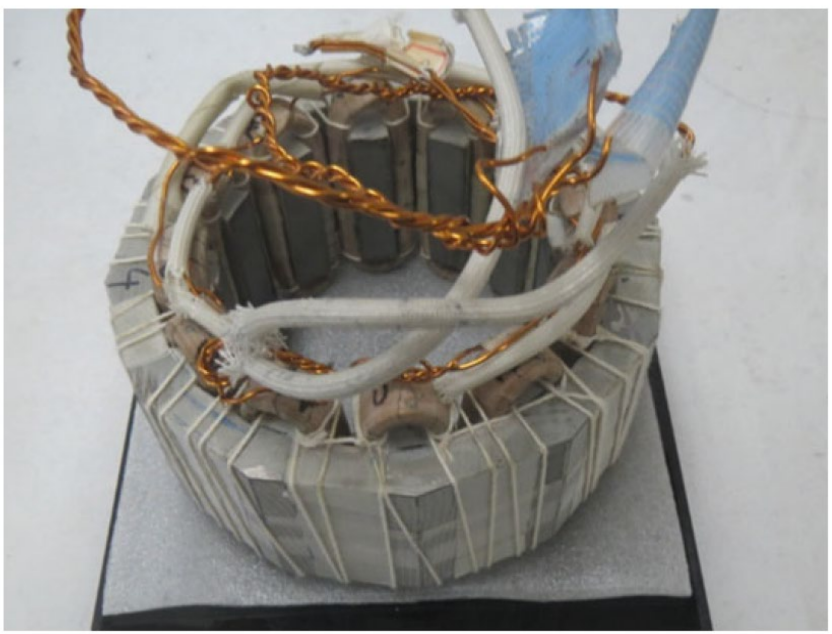


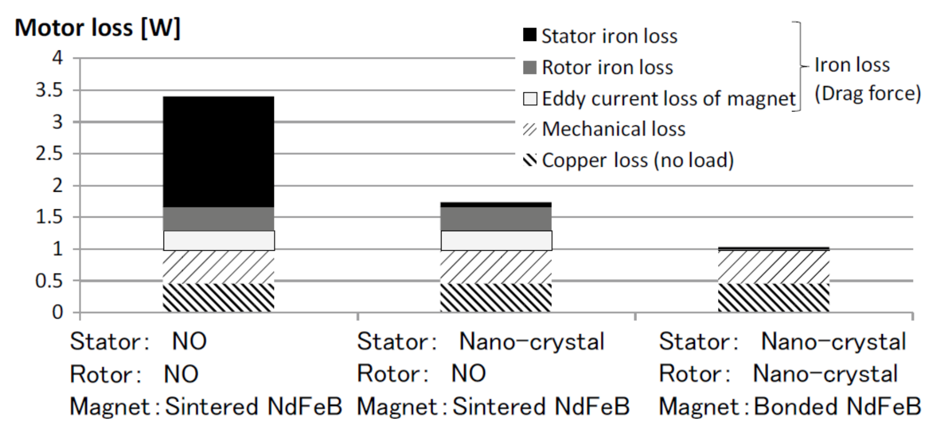


Excellent low loss magnetic properties and near-zero magnetostriction relative to Fe-based amorphous.

Limitations include (1) reduced saturation flux densities and (2) laminate manufacturing and robust performance during high rotational speeds due to ***brittle mechanical properties***.







Figs. reproduced from “Magnetic materials for motor drives systems”, K. Fujisake editor, Springer 2019.

PITT | SWANSON ENGINEERING   AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

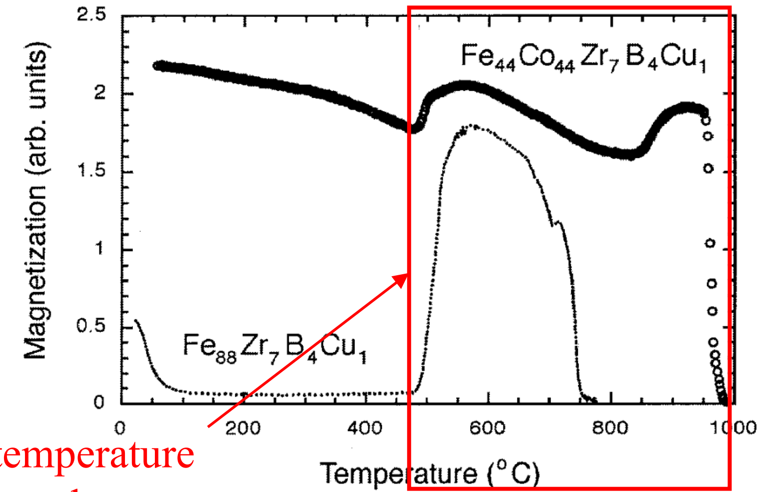
FeCo-based Nanocrystalline (CMU)

Like bulk material, attractive due for high temperature, high induction applications

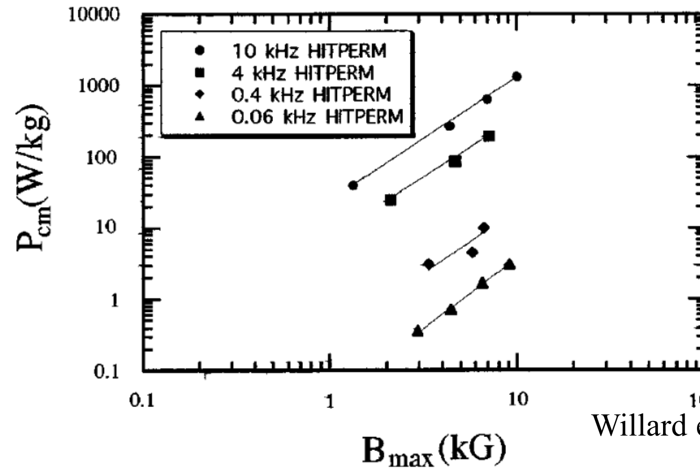
Nanocrystalline FeCo-based alloys offer opportunity for high-speed applications also.

Limitations include (1) magnetostriction, and (2) laminate manufacturing and robust performance during high rotational speeds due to ***brittle mechanical properties***.

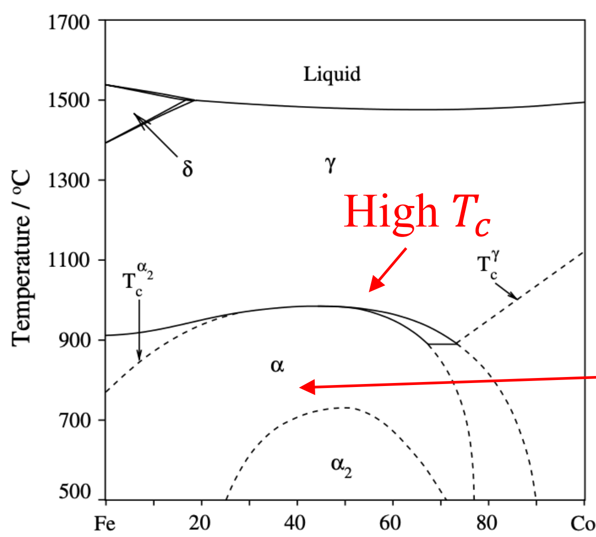
Yoshizawa & Yamauchi (1989) *J Jpn Inst Met* **53**



Much better high-temperature behavior than Fe-based



Willard et al. (1999) *J Appl Phys* **85**



Nishizawa & Ishida (1990)

Exceptional magnetic properties from ordered phase

Nb content can range 0 - ~10 wt.%.

Not yet commercially available.

Co-based Nanocrystalline (CMU)

Exhibits large induced magnetic anisotropy, high resistivity, and relatively low permeability. Primary advantage is substantial improvement in mechanical properties.

High Curie temperatures like HITPERM (NC-FeCo) but with much smaller magnetostriction and lower Bs

Substantially improved mechanical properties mitigates concerns of laminate manufacturing and robust operation at high speeds.

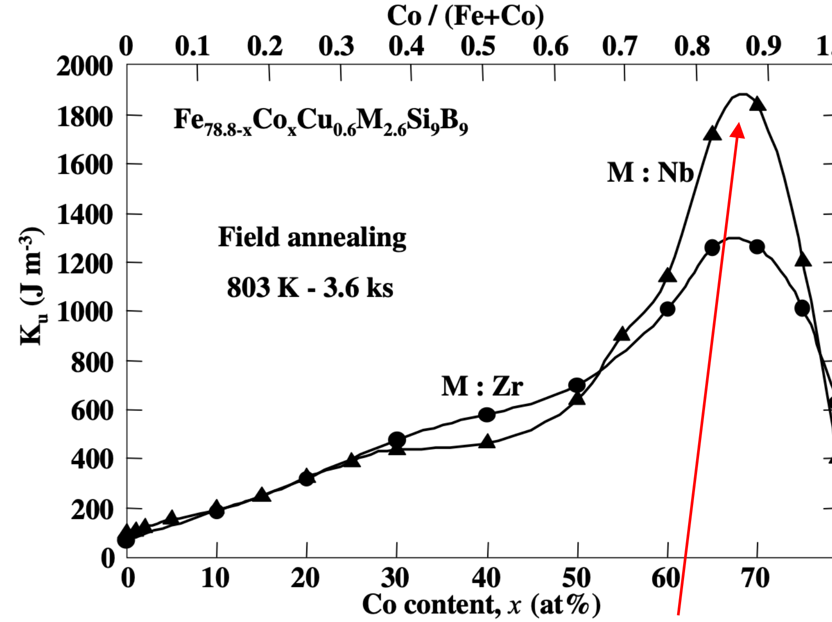
Willard et al. (2002) *IEEE Trans Mag* **38**

Alloy	T_{ann} (°C)	D (nm)	m_s (emu/g)	H_c (Oe)	λ_s (ppm)
1 (FCC)	550	10±3	142	0.3	11.5
1 (BCC)		10±1			
2 (FCC)	550	17±3	141	1.6	13.5
2 (BCC)		9±1			

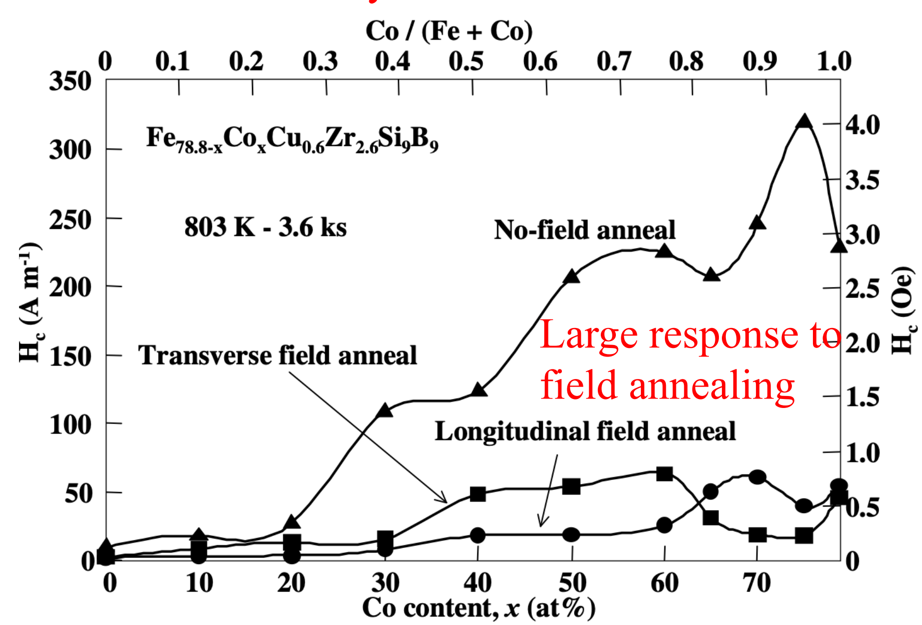
*Alloy 1: $(Co_{0.95}Fe_{0.05})_{88}Zr_7B_4Cu_1$
Alloy 2: $(Co_{0.95}Fe_{0.05})_{88}Zr_7B_4$

Not yet commercially available.

Yoshizawa et al. (2004) *Mat Sci Eng A* **375-377**



High anisotropy possible for Co-rich alloy with Nb addition

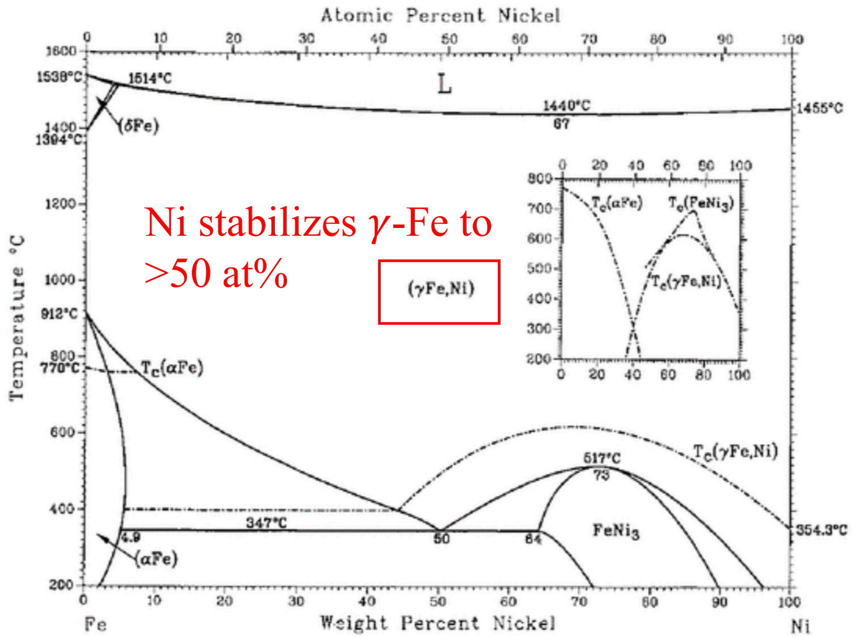


Yoshizawa et al. (2004) *Mat Sci Eng A* **375-377**

FeNi-based Nanocrystalline (CMU)

Swartzendruber, Itkin, & Alcock (1992)

Like Co, Ni used to increase ductility relative to Fe-based alloy but at significant reduction in raw material cost as compared to Co-based

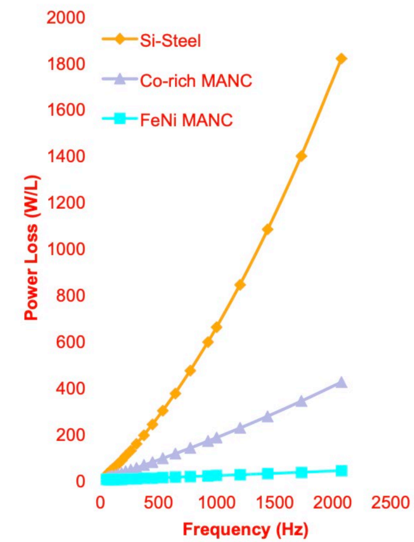


...also allows for a thinner ribbon, reducing eddy losses, ***substantially improved mechanical properties mitigates concerns of laminate manufacturing and robust operation at high speeds***.

	H_c (A/m)	B_s (T)	t (μm)	$W_{1.0/400}$ (W/kg)	$W_{1.0/1k}$ (W/kg)
NC-$(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{15}$	7.0	1.5	20	0.9	2.3
NC-$Fe_{85}B_{13}Ni_2$	4.6	1.5	13.4	2.3	6.3
NC-$Fe_{89}Hf_7B_4$	5.6	1.59	17	0.61	1.7
Fe-based amorphous	2.4	1.56	23.9	1.6	4.7
3% Si-steel	55	1.4	100	8.5	27.1
6.5% Si-steel	18.5	1.3	100	5.7	17.2

Reproduced from Aronhime et al. (2017) *JOM* **69**, with data from Suzuki et al. (2017) *Appl Phys Lett* **110**, Suzuki et al. (1993) *J Appl Phys* **74**, and Chen (1986) *Magnetism and Metallurgy of Soft Magnetic Materials*

Not yet commercially available.



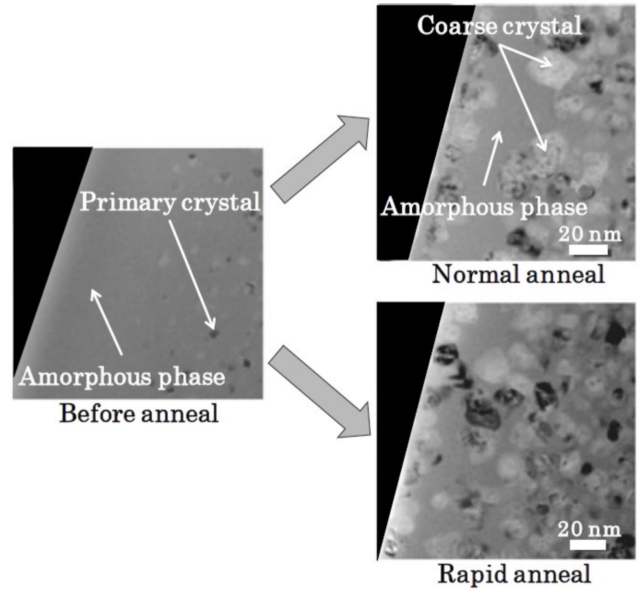
Very low losses → good for high-speed motor application

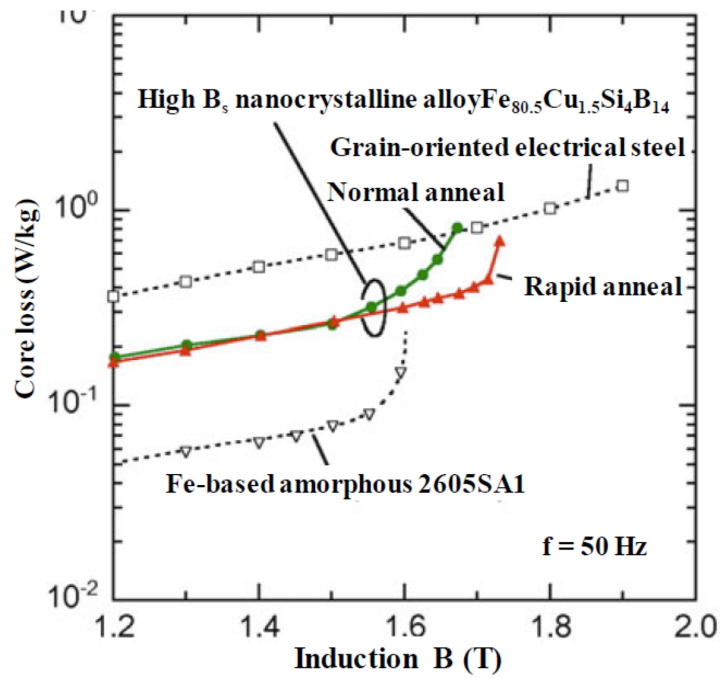
Fe-Based Nanocrystalline (High Bs – Rapid Annealing)

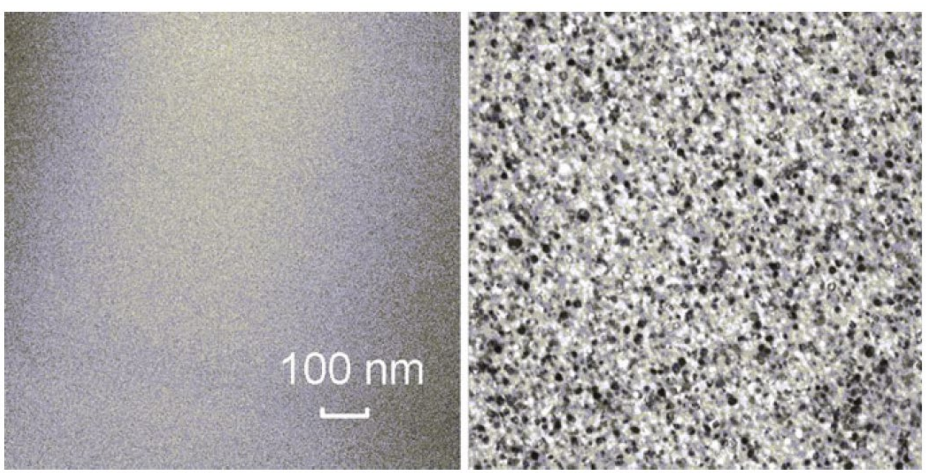
Reduced Nb content and other glass formers.

Rapid thermal processing to achieve desired microstructure with larger ferromagnetic content.

Primary limitations: difficulty manufacturing laminations of substantial size given the need to carefully control rapid thermal processing conditions.







(a) Before anneal (b) After rapid anneal

Not commercially available.

Figs. reproduced from "Magnetic materials for motor drives systems", K. Fujisake editor, Springer 2019.

Acknowledgements

AMPED ADVANCED MAGNETICS FOR POWER & ENERGY DEVELOPMENT

Carnegie Mellon University

University of Pittsburgh

NC STATE UNIVERSITY

CBMM

Industry Sponsored Project
Data Sheet Development

University of Pittsburgh / AMPED – CBMM

- Standardized Testing of Materials and Electromagnetic Components
- Benchmarking of Nanocrystalline Soft Magnetic Cores vs. Industry Standard
- Electric Motor Applications Alloy Review

We acknowledge Companhia Brasileira de Metalurgia e Mineração (CBMM) for funding support of the work.