Selecting

Optimal Lamination Materials

Steve Constantinides

Orlando, Florida, January 23, 2019

Magnetics & Materials LLC

Why...

Why is the selection of soft magnetic material important?

- Limits device performance
- Affects product cost
- Constraints on material availability
- Product efficiency to meet increasingly more stringent standards

Key Figures of Merit

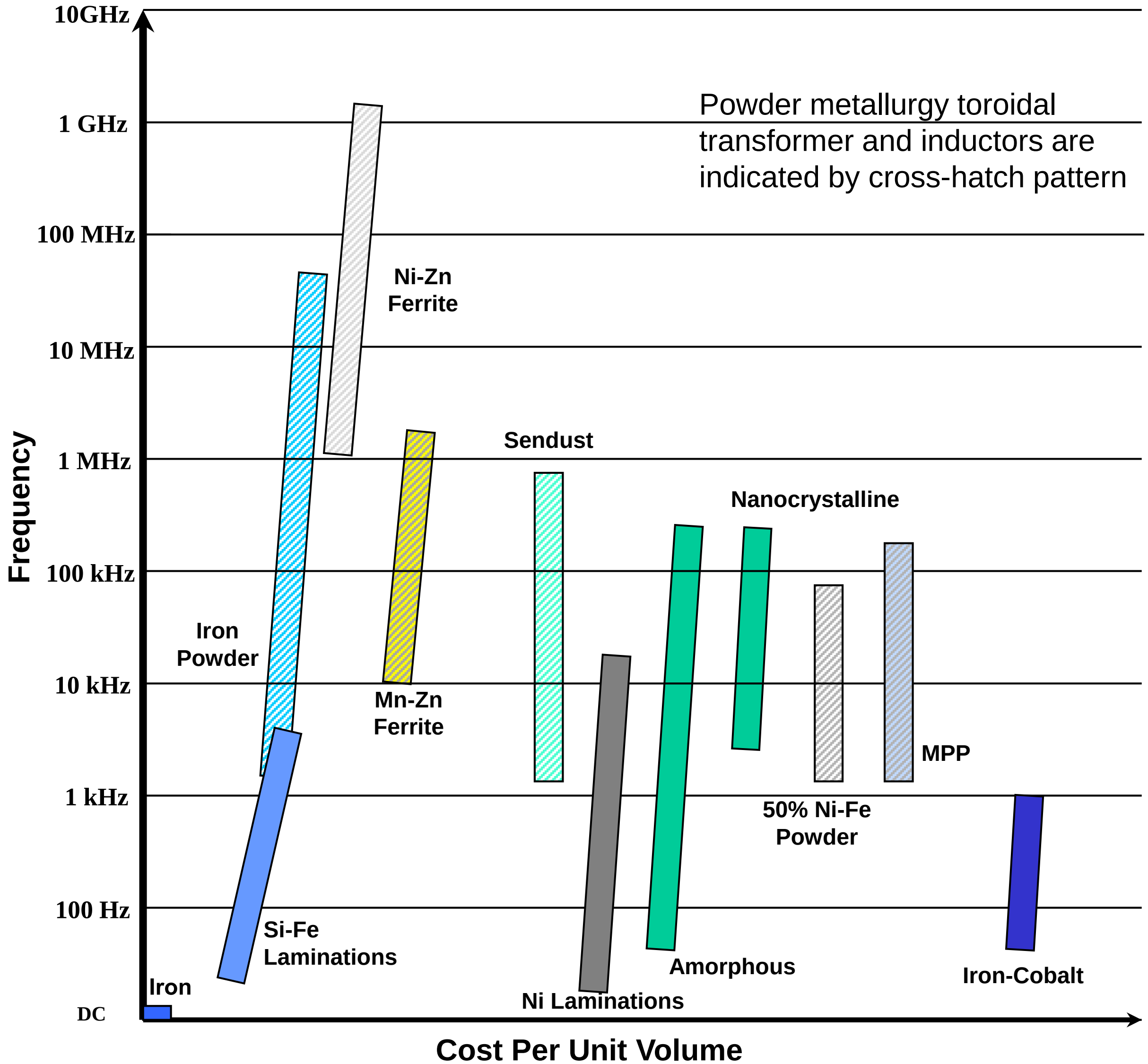
- High permeability: initial (μ_0) and maximum (μ_{max})
  - Ease of magnetization
- High saturation magnetization (M_S, J_S)
  - Flux carrying capability
  - Relates to required product size
- Low coercivity (H_{cB})
  - Relates to hysteresis energy loss
- High resistivity (ρ)
  - Relates to eddy current energy loss
- Hysteresis loop shape
  - Complex hysteresis energy loss factor

Key Figures of Merit (Other)

Other

- Usable temperature range
- Small magnetization change with temperature (RTC)
- Corrosion resistance
- Compromise of physical strength and malleability
  - Bend, form, stamp and press but with adequate yield strength to resist deformation in operating equipment
- Manufacturability and formability
- Low magnetostriction

Key Figures of Merit (Cost)



Material Cost

For example, frequency of rotating motor (sinusoidal excitation):

$$f = \frac{\text{rpm x poles}}{60}$$

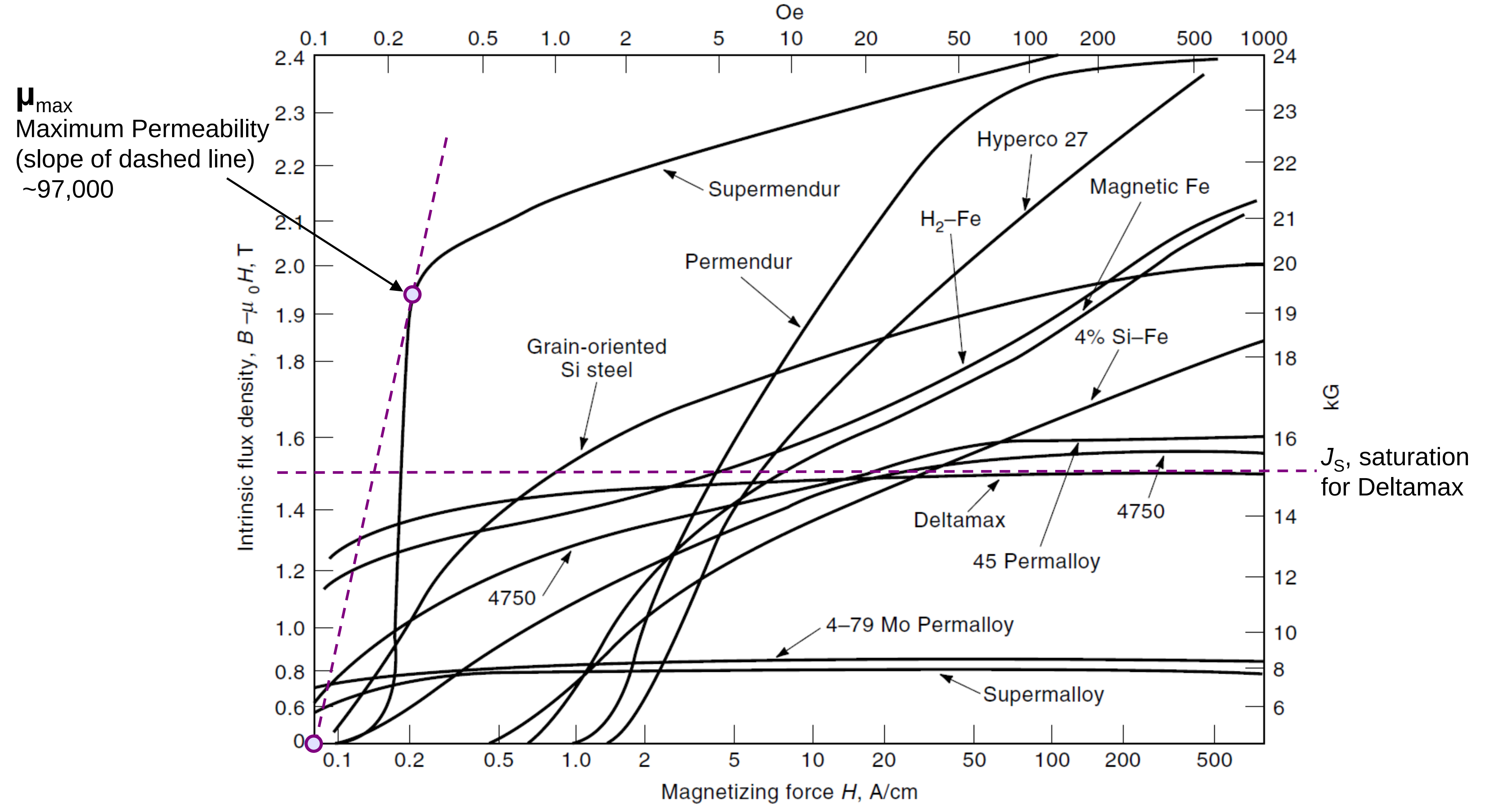
(10,000 **x** 8)/60= 1,333 Hz

Cost of Operation

		Hours/day	Days/week	Weeks/year	Hours / year
Cost reduction through efficiency improvement		24	7	52	8736
Motors for comparison purposes are single phase		1 HP =		745.7 watts	

Motor Horsepower (HP)	**0.5**	**10**	**100**	**500**	**1000**	**1000**
Watts	373	7,457	74,570	372,850	745,700	745,700
Motor % Load	100%	100%	100%	100%	100%	100%
Energy Cost, cents per kWh	$ 0.10	$ 0.10	$ 0.10	$ 0.10	$ 0.10	**$ 0.16**
Base motor efficiency, %	**70%**	91%	91%	91%	91%	91%
Cost of operation per hour	$ 0.05	$ 0.82	$ 8.19	$ 40.97	$ 81.95	$ 131.11
Cost of operation per year	$ 465	$ 7,159	$ 71,587	$ 357,936	$ 715,872	$ 1,145,395
High efficiency motor, %	**85%**	94%	94%	94%	94%	94%
Cost of operation per hour	$ 0.04	$ 0.79	$ 7.93	$ 39.66	$ 79.33	$ 126.93
Cost of operation per year	$ 383	$ 6,930	$ 69,303	$ 346,513	$ 693,025	$ 1,108,840
Cost savings per year, $	**$ 82.11**	**$ 228.47**	**$ 2,284.70**	**$ 11,423.49**	**$ 22,846.98**	**$ 36,555.17**

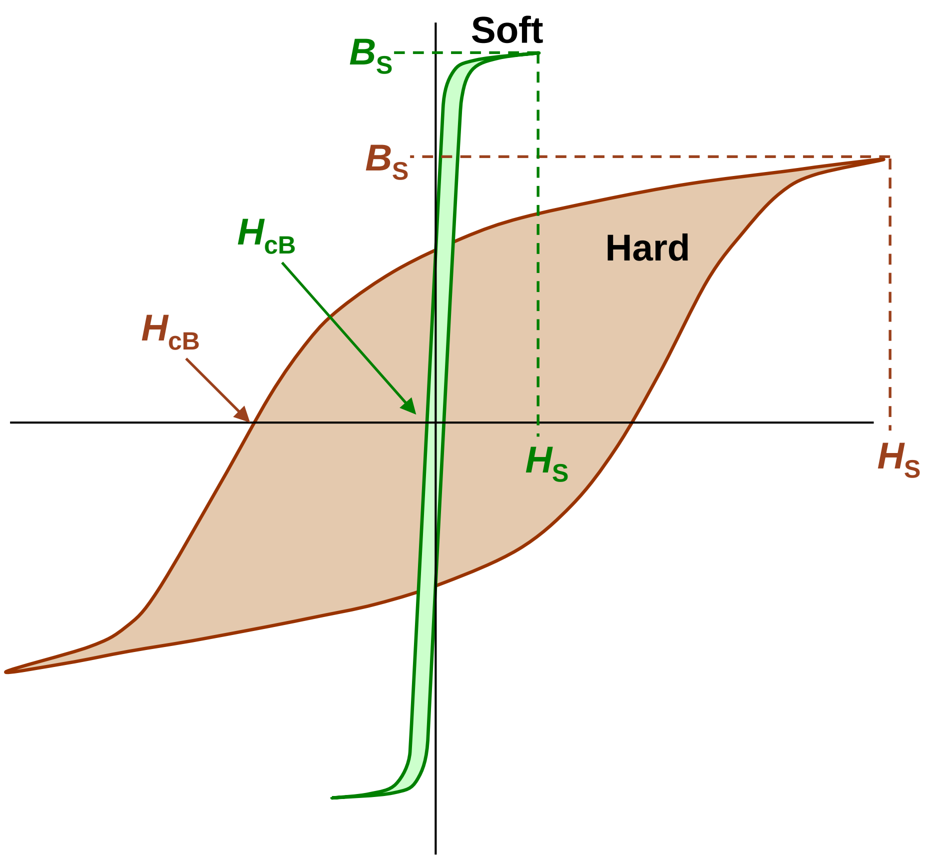
Permeability and Saturation



Source: Kirk-Othmer Encyclopedia of Chemical Technology; Magnetic Materials, Bulk; Jack Wernick, Bell Telephone Laboratories, Inc.

Hysteresis Energy

Difference between permanent and soft magnetic materials



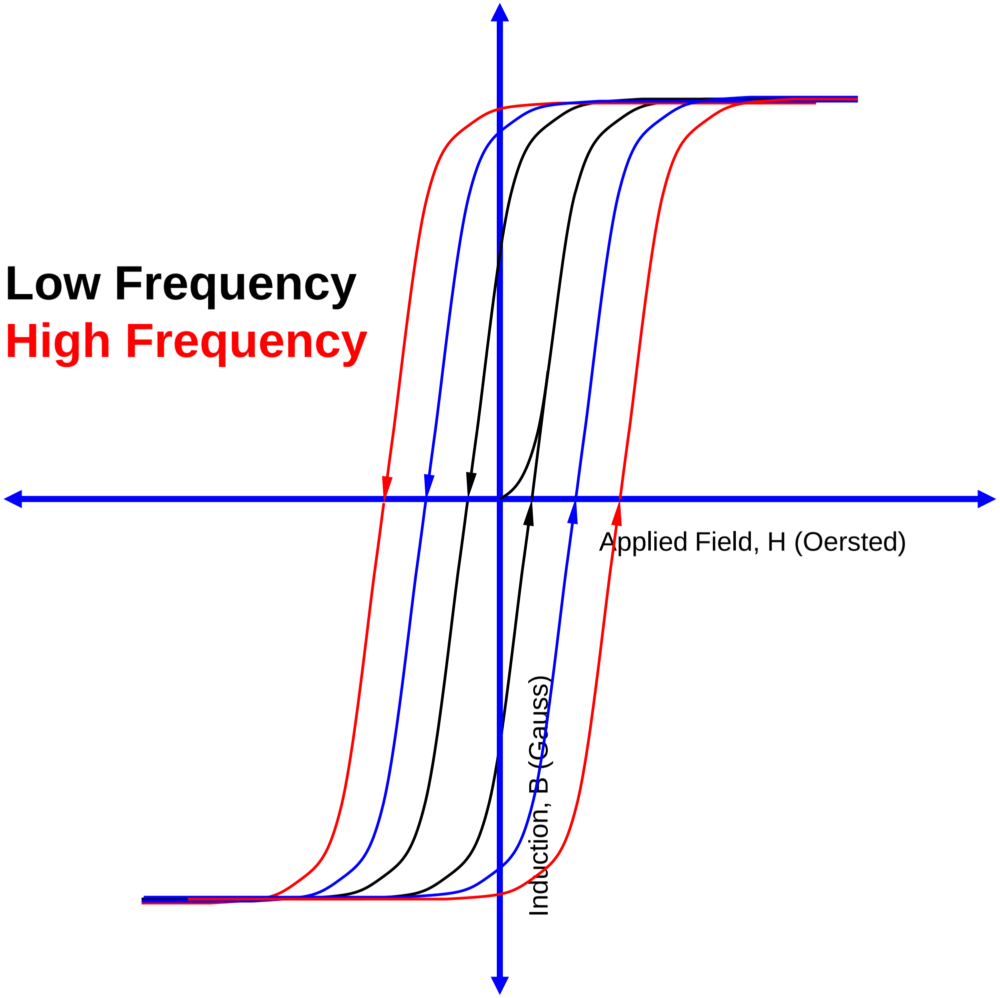
- A narrow hysteresis loop implies a small amount of dissipated energy. This is desirable to minimize hysteresis energy loss in transformers and rotating machinery (motors).
- The energy expended in driving the material through its hysteresis loop is represented by the area within the loop (the shaded area).
- A narrow loop with low hysteresis energy is typical of soft magnetic materials.

These are “Normal” or “B” curves, not the B-H Intrinsic curves.

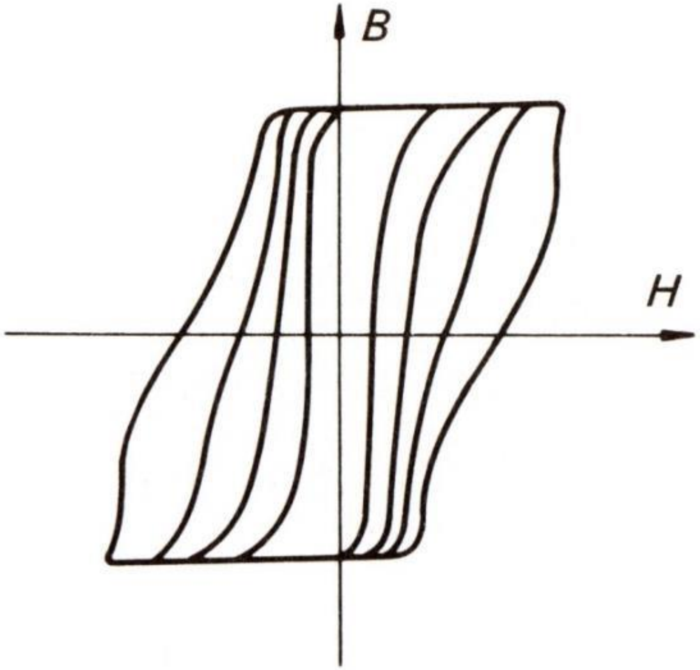
Hysteresis Loss - Frequency Effects

Increase in H_{cB}

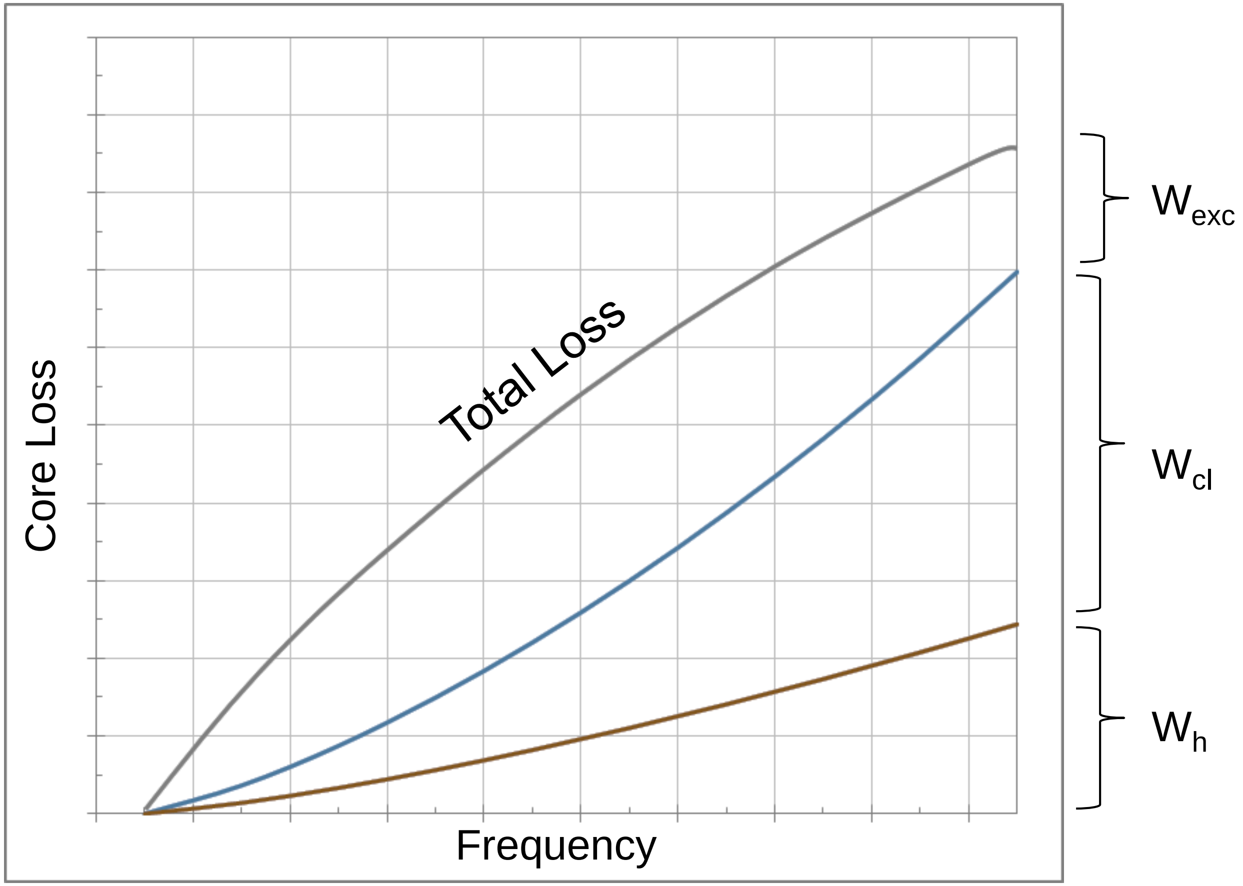
Low Frequency
High Frequency



Loop shape distortion



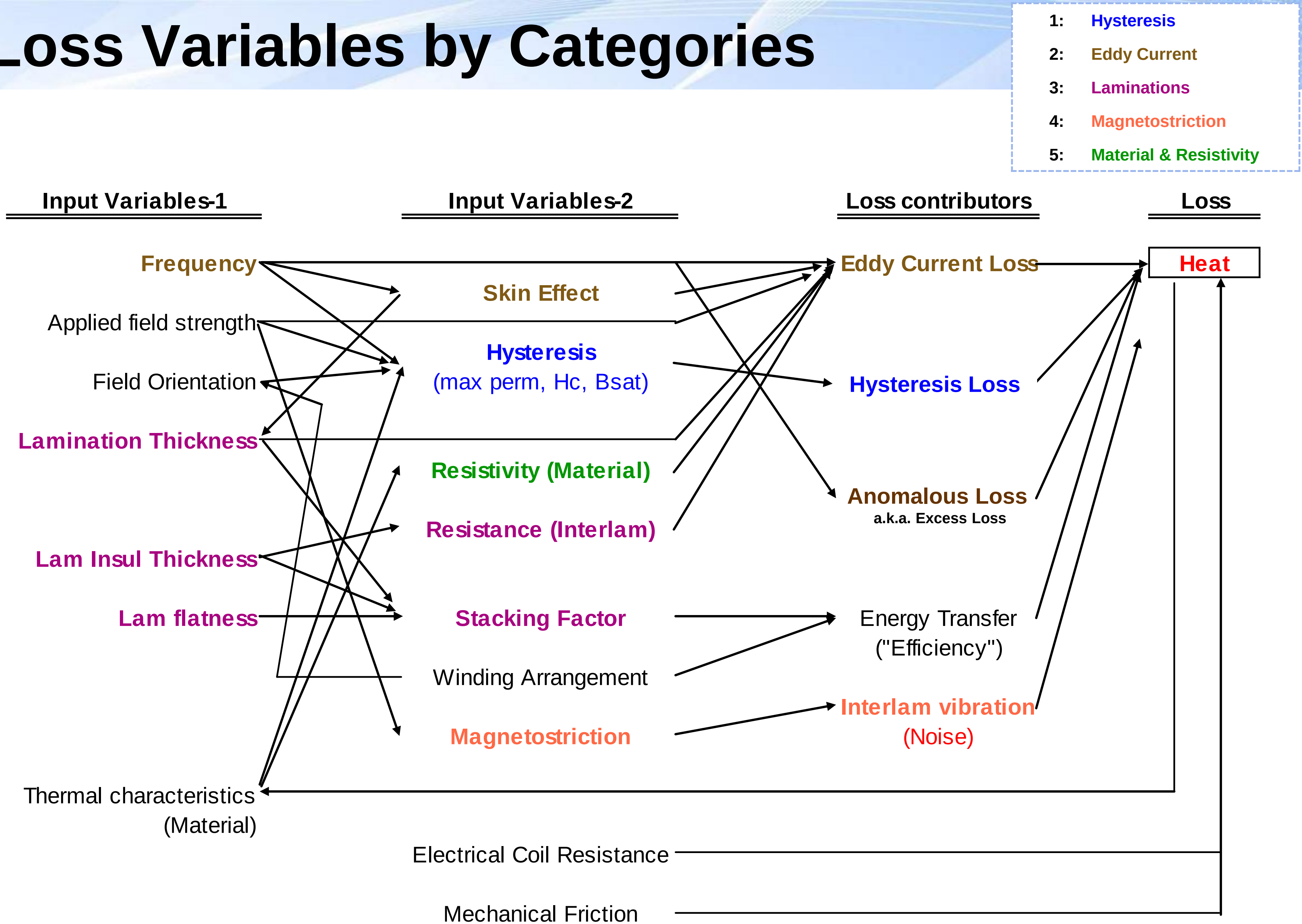
Core Loss



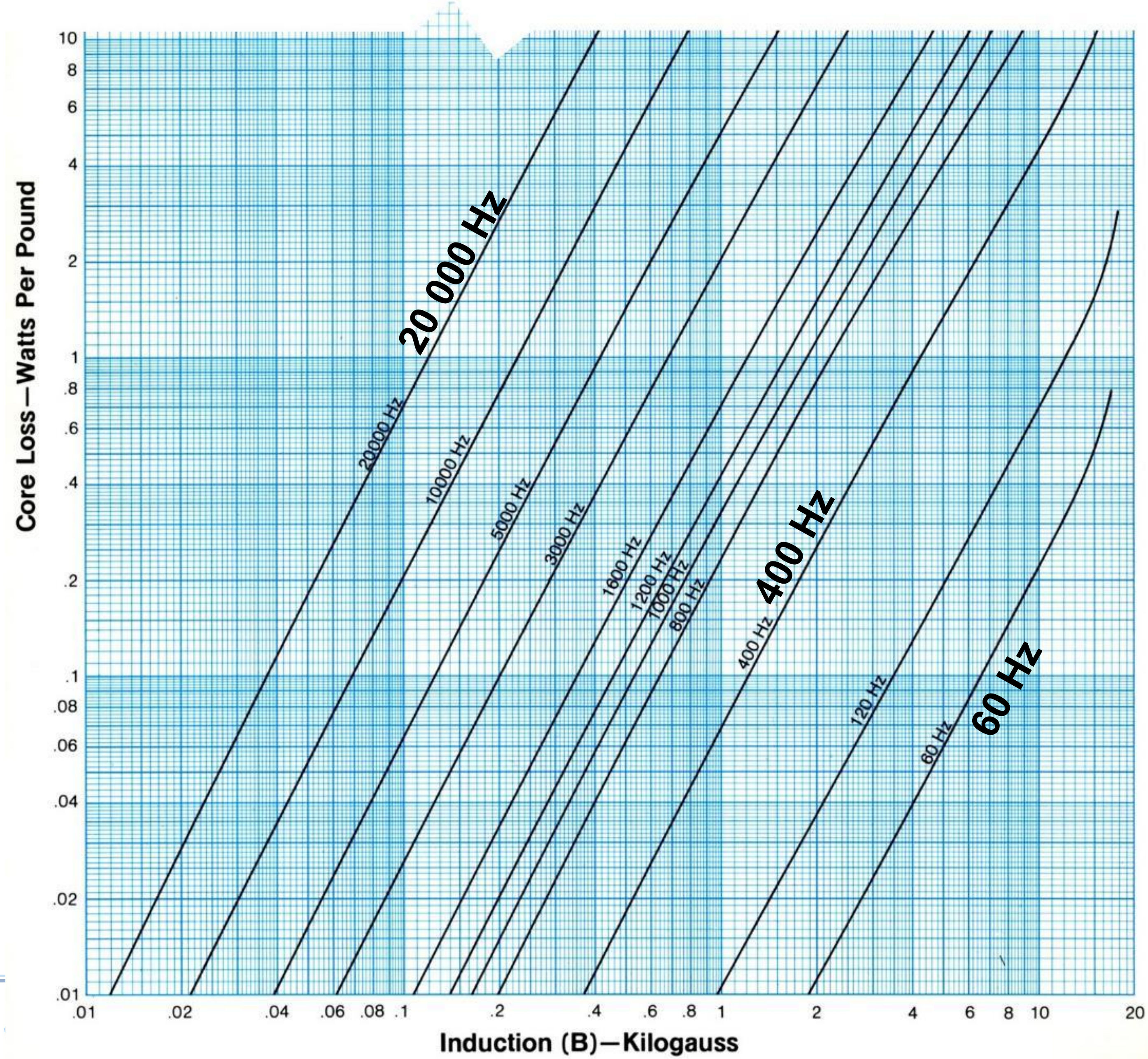
$$W = W_h + W_{cl} + W_{exc}$$

Total core loss = Hysteresis Loss + Classical (eddy current) loss + Excess or Anomalous Loss

Loss Variables by Categories



Core Loss Measurements

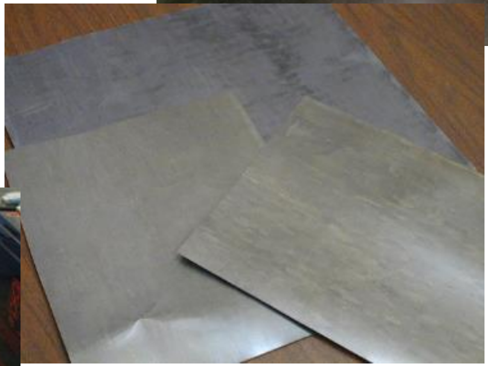


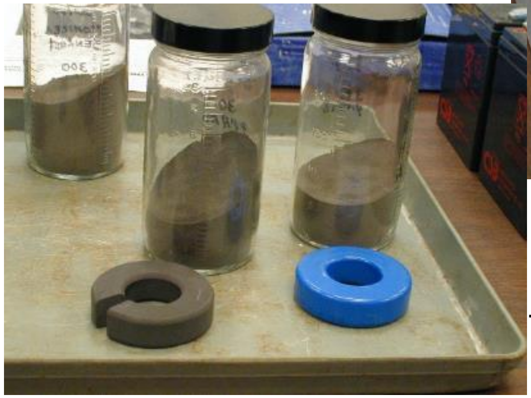
0.011 Silectron 53 (AISI M4) Core Loss

Test: Epstein; SRA; Parallel; A343

Soft Magnetic Material Forms

- Bulk Materials
- Sheet or Strip Products
- Powders





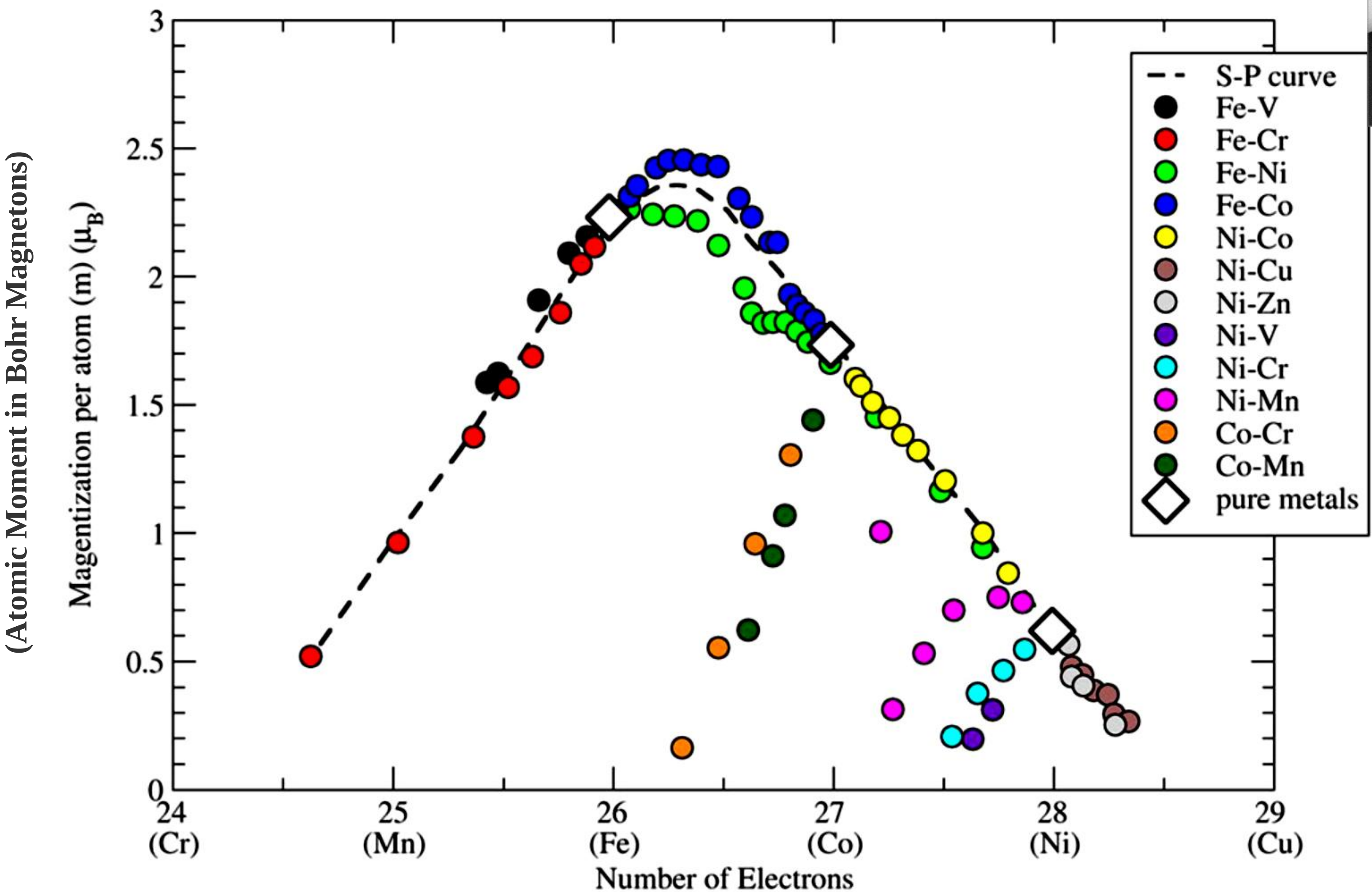
Converted to composite or fully dense bulk material, e.g. SMCs

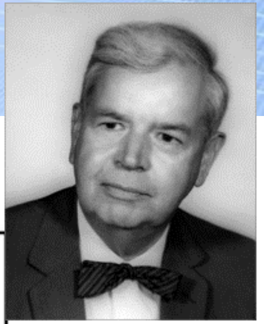
IEC Classifications for Soft Magnetic Materials

Source: IEC International Standard 60404-1 ed3.0 (2016-10)

- A. Irons
- B. Low carbon mild steels
- C. Silicon Steels
  - C1. Solid material
  - C2. Flat material
    - C21. Isotropic steels
    - C22. Anisotropic steels
    - C23. Thin silicon steels
- D. Other steels
  - D1. Solid material
  - D2. Flat material
- E. Nickel-Iron alloys
  - E1. 72-83 Ni
  - E2. 54-68 Ni
  - E3. 45-50 Ni
    - isotropic
    - anisotropic
  - E4. 35-40 Ni
  - E5. Approx 30 Ni (temp. compensation)
- F. Iron-Cobalt alloys
  - F1. 47-50 Co
    - isotropic
    - Non-isotropic
  - F2. 35 Co
  - F3. 23-27 Co
- G. Other Alloys
  - G1.Al-Fe alloys
  - G2. Al-Si-Fe alloys
- H. Soft Magnetic Ceramics
  - H1. Soft ferrite
- I. Amorphous
  - Amorphous metallic glass
- J. Nano-crystalline
  - Nano-crystalline

Slater-Pauling Curve





John C. Slater

Linus Pauling

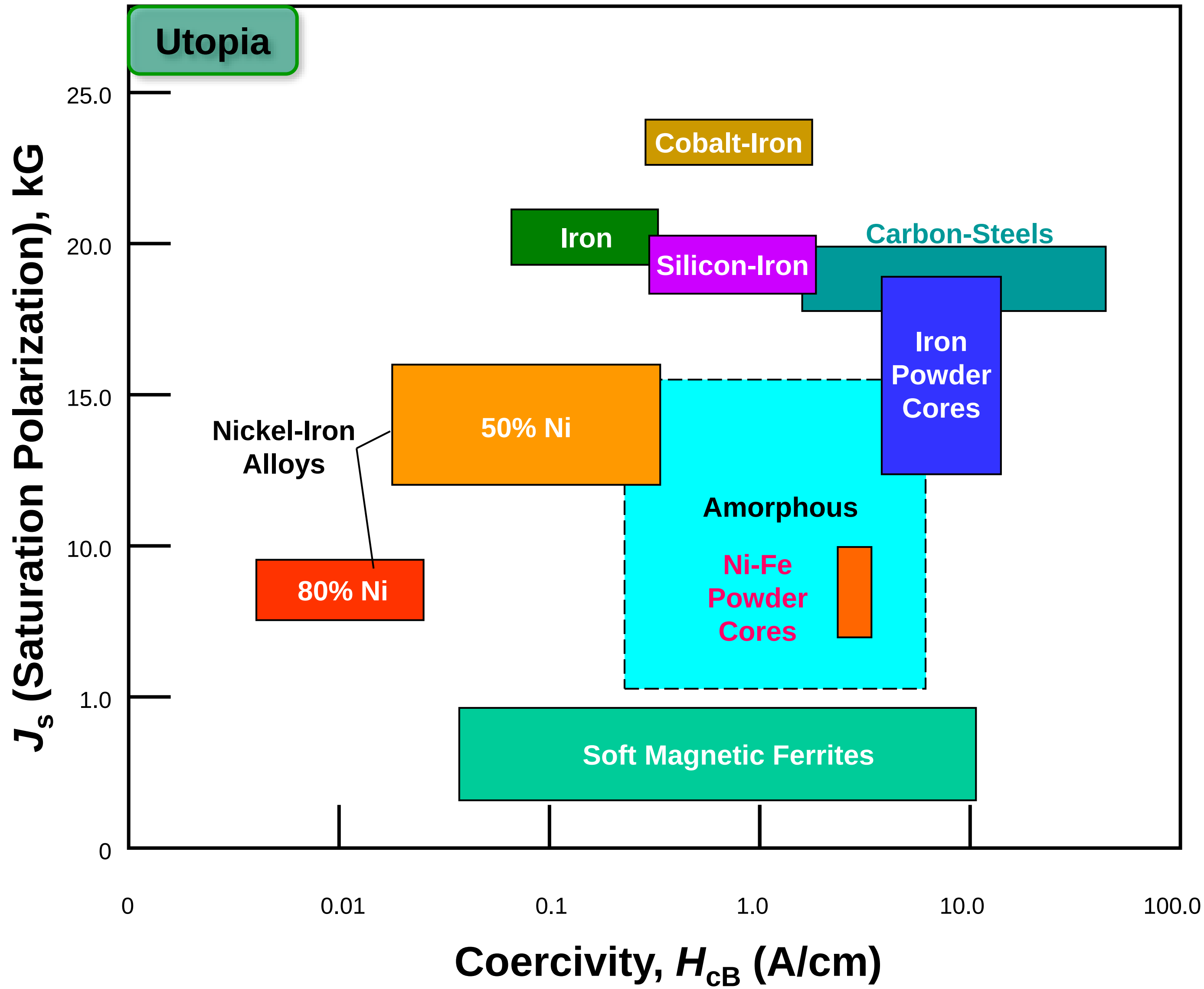
R.M. Bozorth, Ferromagnetism, IEEE, 1993, p.438-441

Color-edited by Dr. Bill McCallum

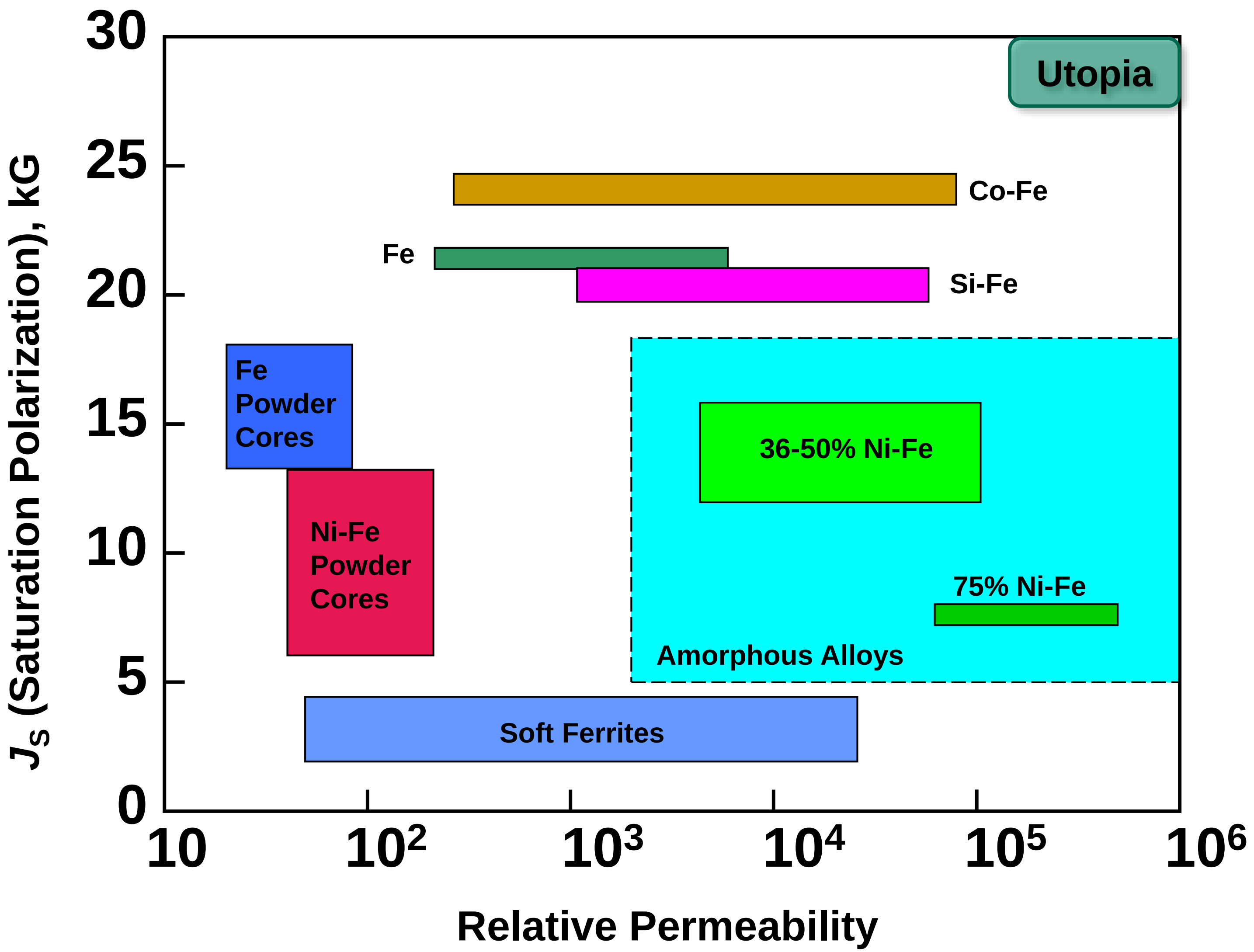
Soft Magnetic Materials: Compositions and Properties

	Material	Composition (%), Fe bal.							J_S	H_{cB}	μ_{init}	μ_{max}	Resist.
		Co	Cr	Ni	Mo	V	Cu	Other	G	Oe			μ-ohm•cm
Soft Magnetic Materials	Low carbon steel (M-19)								19,000	0.2-0.5	300	10,000	47
	Iron-Silicon (Si-Fe)							3 - 6	19,700	0.6	350	50,000	50
	Deltamax			50					16,000	0.04-0.16	500	100,000	45
	Alloy 4750			48					15,500	0.02-0.10	7,000	100,000	45
	Mu Metal		2	77			5		7,500	0.01-0.03	20,000	~100,000	60
	Supermalloy			79	5				7,800	~0.005	60,000	800,000	65
	Perminvar (7-70)	7		70					12,500	0.6	850	4,000	16
	Kovar	17		29					12,000			3,000	49
	Perminvar (45-25)	25		45					15,500	1.2	400	2,000	19
	Hiperco 27	27	0.6	0.6					24,200	1.0	650	10,000	
	Hiperco 35	35	0.5						24,200	1.0	650	10,000	20
	2V-Permendur	49				2			24,000	2.0	800	4,900	26
	Supermendur	49				2			24,000	0.2		92,500	
	Hiperco 50A	49				2			24,000	< 1		15,000	40
	Permendur	50							24,500	2.0	800	5,000	7
	Metglas 2705M	79		3.5	3.8			9.2	7,700	0.4		600,000	136
	Metglas 2714A	85		3				8	5,700			1,000,000	142

Comparing Magnetic Properties



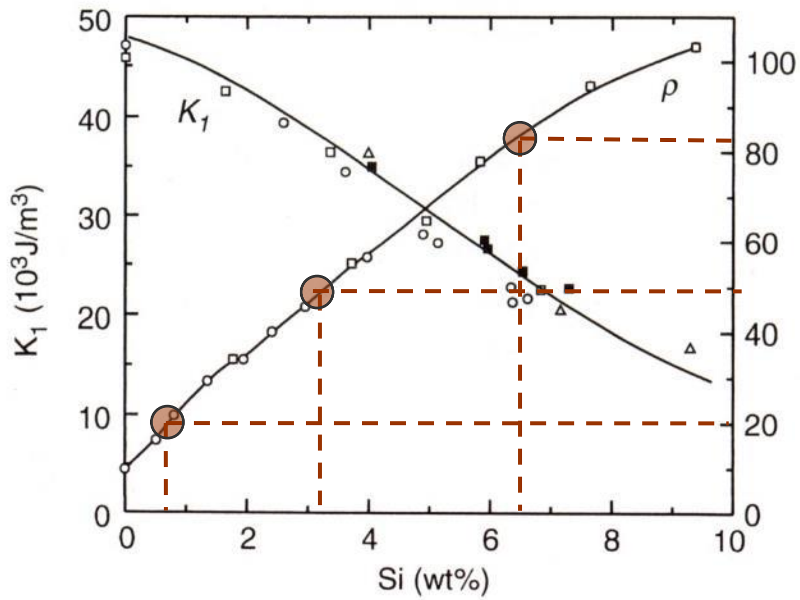
Saturation vs. Permeability Comparisons



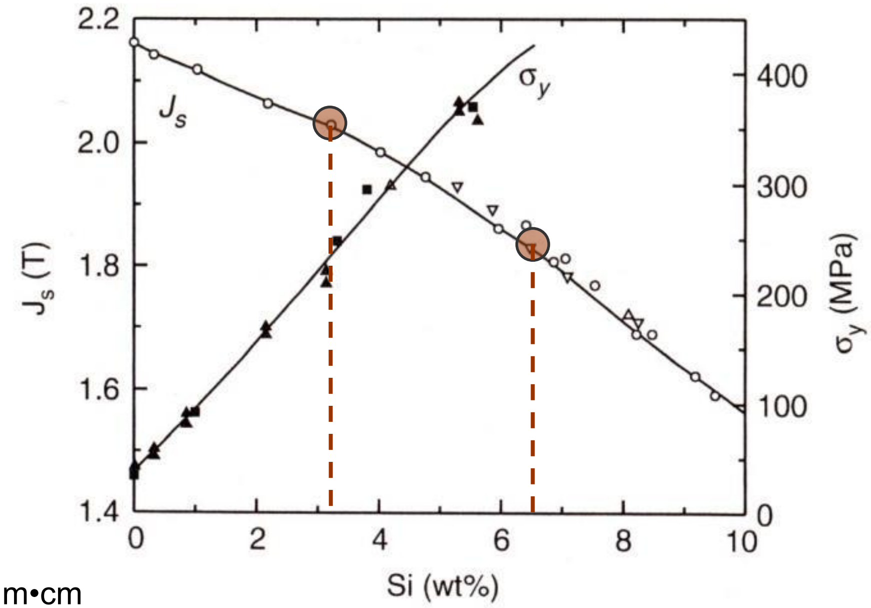
Resistivity of Silicon-Iron (Si-Fe)

Composition change to increase resistivity also...

- Decreases saturation polarization
- Increases yield strength (brittleness)



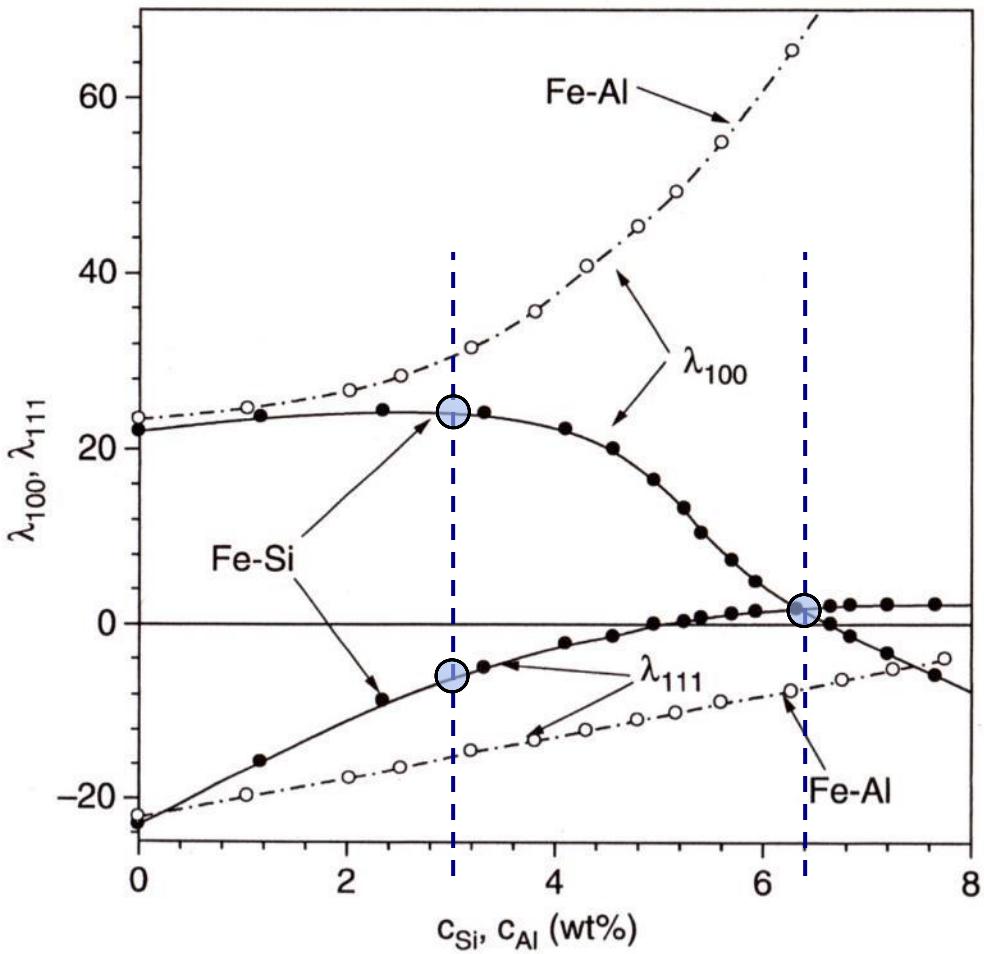
or micro-ohm•cm



K_1 = Magnetocrystalline Anisotropy constant
ρ (Rho) = Electrical Resistivity

J_S = Saturation Polarization
Sigma = Yield Stress

Magnetostriction of Si-Fe

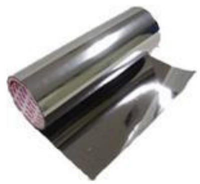


Measurement and Characterization of Magnetic Materials, Fausto Fiorillo, p.49

6%+ Si-Fe... Other materials

- Ames Laboratory
  - Researchers developing new steel for better electric motors
    A research team led by Cui is working to meet the demand for better materials and performance in electric motors. To support their work, they've just won a three-year, $3.8 million grant from the DOE's Vehicle Technologies Program.
  - https://www.news.iastate.edu/news/2016/09/27/electricalsteel
- AK Steel
  - AK Steel Receives New $1.2 Million Award from U.S. Department of Energy to Explore the Development of New Steels for Lightweighting for Automotive Applications
    The three-year project will be conducted in collaboration with DOE, Oak Ridge National Laboratory Materials Science and Technology Division, and the Advanced Steel Processing and Products Research Center in the Department of Metallurgical & Materials Engineering at the Colorado School of Mines.
  - https://ir.aksteel.com/news-releases/news-release-details/ak-steel-receives-new-12-million-award-us-department-energy

Metglas®



Key Products:

Metglas®
Amorphous Metals
Glassy Metals
Transformer Core Alloys
Metglas Brazing Filler Metal
Distribution Transformer Core Ribbon
Industrial Transformer Core Ribbon
Pulse Power Cores

Key End Applications:

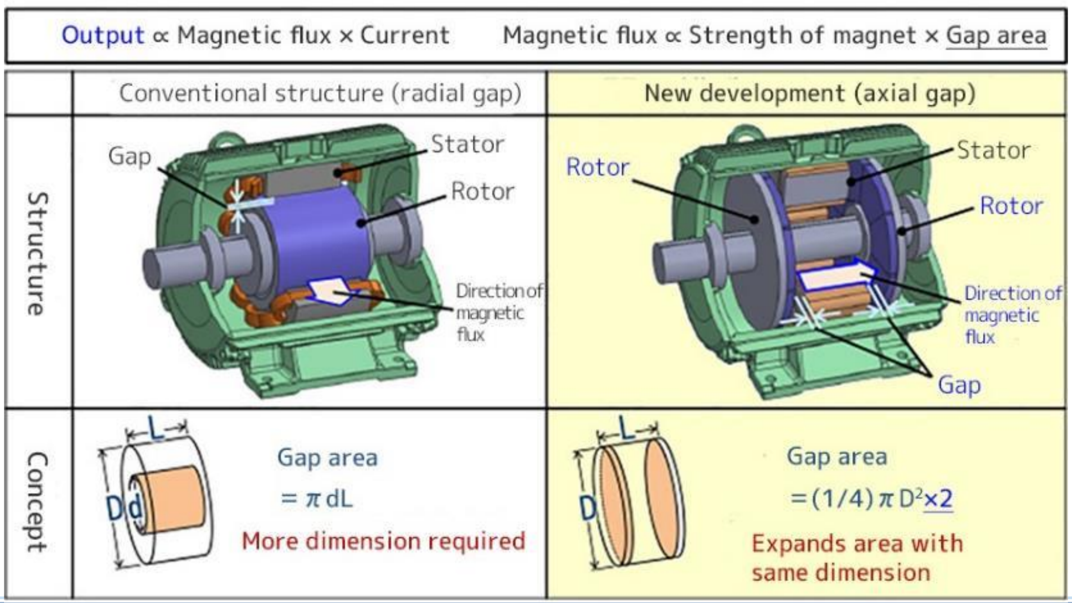
Electrical Distribution Transformers
Industrial Power Distribution Transformers
Material for Anti -Theft tags
High Efficiency Inverters and Inductors
Solar Inverters, Wind Inverters
Harmonic Filters
Pulse Power Cores for Lasers
High Power Magnetic Forms for Medical Use
High Purity Brazing Filler Metals

		2605SA1	2605HB1M	2605SA3	2714A	2826MB
Characteristic	**Unit**	Iron-based	Iron-based	Iron-based	Cobalt-based	Nickel-based
Bsat	Tesla	1.56	1.63	1.41	0.57	0.88
Max. Permeability, μ_{max}	n/a	300,000	300,000	35,000	1,000,000	800,000
Electrical Resistivity	µΩ·cm	130	120	138	142	138
Magnetostriction	$\%\bullet 10^{-6}$	27	27	20	<0.5	12
Curie Temperature	°C	395	364	358	225	353

http://www.metglas.com/metglas_company_history/overview/

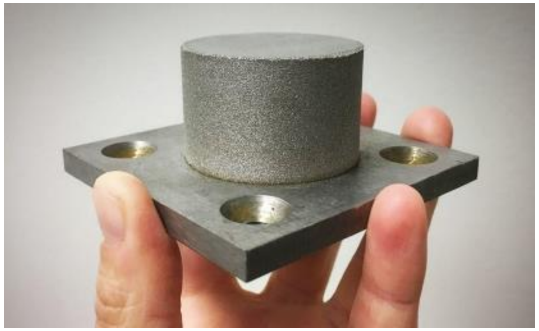
Amorphous Metal for Motors

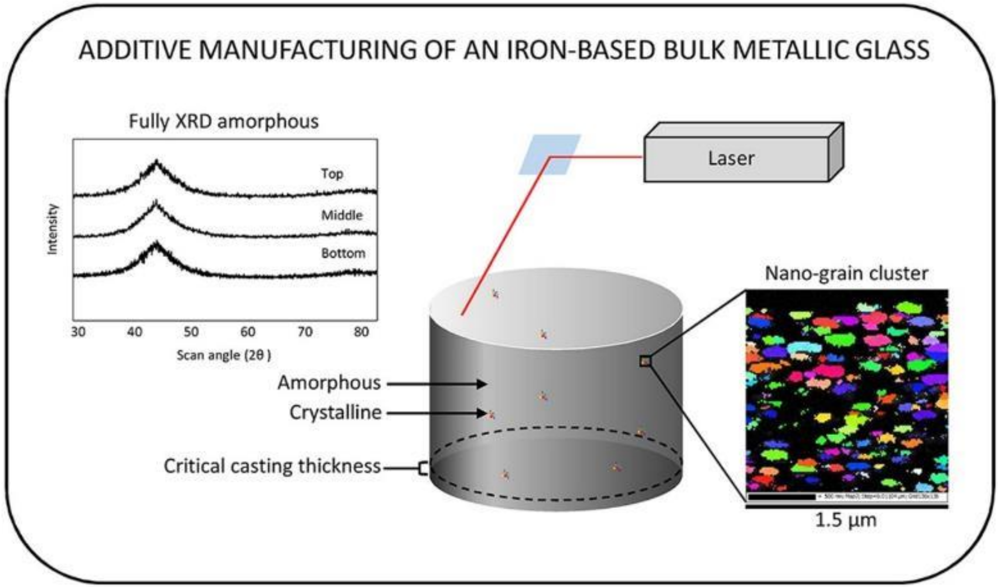
- Developing a Higher-Efficiency Motor Technology Using Amorphous Metals
  - Hitachi news release, October 24, 2018
  - Hitachi Metals, Ltd. (“Hitachi Metals”) has successfully developed a motor core structure whereby amorphous metals known as Metglas® are used for part of the motor core to achieve a higher rate of efficiency. We will promote R&D with an eye to applying this technology to motors for driving EV*2 and propose new applications of materials for motors along with verification data.
- Development of Motor with Amorphous Metal
  - Hitachi publication: November 8, 2018
  - http://www.hitachi.com/rd/portal/contents/story/amorphous/index.html



3-D Printing

- CAMAL Uses #-D-Printing to Create Metallic Glass Alloys in Bulk
  - Press release, March 26, 2018
  - Researchers from the Center for Additive Manufacturing and Logistics (CAMAL) housed in the ISE Department [of NC State University] have now demonstrated the ability to create amorphous metal, or metallic glass, alloys using 3D-printing technology...
  - https://www.ise.ncsu.edu/blog/2018/03/26/camal-uses-3d-printing-to-create-metallic-glass-alloys-in-bulk/





3D Printing

- 3D printing of large, complex metallic glass structures
  - Yiyu Shen, Yingqi Li, Chen Chen, Hai-LungTsai
  - https://doi.org/10.1016/j.matdes.2016.12.087
- Research on additive manufacturing of metallic glass alloy
  - Yiyu Shen, PhD Thesis, spring 2018
  - http://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=3693&context=doctoral_dissertations

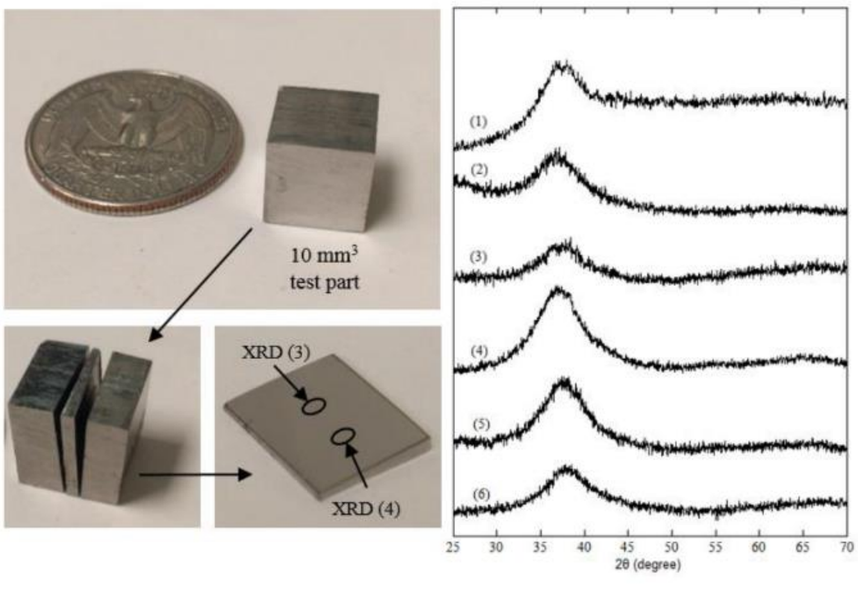
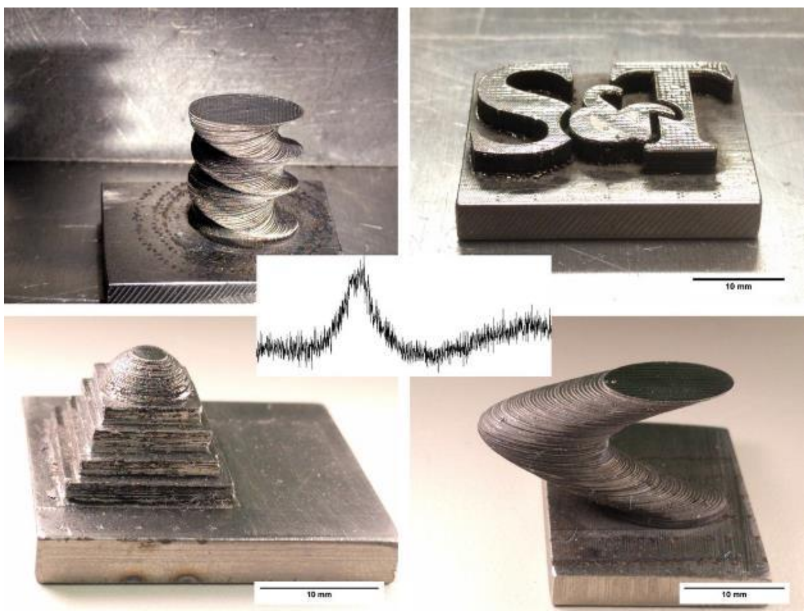
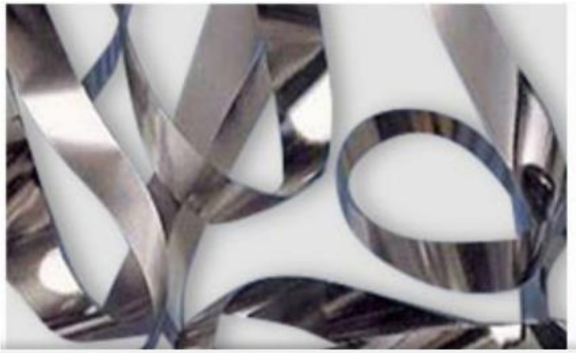
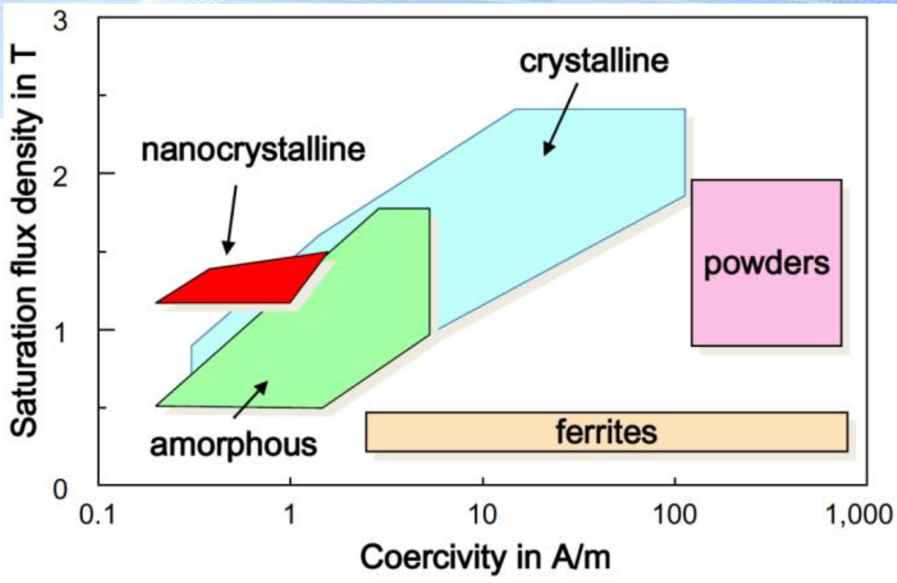


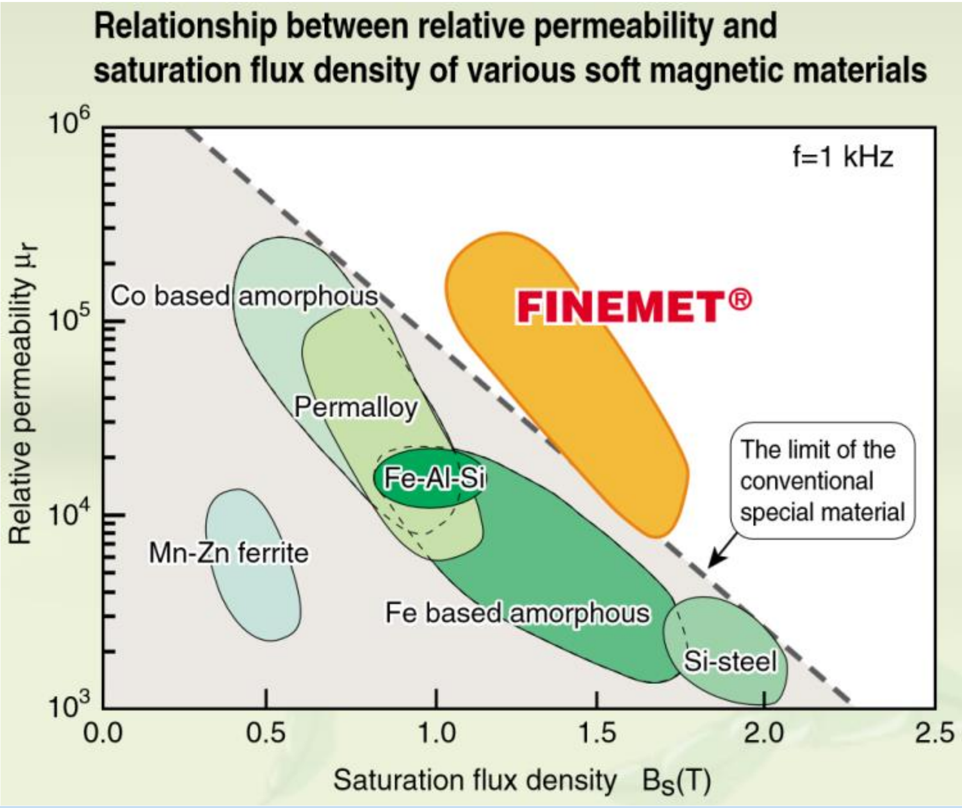
Figure 4. XRD test of printed sample. Left: photo of the 3D test sample; right:

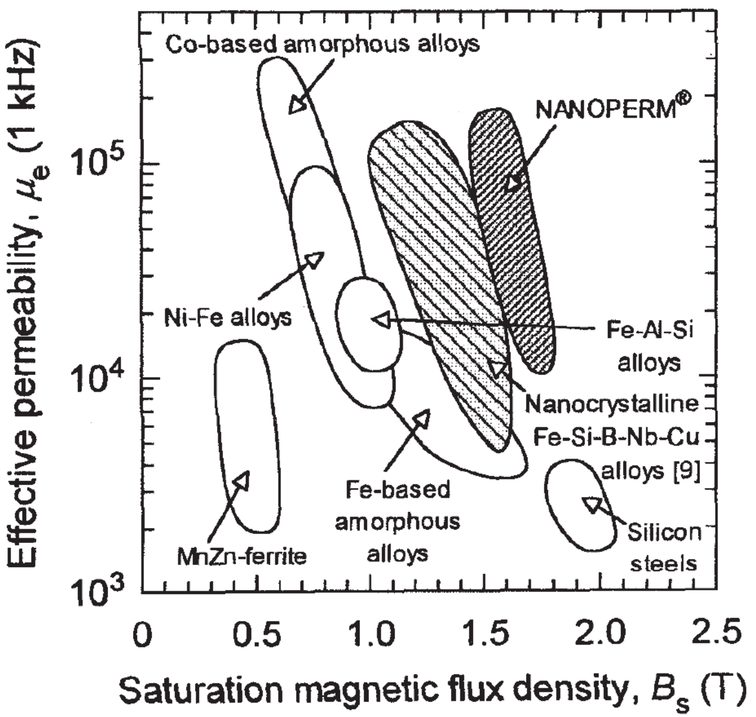


Nano-crystalline









Nanoperm® is a registered trademark of Magnetec GmbH

Summary Data

TABLE 1. Typical values of grain size D, saturation magnetization J_s, saturation magnetostriction λ_s, coercivity H_c, initial permeability μ_i, electrical resistivity ρ, core losses P_{Fe} at 0.2 T, 100 kHz and ribbon thickness t for nanocrystalline, amorphous and crystalline soft magnetic ribbons.

Alloy	D (nm)	J_s (T)	λ_s (10^{-6})	H_c (A/m)	μ_i (1 kHz)	ρ (μΩcm)	P_{Fe}(W/kg)	t (μm)	Ref.
$Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$	13	1.24	2.1	0.5	100 000	118	38	18	(a)
$Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$	14	1.23	~0	0.4	110 000	115	35	21	(b)
$Fe_{84}Nb_7B_9$	9	1.49	0.1	8	22 000	58	76	22	(c)
$Fe_{86}Cu_1Zr_7B_6$	10	1.52	~0	3.2	48 000	56	116	20	(c)
$Fe_{91}Zr_7B_3$	17	1.63	-1.1	5.6	22 000	44	80	18	(c)
$Co_{68}Fe_4(MoSiB)_{28}$	amorphous	0.55	~0	0.3	150 000	135	35	23	(b)
$Co_{72}(FeMn)_5(MoSiB)_{23}$	amorphous	0.8	~0	0.5	3 000	130	40	23	(b)
$Fe_{76}(SiB)_{24}$	amorphous	1.45	32	3	8 000	135	50	23	(b)
80%Ni-Fe (permalloys)	~100 000	0.75	<1	0.5	100 000 (d)	55	>90 (e)	50	(b)
50%-60%Ni-Fe	~100 000	1.55	25	5	40 000 (d)	45	>200 (e)	70	(b)

(a) after ref. [3]
(b) typical commercial grades for low remanence hysteresis loops [10, 11]
(c) after ref. [12]
(d) 50 Hz- values
(e) lower bounds due to eddy currents

Amorphous and Nanocrystalline Soft Magnets; G. Herzer, Vacuumschmelze GmbH & Co KG
Published in Proceedings of the NATO Advanced Study Institute on Magnetic Hysteresis in Novel Materials, Mykonos, Greece, 1-12 July 1996, ed. George C. Hadjipanayis; NATO ASI Series (Series E:Applied Sciences Vol. 338), Kluwer Academic Publishers, (Dordrecht/Boston/London) 1997, (ISBN 0-7923-4604-1)

References

- *Advanced Materials for Motor Laminations: Past, Present and Future*
  - John Petro, Petro and Associates
  - https://metglas.com/wp-content/uploads/2016/12/Advanced-Materials-for-Motor-Laminations.pdf
- *Modern soft magnets: Amorphous and nanocrystalline materials*
  - G. Herzer, Vacuumschmelze GmbH & Co KG, 2013
  - http://faculty.neu.edu.cn/atm/lis/mag/ModernSoftMagnets.pdf
- *Soft Magnetic Material Status and Trends in Electric Machines*
  - A. Krings, A. Boglietti, A. Cavagnino, S. Sprague; IEEE Transactions on Industrial Electronics, Vol.64, No.3, March 2017
  - https://ieeexplore.ieee.org/document/7577727
- *Understanding Electric Motors and Loss Mechanisms*
  - B. Sarlioglu, University of Wisconsin, Madison (WEMPEC), 2016
  - https://www.irc.wisc.edu/export.php?ID=421

Steve Constantinides
Magnetics & Materials LLC
4785 County Road 33
Honeoye, NY 14471
E-mail: steve@magmatllc.com
www.magmatllc.com

Honeoye Lake in the Finger Lakes region of western New York