MagWeb
Magnetic Material Data

MagWeb User Manual

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By

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ABSTRACT

Whether you are designing a traction motor for hybrid electric vehicle, aircraft generator, transformer or loudspeaker, your product is only as good as the **soft magnetic materials** that you employ. For optimal design of your machine, you need their magnetic properties. But so far, your effort is handicapped by lack of comprehensive database of magnetic properties of materials. *MagWeb* is an encyclopedic database of *digitized B(H) and Core Loss* Curves that fills this gap. It will help you to identify an optimal magnetic material for your specific machine.

Till now, the magnetic properties were available only as continuous curves in pdf or picture files. They need to be digitized before inputting into electric machine design software. Unfortunately, both magnetization and core loss curves have inflection points (where the slope peaks). Such inflection point causes numeric instability if the smooth curve is replaced by poorly digitized data. Over past decade, MagWeb has developed proprietary set of tools for derive tabulated data with minimal digitization noise, thereby preventing numeric instability and consequent decrease in computational speed.

MagWeb database presents these digital magnetic properties in excel files. Each file contains digital magnetization curve, permeability curve or core loss curves. This version 4 contains ~ 2400 excel files of digital magnetic properties of diverse materials. It

- added hundreds of core loss curves for Electrical Steels, Cobalt Steels, Nickel steels, Powder Cores
- added scores of magnetization curves for Low Carbon Steels
- added scores of thin electrical steels that is useful for design of traction motors for hybrid vehicles.
- added files on effect of several secondary parameters (temperature, stress, orientation, annealing etc)

In summary, the noise-free digitized data from *MagWeb* can be inputted directly into your machine design software. This will save you hundreds of hours of data search time. You will be able to simulate fast the impact of change in magnetic materials on the performance of your product. Ultimately it will help you in choosing the optimal steel that maximizes the performance of your product.

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1. INTRODUCTION

Soft Magnetic Materials are those resistance to flow of magnetic flux is far lower than that of air. Their unique ability to conduit flux greatly reduces the size of electric machines. Modern civilization would not have been possible without this unique ability. You are unknowingly using them all the time - from large MW generators that produce electricity to transformers that bring it to your home to the car that you drive to your office – all rely on these specialized materials.

So whether you are designing a traction motor for hybrid vehicle, a wind power generator or loud speaker - your products are only as good as the soft magnetic materials that you choose for your machine. *MagWeb* is the world's largest database of properties soft magnetic materials. It lists magnetic properties of almost all magnetic materials produced by almost all manufacturers world wide, which will help you choose the optimal material that maximizes the performance.

The magnetic properties of these materials are characterized by three curves – Magnetization Curve, Permeability Curve and Core Loss Curve. They are called B(H), μ_r(H), P(B, f) curves respectively.

The B(H) magnetization curve plots magnetic flux density response B (Tesla) of the material vs. applied H. Here magnetic field intensity H (A/m) is the amp turns (mmf) per unit length of the magnetic circuit. Relative Permeability $\mu_r = B/\mu_o H$ is the ratio of flux density B vs. vacuum flux density $\mu_o H$ (i.e. if the material is replaced by air), $\mu_o = 4\pi x10\text{-}7\ N/A^2$. The μ_r(H) relative permeability curve plots relative permeability μ_r with H. The core loss curve P(B, f) plots the core loss P (w/Kg) dissipated by a material while carrying alternating flux of density B at frequency f Hz.

A common belief is that a steel with low core loss alone will produce a high efficiency machine. But optimal steel is one that not only minimizes core loss, but also minimizes the copper loss caused by the very magnetizing current that creates the flux. That is, it will demand least possible current to achieve the required flux, thereby minimizing the copper loss.

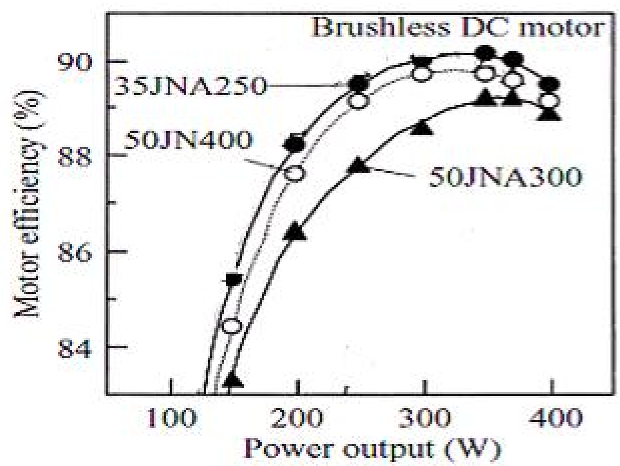

Fig. 1. Your machine is only as good as the magnetic material that you use.

Electrical steels employ Silicon to increase electrical resistance, thereby ***reduce core loss****.* But the act of adding Silicon also *increases* magnetic resistance (i.e. reduces permeability). So high-silicon steels (that reduce core loss) unfortunately demand more current to produce same flux. So unfortunately they ***increase the copper loss***.

Fig. 1 illustrates such impact of steel on efficiency[1]. It shows how a 50JN400 grade (producing higher core loss of 2.86 w/Kg) offers higher efficiency than a 50JNA300 grade (producing lower core loss of 2.63 w/kg) So one needs B(H) curve - in addition to core loss curve - in order to select an electrical steel that maximizes the machine efficiency [2, 3]. So an optimal steel is one

[1] Senda, K. et al., "Electrical Steels for Advanced Automobiles, Core Materials for motors, generators and high frequency reactors", *JFE Technical Report*, No.4, pp. 67-74, Nov. 2004.
[2] Fujimura, H et al, "Effect of magnetic properties of nonoriented electrical steels on characteristics of interior-permanent-magnet synchronous motors", *J. Mag. Mag, Mat*., Oct. 2008

that produces not only the lowest possible loss in iron - and uses least current to produce the required magnetic flux.

Unwittingly, different steels are tailored to be optimal at different operating conditions. So to identify a steel that is optimal at your machine's operating conditions, you need to collect magnetic property data of candidate steels.

MagWeb database is unique in that it lists *digital data for B(H) Curve, Permeability Curve and Core Loss Curve* for nearly all soft magnetic materials produced worldwide. Such comprehensive database will help you in identifying a particular steel (and its manufacturer) that maximizes the efficiency at the operating conditions specific to your machine.

1.1. Folders and Files (2390)

MagWeb groups all soft magnetic materials into 12 categories[4], called *Folders.* Each Folder contains a large number of excel *files*. Each file stores either a B(H) curve and Permeability Curve or Core Loss Curves. This version 4 comprises 2390 files. Table 1 lists the 12 folders and B(H) and Core Loss files contained by each folder. For example, the Electrical Steel (NGO) Folder has 551 B(H)/Permeability curves and 274 core loss curves, 825 files in total.

Table 1. ***MagWeb Folders and Files of Soft Magnetic Materials (2390)***

Folder	Name	B(H) Files	Core Loss Files	Total Files
A	Electrical Steel – Non Grain Oriented	551	274	825
B	Electrical Steel – Grain Oriented	222	180	402
C	Metglas & Nanocrystalline	30	23	53
D	Cobalt Steel	43	194	237
E	Nickel Steel	116	54	170
F	Stainless Steel	43	0	43
G	Low Carbon Steel	156	3	159
H	Castings	52	0	52
I	Iron Powder Core	65	61	126
J	Alloy Powder Core	28	64	92
K	Ferrite	72	92	164
L	Broadband Ferrite	0	67	67
	Total Files in MagWeb	1365	835	2390

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[3] Lee, S., Influence of electrical steel characteristics on efficiency of industrial traction motors, 20th Int. Conf Electric Machines and Systems, Aug. 2017

[4] See also, IEC 60404-1:2016, *Magnetic Materials*, Part 1, Classification. Note that Soft magnetic materials have low coercive force (Hc <400 A/m) while hard magnetic materials, aka permanent magnets, have high coercive force (Hc >10,000 A/m).

1.2. Mislabeling J(H) as B(H)

Unfortunately the standards puritanically characterize[5] the response of a magnetic material by ***Ferric Flux Density J*** (aka *magnetic polarization)* instead of ***Magnetic Flux Density B.*** To derive B from J, one should add the *vacuum flux density* $\mu_o H$,

$$B = J + \mu_o H \quad \cdots \quad \cdots \quad (1)$$

Electrical steel manufacturers (and MagWeb) supply such ***ferric flux density curve J(H)*** *curve.* But Ferric flux density J(H) is a slightly different animal than the magnetic flux density ***B(H)*** that is used by engineers. Specifically, as H increases indefinitely, J(H) converges to saturation induction J_s, while B(H) increases linearly. Further, the slope of J(H) curve [$dJ/(\mu_o H)$] tends to 0, while the slope of B(H) curve [$dB/(\mu_o H)$] tend to 1.

Unfortunately, most steel manufacturers ***mislabel*** their J (H) curve as B(H) curve. Such *mislabeling of J* as B is not uncommon. Even the legendary Steinmetz and ASTM mix up both types of flux densities, and used "B" when they intended to mean "J".

When designers enter the mislabeled J (H) data as B (H) data into their design software, a small mislabeling error occurs. For example when a machine operates at say 1.7T/5,000 A/m, the vacuum carries a flux density $\mu_o H$ of 0.0063 T. Then the entered ferric flux density J = 1.7T actually refers to magnetic flux density B = 1.7063 T. The *mislabeling error* ε_{BJ} = (B-J)/J is ~0.37%. It is so small that the accepted practice of rightfully ignoring it below < 1.8T is harmless.

But it does become significant when designing against core failure. This can occur during short duration peak loading in multiMW generators - in flux concentration hot spots such as sharp corners of tooth/slot and core-ends. In such areas, B/H can be as high as 2.2T/150 kA/m. So the mislabeling error can increase to 10% or higher. Then FEM design software can no longer accurately predict flux densities, unless correct B(H) is inputted. So, to prevent core failure, one *should* convert the measured J to B, and enter such B(H) data; this will correctly locate the flux concentration hot spots.

This mislabeling has an unfortunate effect on extrapolation to saturation[6]. Beyond 1.8 T, a software that assume B(H) data is inputted extrapolates it so B increases linearly (with the slope $dB/(\mu_o H)$ approaching 1). But if it assumes that J(H) is inputted, it will extrapolate J to reach a saturation induction J_s (with the slope $dJ/(\mu_o H)$ approaching 0).

1.3. B(H) Curve

B(H) curve is a locus of tips of a series of hysteresis loops in the B-H plane (not J-H plane, as used by standards). Fig. 2 shows a typical B(H) curve (**blue**) of M250-35A steel (reproduced from *MagWeb*). Such B(H) curve has a characteristic *knee*. Its tangent or slope $B'(H) \equiv dB/(\mu_o dH)$ (aka differential permeability) increases with H first, reaches a peak[7] at an ***Inflection Point*** Q and

[5] Some researchers express J in terms of *magnetization* M, related to J by $J = \mu_o M$
[6] Rao, D. K, Kuptsov, V., Effective use of magnetization data in the design of electric machines with overfluxed regions, *IEEE Trans. Magnetics*, Vol. 51, No. 7, July 1015, paper no. 6100709
[7] Spooner, T. *Properties and Testing of Magnetic Materials*, McGraw Hill, 1927, p.10

then decreases. The inflection point is a known point of computational instability[8] because of digital noise. Computational speed slows around Q, so increases the computational time. To avoid this, MagWeb has developed tools to derive digital **noise-free B(H) data** as described in the next section.

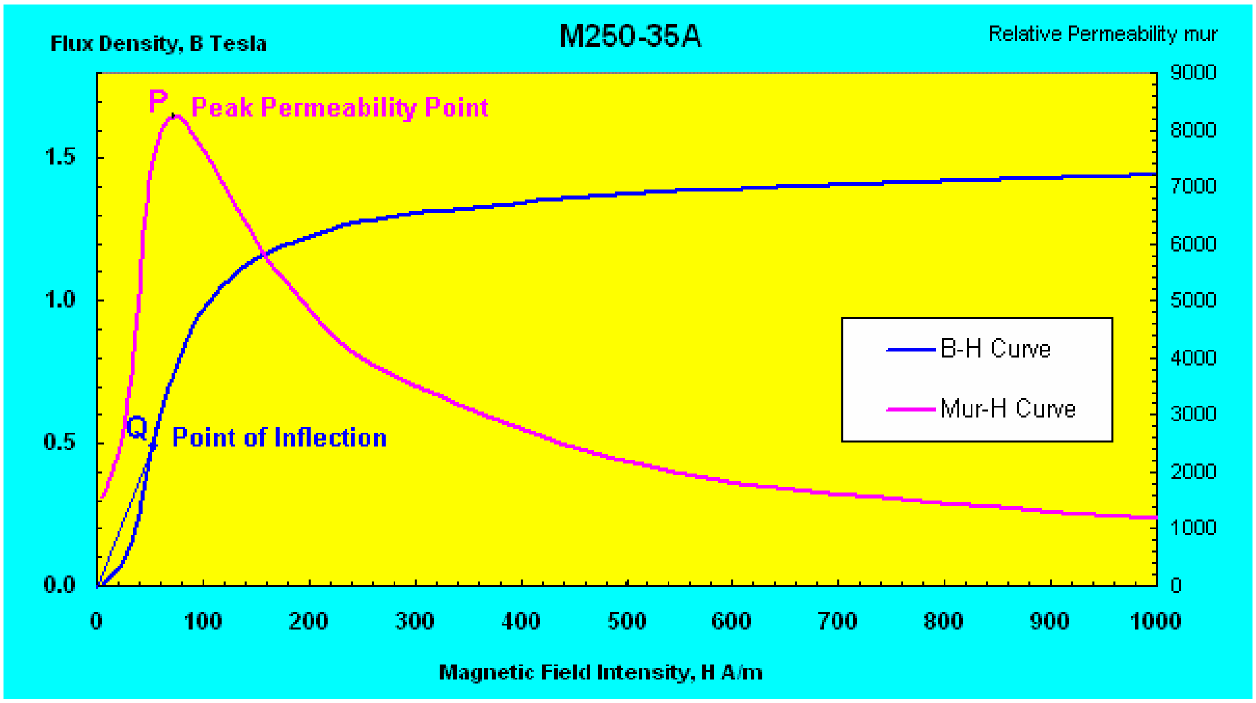

Fig. 2. B-H Curve has an inflection point. It causes poor convergence

1.4. Permeability Curve

The relative permeability μ_r is as important as B(H) curve. It signifies how easily a magnetic material can carry flux, i.e. reciprocal of reluctance. In a highly magnetically resistive material μ_r can be close to 1. In a magnetically conductive material it can be as high as 100,000.

Fig. 2 also shows permeability curve (**pink**) $\mu_r(H)$. The relative permeability increases first, attains a ***peak*** P in the knee region, and then decreases with H. *MagWeb* database has an unique look-up table of permeability μ_r vs. H. The permeability at operating point $\mu_r(B_o,f_o)$ and the peak permeability μ_{pk} are two points on the permeability curve that are useful in evaluating losses in copper, shield effectiveness or thickness required. Here B_o refers to the flux density in tooth and f_o is the electrical frequency, both at the name plate rating of a machine.

Permeability at Design Point. It is useful in comparing two materials. For example, consider two steels for a machine operating at 1.5T, 50 Hz. Both are graded as M250-35A steels, but

[8] Kis, P. *Jiles-Atherton model implementation to edge FEM*, Ph.D Thesis, Budapest Univ.Tech., 2006, p.2.

produced by different firms A and B. MagWeb's database show that permeability of firm A's steel at 1.5T, 50 Hz is 1513 while that of B is 660. So A demands 789 A/m, while B demands 1809 A/m to carry 1.5T at 50Hz. So steel A requires lot less magnetizing current: it produces 1/5th of respective ***copper loss!*** So steel A is a preferable choice for this operating point.

Permeability at Peak Point. Some applications (e.g., magnetic shields, GFI, filters) etc. demand materials with highest peak permeability. For example, a magnetic shield offers best shielding effectiveness if operated at the peak permeability point. The permeability table in the *MagWeb* database will help identify such peak permeability point of operation as a shield.

Permeability also defines ***maximum thickness*** of lamination. To fully utilize the material, maximum thickness of a lamination should ***be less than two skin depths ($t < 2\delta$).*** Skin depth is inversely proportional to permeability and frequency. So materials with higher permeability or those operating at high frequencies will require thinner steels. For misuse of Metglas or Nano materials that violate this design guideline, pl. see section 5.

1.5. Digitized B(H) Data

Traditionally, most B(H) curves are supplied as continuous curves, either on paper or pdf files. But such paper or pdf files cannot be fed into FEM design software. One needs to convert the continuous B(H) into tabulated data points. Digitization is the process of converting a continuous B(H) curve in to table of B and H values at discrete points. But the *act of digitization* unwittingly introduces ***digitization noise***, which can slow the computational speed.

The digitization noise can best identified by examining ***the B'(H) slope curve.*** An ideal slope curve will have only ***one peak***: Unfortunately, the act of digitization causes digital noise around the peak, which results in more than one peak. Such multiple peaks occur for example when one picks points slightly offset from mean of a thick-lined B(H).curve. Such offsets introduce unintended noise in the slopes, causing digital noise.

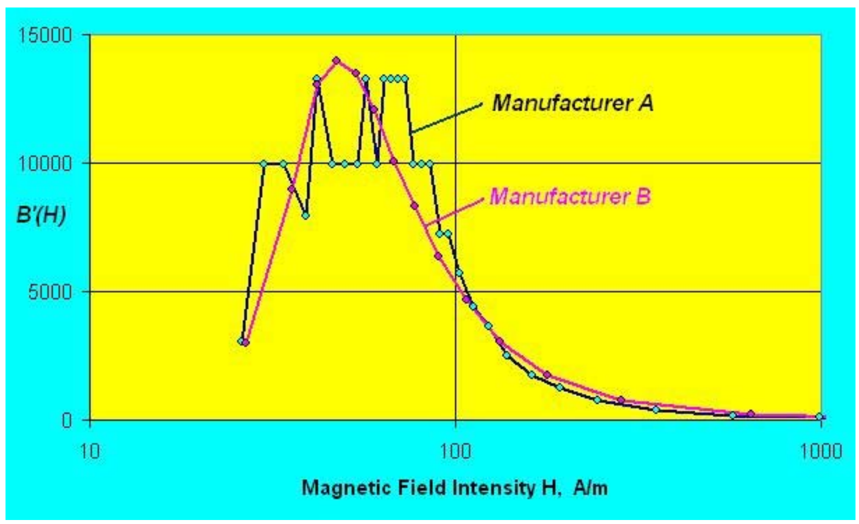

Fig. 3. B'(H) curve for firm A's steel has digitization noise.

For example Fig. 3 compares B'(H) slope curves for two M250-35A grade steels for two firms A and B. The slope curve for firm A shows multiple peaks (i.e. it has digitization noise), while that from firm B has only one peak (i.e., it has no digitization noise).

A slope curve with digitization noise confuses the Newton iteration that is often used in FEM software. The computer struggles to find the real peak buried within multiple peaks created by digitization noise. This in turn slows the speed of computation, thereby increasing computer time[9]. Sometime the solver may fail to converge, causing numerical instability. To avoid them, one needs B (H) data[10] that is free from digitization noise.

B(H) data is said to be free of digitization noise when its tangent curve B'(H) has only one peak, that too at the point of inflection. Such digitization noise- free B(H) data obviously will minimize the computational time.

Over past several years, *MagWeb* developed several proprietary tools needed to develop digitization noise-free B(H) data. Its database, being free of digitization noise, does not cause computational instability.

1.6. Naming the MagWeb Files

A BH file of *MagWeb* database contains BH curve, permeability curve or Core Loss data.
Each file name contains following information: The commercial name, thickness or chemical composition end with "@". The test conditions at which data is measured (flux density, frequency, temperature, time etc) or parameters that distinguish several curves (e.g., stress, frequency etc.) are listed next. For example the file "Hiperco50 @500C for 2000 Hr; 300 to 2000 Hz" presents 6 core loss curves for Hiperco 50A material (that is kept at 500 C for 2000 Hr age), the 6 curves spread over 300 to 2000 Hz range.

In addition, it lists Manufacturer, brand name, thickness, and annealing schedule. It also lists Saturation Induction J_s, Resistivity ρ etc if available. Top two rows contain this information. row 1 contains data while row 2 contains descriptors of the data. Their format is shown below.

Table 2. ***Header Rows in each data file***.

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Electrical Steel GO	Posco, South Korea	Posco		0.009	0.23	Fully Processed	DC	2.020	2.083	B002
	Manufacturer	***Brand***	***gage***	***inch***	***mm***	***Annealing***	***Hz***	***Bsat***	***MS/m***	*Curve*

C1 - Material Category (electrical steel, metglas etc)
C2 - Manufacturer
C3 – Trade Name of the material
C4, C5, C6 - Thickness in gage, inches and mm respectively. .
C7 - Annealing condition. For example
"Fully Processed": Manufacturer delivers steel in fully annealed condition.
"Semi-Processed": Manufacturer expects user to anneal steel.
"732C anneal": steel is annealed per a 732 C anneal schedule.
C8 - Frequency in Hz. For example, 50 Hz means B-H data is measured at 50 Hz.
C9 - Saturation Induction J_s (Tesla) if available.
C10 – Electric Resistivity in $\mu\Omega$m, if available.
C11 - MagWeb Id. It is a unique 4-digit code assigned to each file.

B(H) data is listed in col. 1 to 4. These columns contain H (A/m), B (tesla), μ_r and B'(H) curve respectively. MagWeb stores data with 8-decimal digits, but displays only 2 or 3 decimal digits. If greater accuracy is needed, one can display the hidden decimal digits using excel.

[9] Hameyar, *Numerical Modeling and Design of Electric Machines*, WIT Press, 1997, p. 93
[10] To avoid convergence issues, some FEM software replace measured B(H) with an "artificial" one that has constant slope below POI. Essentially they "remove" the POI. But if operating is below POI, it leads to large errors. See e.g. https://www.jmag-international.com/library/jmag_atoz/03.html. or https://www.emetor.com/blog/post/influence-b-h-curve-convergence-finite-element-solution/

2. A. ELECTRICAL STEELS – NON-GRAIN ORIENTED

MagWeb's ***Electrical Steel (NGO) Folder*** has 825 excel files listing magnetic properties of these materials, produced by 16 manufacturers. Of these, 551 files contain B(H) magnetization curves/permeability curves while 274 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US Website, click on *MagWeb Database - A. Electrical Steels (NGO).*

Electrical Steels are steels that make every effort to **remove** Carbon as much as possible, in an effort to improve its magnetic properties. Removal of carbon reduces core loss and stabilize it (i.e. prevents "aging" or increase of core loss with time). Carbon is magnetically harmless below its solubility limit of 70 ppm. In most electrical steels, carbon is less than 30[11], 50[12,13], 200[14], 800[15] ppm - depending on whom you ask. Silicon (up to 4%) is added to reduce core loss, but it unwittingly degrades permeability. Silicon also causes these steels to be are more brittle than structural steels. Note: Structural Steels **add** Carbon as much as possible to improve its mechanical properties, so unwittingly degrade its magnetic properties.

Coating. Electrical steels have a smooth surface finish, with tightly adherent oxide coating developed during manufacture (often called as C-0). Steel producers also apply an additional coating, which is so thin that it just covers surface blemishes. So they are really not insulative, but resistive. They just increase the surface resistance, so reduce interlaminar loss. (Un-annealed or uncoated electrical steels can be procured only as special order.) Manufacturers supply them in the form of 3 to 4 ft diameter coil rolls.

Thickness. Manufacturers supply those for 50/60 Hz machines in 0.35, 0.5, 0.65 mm (0.014, 0.018, 0.025 inch) thickness. They also supply thinner gages (for 400 Hz machines such as hybrid vehicle motors, aviation generators) in 0.2, 0.27, 0.3 mm (0.008, 0.010, 0.012 inch) thickness. They also supply ultra-thin gages (for inductors and transformers) in 0.1, 0.12, 0.18 mm (0.004, 0.005, 0.007 inch) thickness. ***Orientation*** of flux relative to the Rolling Direction (RD) influence their properties.

Grain-Oriented steels employ silicon up to 3.5% to offer lowest possible core loss at highest possible permeability. But their properties are highly directional. Their core loss is low only along the Rolling Direction. In this direction, their core loss ranges 0.5 to 1 w/kg, while permeability ranges 40000 to 80000. Their magnetic properties along the Transverse Direction are poor. So they are mainly used in transformers. Their grains can be as large as 3 mm.]

Non Grain Oriented steels, dealt in this section, go by other names, such as Cold Rolled Non-Oriented Steels, Non-Oriented Electrical Steels or Non-Oriented Silicon Steels. Abbreviations such as NGO, NOES, NO, CRNO are common. Their core loss and permeability are lower than that of GO steels. They are less expensive and more omni-directional. So they are used in electric motors. in a wide variety of market segments, e.g., industrial motors, fans, pumps, rolling mills, oil/gas, machine tools etc. They contain ***up to 3.5% silicon*** to reduce core losses. "Relay steels" are those with ***1.5 to 2.5% Si*** steels that are thicker than 1 mm. Their grain sizes can be as small as 0.05 to 0.2 mm.

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[11] AK Steel, Selection of Electrical Steel for Magnetic Cores, *Product Data Bulletin*, 2007, p. 7
[12] Electrical steel, https://en.wikipedia.org/wiki/Electrical_steel
[13] Dorner, D., Non-Oriented electrical steel sheet for electric vehicle drives, *ThyssenKrupp Techforum*, Issue 1, 2009.
[14] ASTM A677, Standard Spec. for NonOriented Electrical Steel.
[15] US Govt, Non-Oriented Electrical Steel CVD, http://enforcement.trade.gov/download/factsheets/factsheet-multiple-non-oriented-electrical-steel-cvd-prelime-031914.pdf

Standard ***Grade*** of electrical steel list their thickness, maximum core loss at 1.5T, 50 Hz ($W_{15/50}$) and minimum flux density at 5000 A/m (B_{50}). Respective minimum permeability μ_{50} can be calculated from the listed B_{50} from $\mu_{50} = B_{50}/(5000\mu_o)$. For example, grade M250-50A refers to 0.50 mm thick NGO steel, with $W_{1.5/50}$ = 2.50 w/kg, B_{50} = 1.6T (i.e. μ_{50} = 255).

Core Loss The maximum core loss $W_{15/50}$ prescribed by the standards range 2 to 16 w/kg,

- ***High grades*** (2.5 to 3.2% Si) offer lowest loss of 2 to 3 w/kg.
- ***Medium grades*** (1.5 to 2.5% Si) offer 3 to 6 w/kg.
- ***Low grades*** (0.5 to 1.5% Si) to offer high core loss of 6 to16 w/kg.

But all manufacturers deliver steels whose typical core loss is significantly lower than $W_{15/50}$. This *typical* core loss P(1.5T, 50 Hz) can be read off from the typical core loss curves supplied by them. Typical core loss of a grade is usually closer to the maximum core loss of next lower grade. For example for M250-50A grade, standards prescribe max. core loss $W_{15/50}$ of 2.5 w/Kg. But Fig. 4 shows that Cogent's M250-50A /Nippon's 50H250 offer core loss P(1.5T, 50Hz) of 2.38 / 2.24 w/Kg.

Permeability Peak permeability of NGO steel ranges 4000 to 8000. Standards prescribe permeability μ_{50} at 5000 A/m. But all manufacturers deliver steels whose permeability at 1.5T, 50Hz operating point is significantly higher than μ_{50}. This permeability μ_r (1.5T, 50 Hz) can be read off from the permeability curve in the MagWeb database. For example for M250-50A grade, standards prescribe min. permeability μ_{50} of 255. But Fig. 4 shows that Cogent's M250-50A / Nippon's 50H250 offer permeability μ_r (1.5T,50Hz) of 746 /1033.

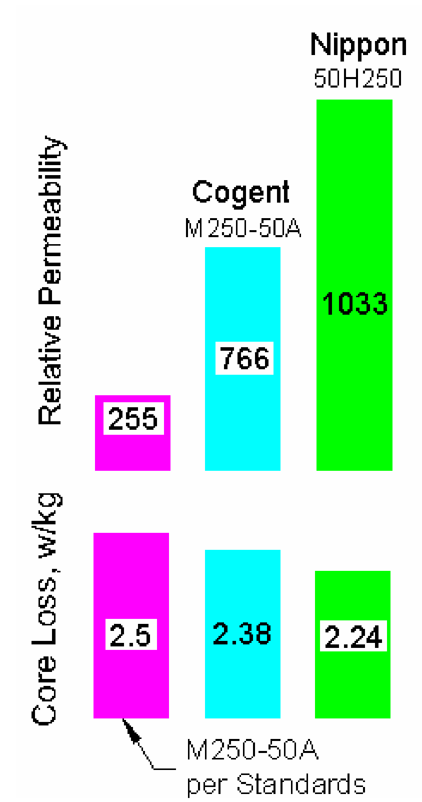

Fig. 4. Properties of actual steels greatly differ from grade standards.

Some producers offer ***"High Permeability" HP*** **grade** steels. For example M530-50A offers B_{50} of 1.65 T (μ_r=263), while its HP grade M530-50HP offers 1.71 T (μ_r =272). This higher flux density gives a ***misleading*** perception that the HP grade is superior. But, at 1.5T, 50 Hz, the permeability of M530-50A is 2083 while that of M530-50HP is 1721. So M530-50A requires magnetizing current of 573 A/m while its HP grade M530-50HP requires 694A/m. So the HP grade causes more copper loss! So don't be fooled by the perceived superiority of HP grade steels! Some also offer a "High Strength" HS grade steel which is useful in machines where strength is critical (e.g. hybrid vehicle motors with bridges).

2.1. Electrical Steels are not perfectly Isotropic

The core loss and permeability of NGO and GO steels do vary with the angle α between applied field and rolling direction. That in NGO does not vary as sharply as in GO steels. To counter such anisotropy, the designer should use magnetic properties measured in a 50/50 Epstein frame. In sensitive machines, the laminations must be suitably "rotated" along the stack.

Core Loss Anisotropy - The EN 10106 standard defines anisotropy T of electrical steels as

$$T = \frac{P_1 - P_2}{P_1 + P_2}$$

where P_1 and P_2 are losses in samples cut in Transverse Direction (TD) and Rolling Direction (RD) respectively. [This definition cleverly halves true anisotropy, which is $(P_1-P_2)/P_2$].

In NGO steels, this EN anisotropy can vary from 6 to 30% (so true anisotropy is double, as high as 60%!). Thinner steels demand more rolling passes, so suffer from higher anisotropy. Anisotropy also ***varies greatly from firm to firm.***

B(H) Curve Anisotropy – It is more subtle and complex Fig. 5 (reproduced from MagWeb database) shows how the angle α affects B(H) curve of NGO steel. See "M-6 and M-19 Effect of Angle" excel file for more details.

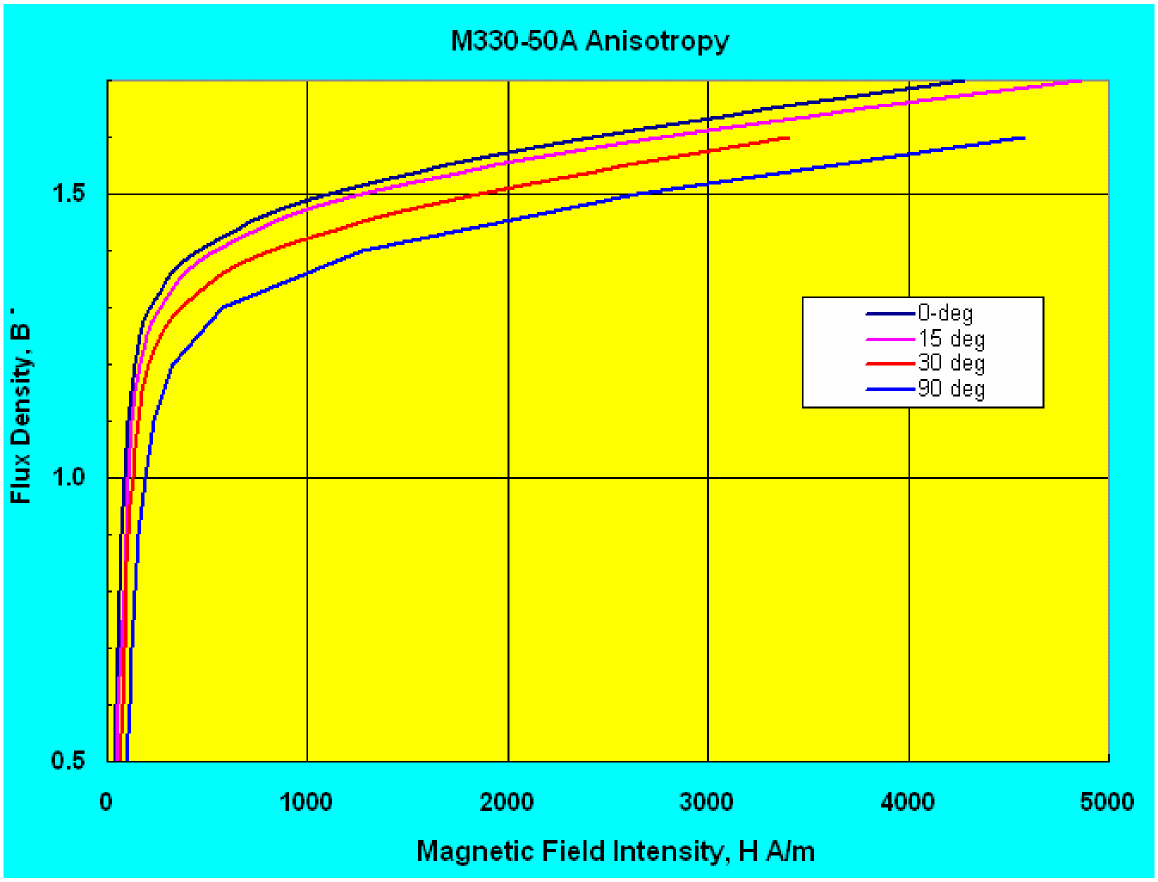

Fig. 5. Magnetic Properties of NGO steels vary somewhat with direction.

2.2. Same Grade does not mean same efficiency

International Standards on steel grade may make you think that different steels of same grade, but made by different firms, will produce same efficiency. They don't! Example: Three European firms P. Q, R produce NO20 grade electrical steels. But at 1.5T/50 Hz, their permeability is 2150, 1103, 455 respectively. They require magnetizing currents of 555, 1082, 2620 A/m respectively. So the NO20 steel from firm P requires only 1/5th of the magnetization current needed by firm R.

Its copper loss will be 1/25th of firm R. So ***choice of supplier affects efficiency, irrespective of the grade***.

The reason is that the core loss depends (in addition to C and Si) very subtly on how precisely the trace impurities are controlled. These include, Oxygen, Sulphur, Titanium and Nitrogen[16] For example, an increase of Sulphur from 20 to 40 ppm can increase core loss by 20%! These trace impurities differ from manufacturer to manufacturer. So the magnetic properties of electrical steel vary greatly with the manufacturer, even if they are of same grade and composition is same.

So MagWeb lists the properties of steels by each manufacturer, *irrespective of their grade.* So this database will help you to identify specific steel from a specific producer that offers highest efficiency for your product.

2.3. Inch-steels from USA are different from mm-steels

Another misconception is that the inch-steels from USA (which are based on Electrical Steel Standard Gage ESSG) can be interchanged with other mm-steels (which are based on international standards such as IEC/EN/JS). The mm-steels are produced at 0.35 mm, 0.50 and 0.65 mm thickness. The inch- steels are produced at 29, 26, 24 gages, i.e., 0.014", 0.0185" and 0.025" thickness. But the 0.35 mm (0.01378") IEC steel is 1.6% thinner than its 0.014" inch-steel. The 0.5 mm (0.0197") IEC steel is 6.4% thicker than its 0.0185" inch-steel. The 0.65 mm (0.0256") thick IEC steel is 2.4% thicker than its 0.025" thick inch-steel.

The minute difference in thickness affects the number of laminations required to build a stack. For example, a 10" stack requires (theoretically) 726 laminations of 0.35 mm thick steel, but only 714 laminations of 0.014" thick steel. They apparently affect the total cost of a core! What is worse, it affects amount of iron in a stack, hence true flux density.

2.4. CRML (Semi Processed) Steels

CRML ***(Cold Rolled Magnetic Laminations)*** refer to "ultra-low carbon" steel sheets that are uncoated and unannealed by the steel producer. Low grade CRML have carbon <0.06%, high grades < 0.02%, while best (costlier) grades have <0.005%. They usually have little or no silicon. In USA they are produced per ASTM 726; different producers grade them as Type 2-6, or Grade Q, CQ etc. (In Europe, they called semi processed steel, produced to a different Standard EN10341. They are identified by an end code K.)

They are characterized by temper-rolling, which produces rough surface with mat finish. When stacked, the rough-surfaces contact only at few high points. This prevents them from sticking. Contact at only high spots reduces eddy loss even without surface coating. It also increases the surface resistivity.

Core Loss. To reduce carbon to <0.005%, the user (motor maker) is burdened with the task of a decarburizing anneal after stamping. This greatly reduces core loss and prevents aging. ***MagWeb*** lists core loss of several CRML steels. The published core loss data refers to that expected after a decarburizing anneal. Example: The core loss at 1.5 T/50 Hz of a 0.018 inch thick un-annealed CRML ranges 8 to 12 w/kg. Decarburizing anneal reduces it to about 3 w/kg.

[16] Bozorth, R. M., *Ferromagnetism*, Van Nostrand Co., New York, 1951. p. 52

Several suppliers, such as JFE and Arcelor also offer CRML in annealed state. Their magnetic properties can rival those of low grade NGO steels, but at a lower cost. For example, annealed CRML can produce core loss as low as ~2.6 w/kg.

Permeability. Because of reduced number of rolling steps, their permeability is generally higher than NGO steels. This in turn reduces the magnetizing copper loss, so increases efficiency.

Cost. CRML steels are less expensive than the NGO steels. Unannealed CRML also produces very low wear on stamping tool, further reducing tooling cost.

Applications. They are used where cost is more important than efficiency or overheating. It is the preferred in high volume, small size motors (<1kW) that have intermittent duty cycles which can tolerate large core loss (~10 w/kg) for short time. Examples: household motors (vacuum cleaners, hair dryers, handheld mixers, sump pumps, power tools, toys etc) and automotive (engine fan motor, seat adjuster motor, starter-motor, power window motor etc.). They are also used in lifting magnets, holding electromagnets etc.

MagWeb
Magnetic Material Data

3. B. ELECTRICAL STEELS - GRAIN-ORIENTED

MagWeb's ***Electrical Steel (GO) Folder*** has 402 excel files listing magnetic properties of these materials, produced by 13 manufacturers. Of these, 222 files contain B(H) magnetization curves/permeability curves while 180 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US Website, click on *MagWeb Database - B. Electrical Steels (GO).*

The ***Grain Oriented Electrical Steels*** use ~ 3.25% Silicon to reduce losses. They have ultra low carbon (< 10 ppm)[17]. But annealing changes the chemical composition, so manufacturers don't commit to specific % of C or Si. Their saturation induction J_s ~2.03 T.

Grades. They are available in three grades – conventional, high permeability (aka **HiB**) and domain refined (aka **laser scribed**). The grain size of conventional GO steels is ~ 3mm, while that of HiB steels is about 8mm.

Japanese steel producers use "tt-xx- ccc" to grade them. Here, "tt" denotes thickness (mm x 100), "xx" denotes the "type" – with Z for conventional, ZH for HiB steel, ZDKH for HiB steel with laser scribing. "ccc" denotes for core loss (w/kg x 100) at 1.5 or 1.7T, 50 Hz. For example 27ZDKH95 refers to 0.27 mm thick laser scribed HiB steel with 1.7/50Hz core loss not exceeding 0.95w/kg.

European standards use the nomenclature "Mccc-tt-x". Here, "M" is for electrical steel, "ccc" is for core loss (w/kg x 100) at 1.5T/50Hz , "tt" is for thickness (mm x 100). "x" is for "type": A for fully processed NGO steel, K for semi-processed steel NGO steel, P for a high permeability material, N for core loss measured at 1.5T/50Hz, S for core loss measured at 1.7T/50Hz . For example, M105-30P refers to 0.3 mm thick high permeability steel with the 1.7T/50 Hz core loss less than 1.05 w/kg.

Permeability. They are made by a complex process that vastly increases permeability and reduces core loss – but only in the rolling direction. If the flux direction deviates even by a small angle from the rolling direction (e.g. 10^o), the permeability can drop sharply. If the flux flows in Transverse Direction at 90^o (TD or hard axis), its permeability could reduce by an order of magnitude.

The complex manufacturing process increases peak permeability of HiB steels to 60,000 or more. However, such high-permeability is a ***double-edged sword***. It concentrates magnetic flux to such a thin skin. The mid core can be devoid of flux, simply wasted.

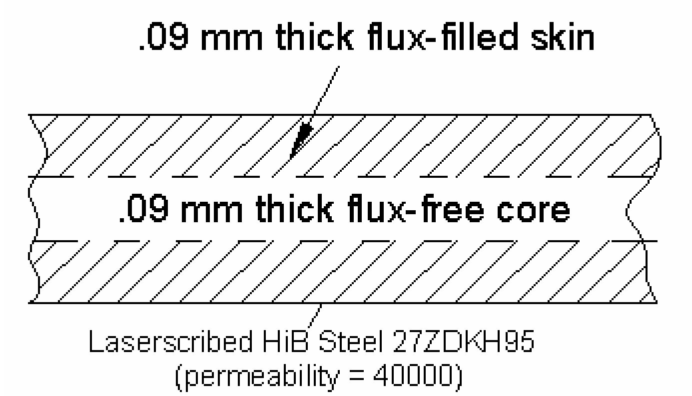

Fig. 6. Too high permeability can prevent flux from flowing in a central core of a lamination

For example, Fig. 6 shows a 0.27 mm thick laser scribed HiB steel lamination 27ZDK95 with resistivity of 50$\mu\Omega$ cm. Consider an application that attempts to carry a 400 Hz flux at relative permeability of 40,000. Such 400Hz flux fills only in 0.09 mm thick skins as shown. *Flux does not flow in the central core* of 0.09 mm thickness (i.e., 33% of iron is wasted). This also increases flux density by 33%, so greatly increases core loss!

[17] Ramanathan, S., Study of dislocations...on magnetic properties of grain oriented electrical steel, *Ph. D Thesis*, Cardiff University, 2013, p. 2

Core Loss. At 1.5T, 50 Hz, core loss of GO steels ranges 0.5 to 1 w/kg. This core loss is only along the Rolling Direction (RD or easy axis). It could triple along TD! For example, in the transverse direction, the core loss in M-6 is 40% greater than that in M-19!

Cost. The GO steels are more expensive than the NGO steels. The cost is also greatly affected by import duties imposed by specific countries.

Applications. Because they are more or less isotropic, they are used mostly in applications where flux flows along rolling direction. Examples include transformers, tape core inductors. They are also used in large MW generators (which have low pole count) and hydro and wind units (which have high pole count). Their cores are built with segments such that flux flows mostly yolk or teeth respectively. But, in teeth (of low pole count utility generators) or in the back iron (of high pole count hydro units) ***flux flows inefficiently*** in the Transverse Direction. In these areas its high magnetic resistance ***chokes the flow of flux***. Such flux-choked regions should be modeled by separate B(H) and core loss curves for transverse direction. For some steels, MagWeb provides property files one for rolling and other for transverse directions.

So the GO steel should never be used in radial gap motors where the flux flows in all directions. At present few have tested GO steel in axial gap machines, but are not yet commercialized.

Steels of same grade may produce different efficiencies

Most steel firms furnish cross-index tables of equivalent grades[18] . They show "equivalent-grade" GO steels produced by other firms that produce same "maximum" core loss. But in reality, such cross-index tables are literally useless as different steels have different core loss and B(H) curves, so produce different efficiencies.

For example, Fig. 7 compares the core loss curves of ***five M-6*** grade steels, produced by five firms (AK Steel, ATI, Cogent, Nippon and Posco). It shows that, core loss of these equivalent grade steel varies by ***as much as 30%***! This in turn causes differences in efficiencies.

So MagWeb lists the properties of GO steels produced by each firm, *irrespective of whether they are of the same grade*. Such firm-based data will help designers in identifying the firm that produces most efficient grade.

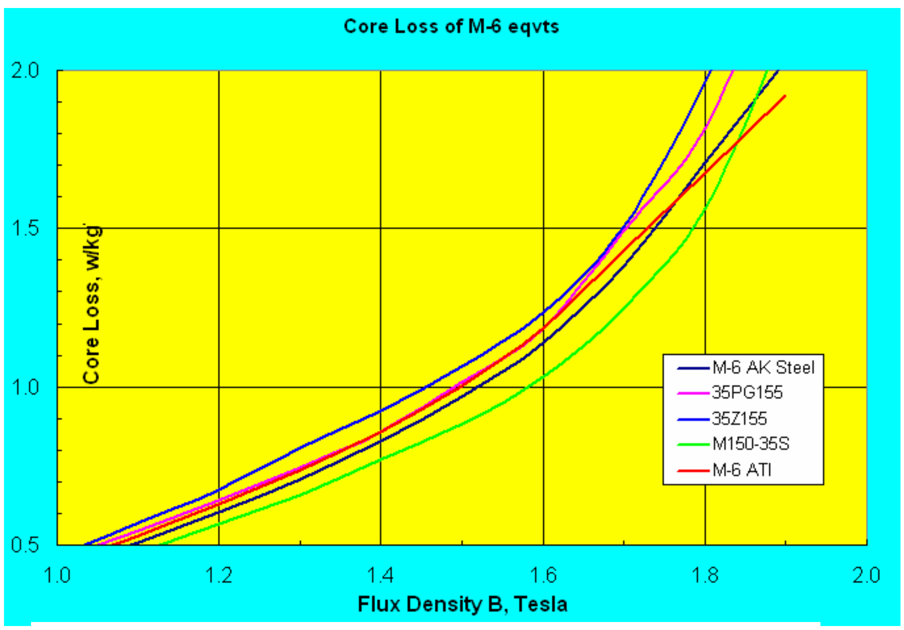

Fig. 7. Different M-6 Grade steels are optimal at different flux densities.

[18] example: Cold Rolled Grain Oriented Electrical Steel produced by Bao Steel, China for international market, mmriii.com

4. CORE LOSS

MagWeb contains thousands of core loss files for a variety of materials. Each file plots several core loss curves at varying frequencies. Core loss curves for electrical steels are available up to10 kHz, for Metglas and Nickel steels up to 100 kHz, and for Ferrites up to ~1GHz or more.

At present there is a strong interest in selecting optimal steel for traction motors for hybrid vehicles. A designer often tries to keep core loss below 5w/kg. So which steel meets this need? A trial candidate is 0.5 mm thick M250-50A grade. MagWeb's database shows that its core loss at 1.5T, 400Hz is 23.4 w/kg. This is awfully high. So next try a thinner 0.35 mm M270-35A grade: It reduces core loss (by 26%) to 17.3 w/kg. A thinner grade of 0.2mm thick, NO20 steel further reduces core loss (by 48%) to 0.2 mm. Since this is still higher than 5w/kg, one has no recourse but reduce design flux density from 1.5 to 1T in order to limit core loss.

As indicated earlier, the magnetizing current needed to produce the flux is as important as core loss incurred in iron while carrying the flux. MagWeb's exhaustive listing of P(B) core loss curves and B(H) curves can help you identify a most efficient steel grade for your product.

In addition to the effect of manufacturer, material thickness, flux density and frequency on core loss *MagWeb* also graphs the effect of secondary factors wherever available. These include annealing, flux direction, pwm harmonics, temperature, stresses, clamping pressure, coating, burrs, etc.

A surprising fact is that the core loss curve for electrical steels ***has an inflection point*** (as with B(H) curve)***.*** Its slope P'(B) increases at first, reaches a peak at the inflection point and falls beyond.

Fig. 8 shows core loss curve for M-19 steel at 50 Hz. It shows the slope P'(B) = dP/dB in red color. This indicates that the slope initially increases and reaches a peak at the inflection point P. ***Beyond this inflection point, the slope decreases with increasing flux density.*** .

MagWeb data reveals that electrical steels have inflection point ranging 1.3 to 1.9T - depending on the grade and manufacturer. For M-19, this inflection occurs at 1.5 T.

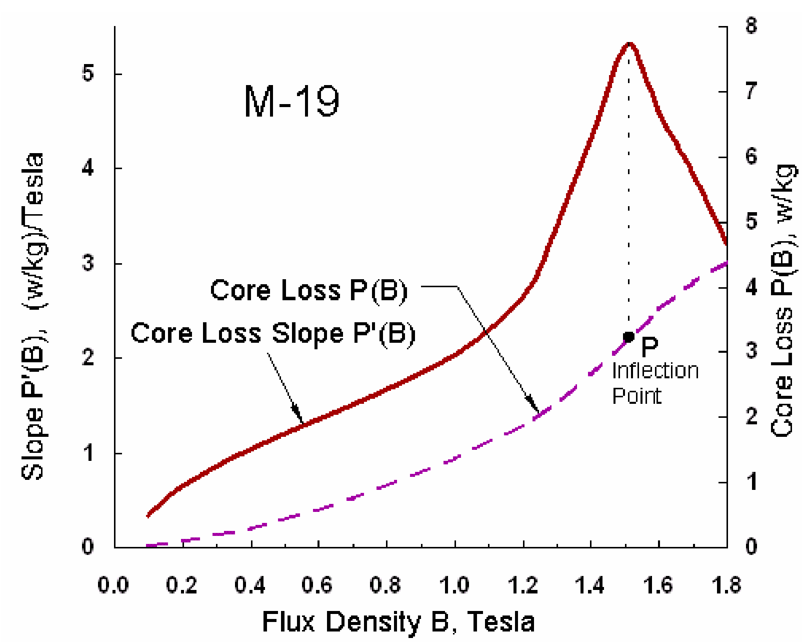

Fig. 8. Core Loss Curve also have an Inflection Point P.

Obviously, the presence of an inflection point affects the accuracy of a core loss model. A core loss model P(B) is said to **faithfully** reproduce the measured data if its slope P'(B) reduces beyond the inflection point.

Over past 100 years, several experts, ranging from Steinmetz[19] (in 1900's) to Bertotti (in 1990's) to Ionel[20] (in 2010's) have developed scores of core loss ***models***. All these models express the core loss model P(B) as sum of several mechanisms, such as hysteresis loss, eddy loss, anomalous loss etc. For example, a popular Bertotti model[21], assumes that the core loss is sum of these three mechanisms,

$$P = K_h f B^m + K_e (f B)^2 + K_a (f B)^{1.5} \quad \text{.. .. (1)}$$

This model assumes that the coefficients K_h, K_e, K_a (called hysteresis, eddy and anomalous loss coefficients) are all positive. Its slope P'(B) is,

$$P'(B) = mK_h f B^{m-1} + 2K_e f^2 B + 1.5K_a f^{1.5} B^{0.5} \quad \text{.. .. (2)}$$

What is more, it assumes that the exponent m is positive and greater than 1. Since all coefficients are positive, the Bertotti model ***predicts*** that the slope *will monotonically increase* with B. So per this model, core loss should not have an ***inflection point!***

In fact, all core loss models proposed so far unknowingly assert that there will be no inflection point in the core loss curve. But test data shows that electrical steels do have an inflection point! So, there is still a need for a true core loss model that faithfully reproduces the observed core loss curve with an inflection phenomenon. Otherwise, values predicted by the models beyond inflection point can be unfaithful.

[19] C. P. Steinmetz, "On the law of hysteresis" *Proc. IEEE,* Vol. 72, No. 2, pp. 196 - 221, Feb. 1984. (original paper in Trans. AIEE Vol. 9, pp. 1-64, 1892)
[20] D. M. Ionel, M. Popescu, S. J. Dellinger, M. I. McGiip, T. J. E. Miller, S. J. Dellinger, R. J. Heideman, , "Computation of core losses in electric machines using improved models for lamination steels," *IEEE Trans. Ind. Appln*., Vol. 43, No. 6, pp. 1554-1563, Nov. 2007.
[21] G. Bertotti, "General properties of power losses in soft ferromagnetic materials, " *IEEE Trans. Magnetics*, Vol. 24, No. 1, pp. 621-630, Jan. 1988.

5. C. METGLAS & NANOCRYSTALLINE

MagWeb's ***Metglas & Nano Folder*** has 53 excel files listing magnetic properties of these materials, produced by 4 manufacturers. Of these, 30 files contain B(H) magnetization curves/permeability curves while 23 files contain core loss curves. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database - C. Metglas & Nano.*

These materials employ 9% to 15 % silicon to offer low core loss and high permeability at 10K to 100K Hz frequencies. More silicon reduces saturation induction (to less than 1.6T). They also have near-zero magnetostiction. Cores are also made by powdering these ribbons and mold-pressing them. Such powder cores are sold under trade names of amoflux, optialloy and listed in the alloy powder core folder. Obviously they have inferior properties.

(a) Amorphous

Amorphous ribbons do not have grain or domain structure. They are produced by cooling a molten metal over a rotating copper drum. The drum rotates at such high speed that the melt does not have time to form crystalline structure. Boron is added for easy flow of the molten metal. This process produces thin, limited-width *ribbons*. Speed limits ribbon thickness to 25 μm (1 mil). The size of drum limits ribbon width to 200 mm (8").

Metglas produces most of amorphous ribbons and cores. So "amorphous" and "Metglas" are often synonymous. Other firms such as Vacuumschmelze, Amotech, Toshiba, NanoAmor etc also produce them. Metglas manufactures several grades of amorphous ribbons. They are grouped into iron-based, cobalt based or nickel based. Table 7 below sorts these grades by core loss. It shows that iron-based Metglas 2605SC offers 1/3 rd core loss of the popular Metglas 2605S3A. The price of 2605S3A (which uses less Boron) has drastically reduced recently, allowing its wider usage

Manufacturers of Metglas and Nano furnish magnetic properties of raw ribbons (instead of finished toroids). They provide a multi-valued hysteresis loop (instead of a single valued B(H) magnetization curve). For a given H, such loop has two values of flux densities. Such multivalued properties are not accepted by most design software. MagWeb converts such multivalued hysteresis loops into single valued B(H) curve using the *Elenbass Rule*[22]. This rule states that the flux density B at a given H equals average of the two flux densities having same H ordinate.

They are supplied as ribbons, toroidal cores or C-cores. Designers should use the toroids or C-core sold by the manufacturers (instead of raw ribbons as magnetic properties are sensitive to stress). Magnetic properties of C cores are inferior to toroidal cores.

Permeability. Their permeability is high and ranges 100000 to 300000. But one should consider the skin depth at such high frequencies.

Skin Depth. For example, consider Metglas 2605SA1 of 25μm thickness with 42μΩ cm resistivity operating at 100 kHz, 200000 permeability. At 100 kHz, its skin depth is 5μm. So flux flows only in 10 μm skin. So the mid-core of 25–10 = 15 μm is devoid of flux. The mid-core is magnetically equivalent to air! So it wastes lot of costly material. Confining flux to tiny skin also greatly increases flux density and core loss!

[22] Bozorth, *Ferromagnetism*, Van Nostrand Co., 1951, p. 511

Core Loss. They offer low core loss at high frequencies ranging 1000 Hz to 100,000 Hz. Typically, the core loss at 0.75T, 50 Hz ranges 0.01 to 0.06 w/Kg as shown in Table 3.

Table 3. Metglas Ribbons, graded by core loss

Name	Base Element	Composition	J_s, Tesla	Core Loss w/kg At 0.75T, 50Hz
2705M	Cobalt	$Fe_4 Si_{12} Co_{69} B_{12} Ni_1 Mo_2$	0.77	-
2714A	Cobalt	$Fe_4 Si_{15} Co_{66} B_{14} Ni_1$	0.57	-
2605SC	Iron	$Fe_{81} Si_{3.5} B_{13.5} C_2$	1.61	**0.011**
2605HB1M	Iron	$Fe_{90} Si_5 B_5$	1.63	**0.028**
2605S3A	Iron	$Fe_{90} Si_3 B_3 Cr_3$	1.4	**0.036**
2605SA1	Iron	$Fe_{78} Si_9 B_{13}$	1.56	**0.055**
2826MB	Nickel	$Fe_{40} Ni_{38} Mo_4 B_{18}$	0.88	**0.057**
2605CO	Iron	$Fe_{66} Co_{18} Si_1 B_{15}$	1.8	**0.178**

(b) Nanocrystalline Ribbons

Nanocrystalline ribbons have tiny grains (as small as 15 nm). They are made by a process similar to amorphous materials. Except that the molten amorphous material is subjected to intense magnetic field annealing, this develops a tiny crystalline structure. Trace Cu, Nb is added to improve magnetic properties. The ribbons have thickness of 0.001", 0.0008" and width less than 4". But they saturate earlier (at ~1.2 T instead of ~ 1.5 T of amorphous ribbon). Hitachi, Vacuumschmelze are the leading producers, but Magnetec, Arcelor Mecagis, ATM, NanoAmor also produce this material.

Core Loss. Their core loss is lower than amorphous ribbons. One grade (Nanoperm) is usable up to 1.5T, but its core loss is x3 higher. Table 4 below grades them by core loss.

Table 4. NanoCrystalline Ribbons, graded by core loss

Name	Firm	Composition	J_s, Tesla	Core Loss w/Kg At 0.2T, 100kHz
VITROPERM	Vacuumschmelze	$Fe_{73.5} Si_{15.5} B_7 Cu_1 Nb_3$	1.23	**35**
FINEMET	Hitachi	$Fe_{73.5} Si_{13.5} B_9 Cu_1 Nb_3$	1.24	**38**
NANOPHY	ArcelorAperam	$Fe_{74.1} Si_{15.7} B_{6.1} Cu_1 Nb_{3.1}$	1.24	
NANOPERM	Magnetec	$Fe_{86} B_6 Cu_1 Zr_7$	1.52	**116**
HiT PERMa	Carnegie Mellon	$Fe_{67} Co_{18} Si_1 B_{14}$	1.8	**-**
HiT PERMb	Carnegie Mellon	$Fe_{44} Co_{44} B_4 Zr_7 Cu_1$	1.8	**-**

Applications. They are used in high frequency inductors, single phase transformers, power converters, magnetic shields etc. Because ribbons are very thin and narrow, making three phase transformers or motors using these ribbons is still a challenge.

MagWeb
Magnetic Material Data

6. D. COBALT STEELS

MagWeb's ***Cobalt Steel Folder*** has 237 excel files listing magnetic properties of these materials, produced by 4 manufacturers. Of these, 43 files contain B(H) magnetization curves/permeability curves while 194 files contain core loss curves. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database – D. Cobalt Steels.*

Cobalt Steels are alloys of cobalt and iron that offer highest possible saturation induction. They were known earlier as Supermendur, 2V-Permendur etc. They are cast in the form of a billet, then hammer-forged into a bar, which is then rolled to the desired thickness.

***In USA**,* Carpenter sells 6 Cobalt Steels under "Hiperco" brand name. MagWeb has 225 files on them. Carpenter's Hiperco 50 series have ~48.75% cobalt plus 2% V. Such high cobalt makes them very expensive. They are available as strips of 0.006, 0.010, 0.014 inch thickness.

Hiperco 50A – has ~0% C so offers lowest core loss. Similar to Vacoflux 48. Vacoflux 50
Hiperco 50 – has 0.01%C so offers low core loss. Its 0.05%Nb increases ductility.
Hiperco 50HS – has 0.3% Nb to increase yield strength. But its core loss is very high.

Those with lower cobalt (5, 15 or 27%) are less expensive. Their magnetic properties are less attractive as they have higher %C. They are produced in rounds, wires or strips.

Hypocore – a new 5% Co, 2.3% Si strip alloy for high frequency motors (coating is optional).
Hiperco 15 – has 15% Co. Has high resistivity. But its .01%C degrades magnetic properties
Hiperco 27 – has 27% Co. Is highly ductile. But its .01%C causes higher core loss.

In Europe, Vacumschmelze sells 9 Cobalt Steels under brand names of "Vacoflux", "Vacodur". MagWeb has 12 files on these steels. Of these, Vacoflux 48, 50 have 49% Co, 2% V, and so offer best magnetic properties. Vacodur has Nb added to improve mechanical properties. Arcelor/Imphy also produces 3 cobalt steels under brand name "Aperam" or "AFK". Others, such as Xian Gangyan Specialty Alloy, China also sell cobalt steels, but they are properties are not available.

Core Loss vs. Copper Loss. Fig. 9 compares the magnetic quality of 0.35 mm cobalt steels while carrying 1.7T at 50 Hz. It shows that Vacoflux 48 produces the lowest core loss. This cobalt steel also dissipates lowest copper loss as it requires least H of 72 A/m. Hiperco 50A, Vacoflux 50 and Hypocore also produce similar levels of low core loss. *But they will produce* **significantly higher copper loss.** Hypocore requires 4540 A/m which is two orders of magnitude higher than the 72A/m, so produces lot more copper loss.

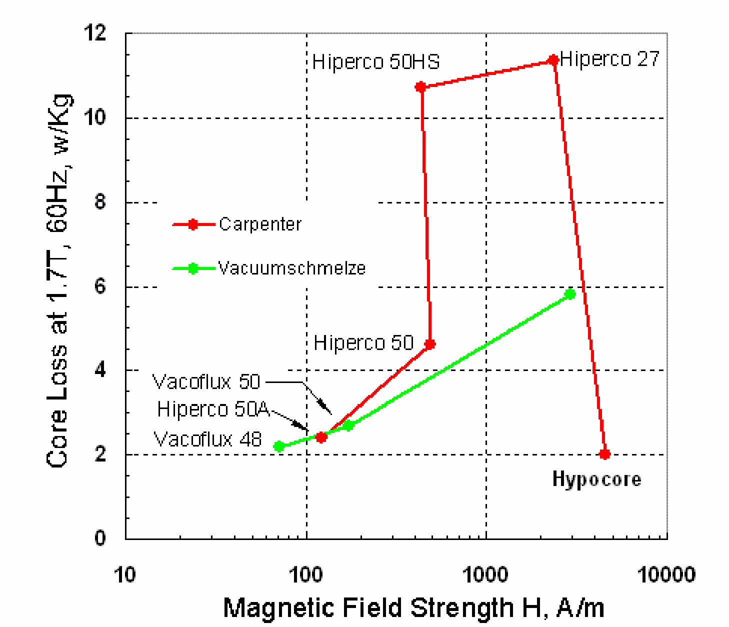

Fig. 9. Vacoflux 48 produces least core loss and copper loss. But Hypocore incurs more copper loss (it needs more magnetizing current to reach same B.)

Saturation Induction J_s of cobalt steels is ~ 2.45 T (only 14 % higher than iron's 2.158T). A recent report indicated that a 50% Cobalt alloy made by hot isostatic press (HIP) offer a higher J_s of ~ 3 T.

Annealing. A cobalt steel that offers lowest core loss may not have high strength. Generally, annealing at a higher temperature allows fuller recrystallization, so reduces core loss - *but it also reduces mechanical strength.* A high speed rotor may demand stronger steel, so may require annealing at lower temperature (so attains higher strength at the expense of higher core loss). On the other hand, stator cores may need lowest-loss steels, so annealing at a higher temperature (to lower core loss) is recommended.

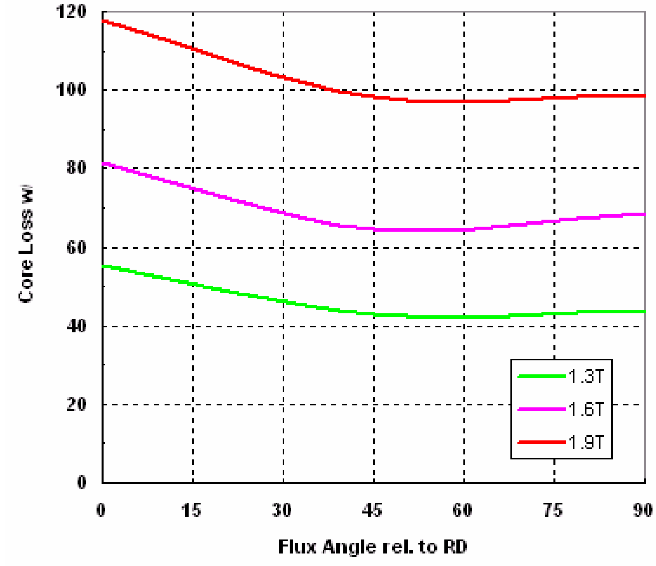

Fig. 10. Core Loss of Cobalt Steels varies with direction of flux.

Anisotropy. MagWeb data shows that magnetic properties of cobalt steels are not independent of direction. It depends on flux angle, which can vary from Rolling Direction (0^o) to Transverse Direction (90^o). Fig. 10 illustrates typical anisotropy of these steels. It shows that core loss of Hiperco 50 at 400 Hz can vary by as much as 20% as one moves from RD to TD.

Aging. Core loss of cobalt steels generally increases with aging. Geist[23] demonstrated that Hiperco 27 is more thermally stable than other cobalt steels.

Yield Strength. Yield strength depends on annealing schedule. Hiperco 50 HS offers highest yield strength ranging 70 to 99 ksi while Hiperco 50 offers 60 to 70 ksi. Hiperco 50A offers lowest at 53 ksi

Stress. The MagWeb data shows that a compressive stress always increases core loss. On the other hand, a small tensile stress (~ 50 MPa) seems to minimize the core loss.

Temperature. In Hiperco 27 only the core loss beneficially decreases with increasing temperature (Fig. 10). Other cobalt steels are not that thermally sensitive.

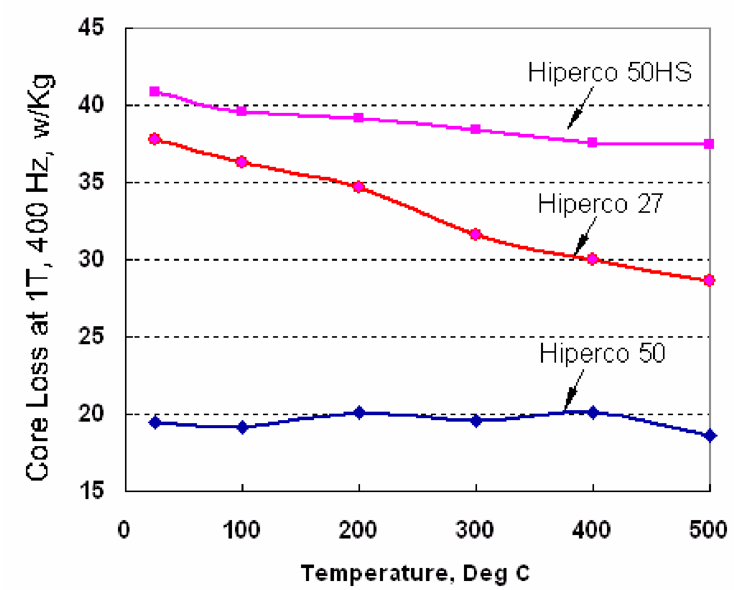

Fig. 11. Hiperco 27's Core Loss beneficially decreases with temperature,

Applications. Cobalt steels are used in aerospace generators and motors which value small size and light weight that override the higher cost of these materials. Their sensitivity to all these factors is documented in the MagWeb database. Such data helps in optimal design of air craft generators.

[23] Geist, et al. Effect of high temperature aging on Hiperco 27, 50 and 50HS alloys, J. Appld Phys. Vol. 93, No. 10, May 2003, pp. 6686-6688.

7. E. NICKEL STEELS

MagWeb's ***Nickel Steel Folder*** has 170 excel files listing magnetic properties of these materials, produced by 7 manufacturers. Of these, 116 files contain B(H) magnetization/permeability curves while 64 files contain core loss curves. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database – E. Nickel Steels.*

Nickel Steels use 30-80% Nickel to greatly reduce the core loss and increase permeability (compared to Grain Oriented steels). But their saturation induction is lower. ASTM 753 divides them into 4 "types". Most common are 50% and 80% Ni steels; but 30% Ni steels are also produced. They are available in 0.001 to 0.014 inch thickness. Most are sold as 1-mil (25μm) thick ribbons, but thinner ones at 0.125 mil (3μm) are also available. They are sold uncoated, but applying an insulation coating can reduce core loss further.

Applications. They are employed in high frequencies ranging 1000 to 100000 Hz in inductors, transformers in communication, EMI Shielding plus anti-shop lifting devices because of their low core loss.

80% Nickel steels offer very high permeability of ~100000 at 0.5 T DC plus low core loss. But its saturation induction (~0.8 to 1.1T) is lower than that of 50% Ni steel. Its trade names are Permalloy, Mumetal, Ultraperm, Magnifer 7904 etc. Its low coercive intensity is attractive for sensitive relays and magnetic shields. But they are sensitive to mechanical stresses. So, to attain the datasheet values of loss and permeability, the finished product must undergo careful annealing as prescribed by the manufacturer.

50% Nickel steels offer lower permeability of ~32000 at 0.5T DC. But its saturation induction of ~1.6T is higher than that of 80% Ni steel. Its trade names are Orthonol, Deltamax, Carpenter 49, Hypernik, 4750, Magnifer50. Of these, Carpenter 49 is sold in NGO ("rotor") grade or GO ("transformer") grade. Cores made of 50% Nickel Steel powders are called MPP cores.

50% Ni steel (unlike 80% Ni steels) is not greatly affected by mechanical stress. So it does not require an exacting annealing schedule. It is also available in several forms such as sheets, plates, bars, rods etc. It is mainly used in audio transformers and inductors which depend on its high incremental permeability.

The core loss of a 50% Nickel steel is comparable to that of Metglas 2605SC or Nanocrystalline materials. But, as with electrical steels, trace impurities differ with manufacturers, so their magnetic properties vary with the manufacturer, even if composition is same.

8. F. STAINLESS STEELS

MagWeb's ***Stainless Steel Folder*** has 43 excel files listing magnetic properties of these materials, produced by 4 manufacturers. All these files contain B(H) magnetization curves/permeability curves. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database – F. Stainless Steels.*

Stainless Steels are 8 to 35% chromium alloys which offer high corrosion resistance. The ferritic 405 and 416 grades contain ~13% Cr, Type 430 has ~18% Cr. These ferritic stainless steels have higher permeability than martensitic ones. They often have upto1.5% Si to reduce core losses. Their yield strength is higher than 1010 series mild steels, but elongation is lower. Other considerations include mechanical strength, thermal conductivity, fabricatability, weldability, and cost requirements.

Applications. Stainless steels are available as plates, slabs, and rounds etc. Applications include industrial solenoids for corrosive fluid pumps, solenoids for antilock breaking systems, fuel injectors, fuel pumps, rotors and motor shafts where corrosion resistance is critical. The MagWeb database contains B(H) Curves for 43 stainless steels. Selection depends on the application requirements of corrosion resistance vs. permeability.

As % chromium increases, corrosion resistance increases, but permeability decreases. Fig. 12 shows that, to create 1.5T flux, a 8% Chr steel may require low magnetizing current (2400 A/m). But a 18% Chr steel may demand two orders of magnitude higher magnetizing current (240000 A/m). MagWeb database allows one to choose the correct stainless depending on magnetic and corrosion requirements.

To attain datasheet values of permeability, the finished stainless part must be annealed. Typical annealing schedule is to heat to 1500F in dry hydrogen, cool at 20F per hour to 110F and air cooling further.

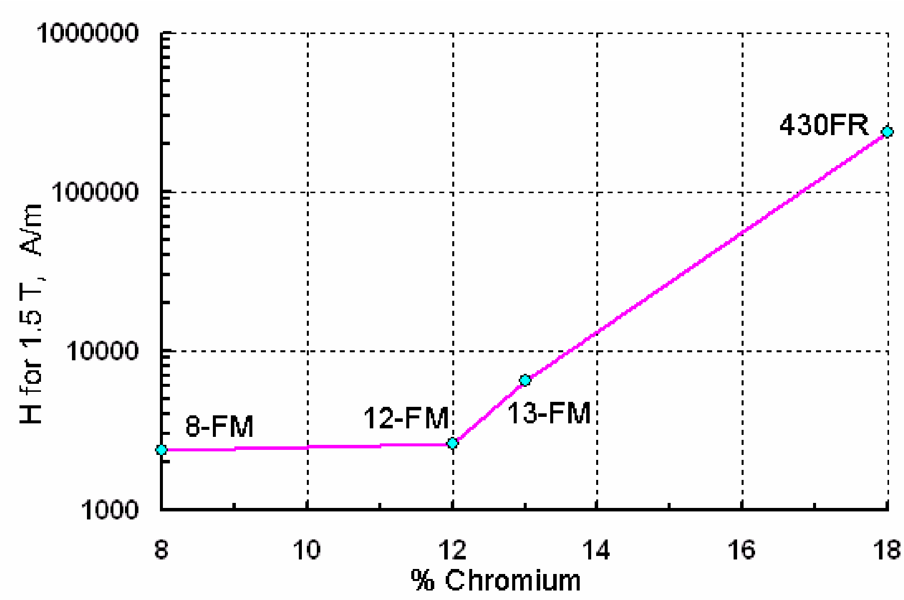

Fig. 12. Magnetizing current needed depends on grade of stainless steel.

Their saturation induction *decreases* as % chromium increases. Thus 8-FM steel (8% chromium) provides high saturation induction (J_s ~ 1.8T); its corrosion resistance is adequate for many applications. On the other hand, the 18-FM steel (18% chromium) degrades J_s to 1.5T, but its excellent corrosion resistance may be necessary in extreme environment applications.

Fig. 13 below presents saturation induction and resistivity of various stainless steels.

Trade Name	% Chr	% Si	Sat. Induction	Resistivity
			Js Tesla	microohm cm
8-FM	8	0.5	1.86	50
12-FM	12	0.5	1.77	57
13-FM	13	1.25	1.7	78
13-XP	13	1.5	1.7	82
18-FM	17.5	0.9	1.5	75.3
405	13	1		60
410	11		1.6	57
416	13	1		57
430	17	1	1.42	60
430F	18		1.42	61
430FR	18	1.25	1.52	76.4
430F-RB75	18	0.5	1.56	60
430F-RB82	18	0.5	1.42	60
430F-RB87	18	0.5	1.42	60
440	18	0.03		60
450	15	1		60
29	29		1.3	63

Fig. 13. Saturation Induction and resitivities of various stainless steels.

Core loss data of stainless steel is rarely published. So it has to be deduced indirectly from its coercive force and resistivity. The resistivity increases from 50 to 76 μΩ cm as % chromium increases from 8 to 18%. Increased % Chr increases resistivity which reduces core loss somewhat. But also increases magnetizing current required by two to three orders of magnitude, which greatly increases copper loss.

8-FM has 8% Chromium and is a Free Machinable. It offers high saturation induction (J_s = 1.86T). Higher J_s facilitates it use in applications that demand high flux density. Their resistivity is however is relatively low, so it is best to restrict it to DC or low frequency applications. It offers adequate corrosion resistance. Harsh environments may need additional coatings.

12-FM and 13-FM have 12 and 13% chromium and are Free Machinable. They have reasonably high saturation induction (J_s ~1.7T). Permeability of 12-FM is similar to 8-FM. The permeability of 13-FM however is poorer. But its resistivity is 50% higher than that of 8-FM. Both have better corrosion resistance than 8-FM.

18-FM has 18% chromium and is Free Machinable. But it saturates at 1.5T. Because of higher % chromium, its magnetic properties are relatively poor. But its corrosion resistance is higher than 8 or 12 % chromium stainless steels, (or even the 430FR solenoid quality stainless steel that has similar % chromium.)

430F series are called "solenoid" quality steel (as detailed in ASTM 838). It has excellent corrosion resistance and low residual magnetism. But its saturation induction of 1.42T is relatively lower than other stainless steels. So it is useful in applications that do not require high flux densities.

430FR is similar to 430F. It also has higher wear resistance and hardness. Its higher resistivity 760 μΩ mm reduces eddy losses. So it can be used to conduct AC fluxes. But as with 430F, it suffers from lower saturation induction (J_s ~ 1.5T). It also has higher coercivity (H_c = 200 A/m) and lower 1T DC permeability (1700).

9. G. LOW CARBON STEELS

MagWeb's ***Low Carbon Steel Folder*** has 159 excel files listing magnetic properties of these materials. Of these, 156 files contain B(H) magnetization curves/permeability curves while 3 files contain core loss curves. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database - G. Low Carbon Steels.*

Low Carbon Steels are those that have carbon ranging 0.02% to 0.2 % C. MagWeb also contains B(H) curves of several steels with 0.2% to 2%C(categorized as "structural steels") - but their magnetic properties are relatively poorer. Steels with more than 2%C are known as cast iron, wrought iron, malleable iron etc. Their properties are listed in the "Cast Iron" folder.

Low carbon steels are available in several forms, such as rounds, flats, tubes, pipes etc in several thicknesses. They are usually thicker than electrical steels. They are also more ductile and machinable.

Their magnetic properties are affected by several parameters. Their manufactures do not tightly control % C, their magnetic properties can vary from firm to firm. Within a firm, they can vary from batch to batch. The can also vary with form and size. Other factors that affect magnetic properties include: rolling (cold, hot), annealing (annealed, unannealed), stress (stressed or unstressed), temperatures (high, low). MagWeb database describes several of these effects and assist in selection of appropriate low carbon steels. It contains B(H) curves for following types of low carbon steels:

- Pure Iron (< 0.005% C)
- Ultra Low Carbon (ULC) Steels (0.005 to 0.01%C)
- Low Carbon Steels (0.02 to 0.2%C)
- Medium Carbon Steels (0.2 to 0.6%C)
- High Carbon Steels (0.6 to 2%C)
- Tungsten Steels
- Rotor Forgings
- Tool Steels

Their B(H) curve is usually measured under DC conditions, using a ring specimen per ASTM A596. A good metric for their magnetic quality is the relative permeability at 1.5 T, 0Hz. A material with 1.5T permeability of 5000 will require low magnetizing current of 240 A/m. That with 500 needs 2400 A/m - an order of magnitude higher current (hence copper loss) to produce same flux density.

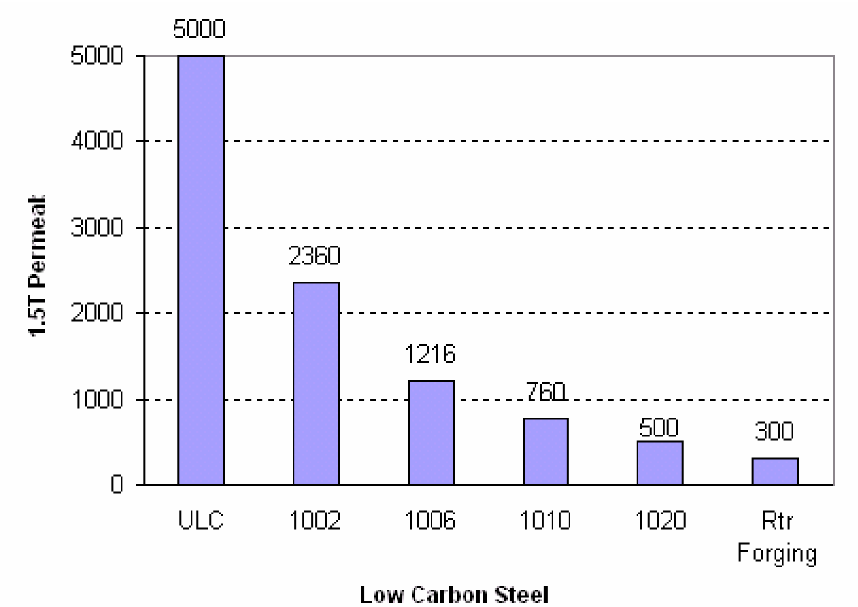

Fig. 14. Permeability of Low Carbon Steel reduces as %C increases.

Fig. 14 shows the 1.5 T permeability for a variety of low carbon steels. It shows that, as carbon increases from 0.005% C (in ULC steels) to 0.2%C (in 1020 steel) the 1.5 T permeability reduces by an order of magnitude. This magnetic degradation is due to precipitated carbon which obstructs flow of flux. It can be countered somewhat by annealing. But annealing can increase the permeability only by a factor 2 at most, not be an order of magnitude. That is, even after annealing, the 1020 steel cannot reach the permeability of pure iron.

Pure Iron

Pure iron is one that has the lowest possible carbon content. It has high permeability and saturation induction of 2.158 T[24] (all other steels saturate earlier). It's extremely low carbon content prevents increase of core loss with time (aging). Lack of Si makes it ductile, but pitifully degrades its ability to carry alternating flux. Its high permeability makes it a good candidate for DC electromagnets.

It is available in sheets, bars, plates and wire. But to attain data sheet values, it must be annealed after machining. It is also available as hydrogen annealed sheet which has much higher permeability.

Pure Iron is originally developed a century ago as ARMCO, OH. But now several manufacturers produce it as well. But, depending on the manufacturer, the impurities can range from 0.02% to 0.5%. Out of this, the carbon impurity can range 0.003 to 0.02% Minute differences in %C impurity causes permeability of all "pure irons" differ with manufacturer.

This folder contains B(H) Curves for Pure Iron from 8 manufacturers. Unfortunately, all label their product as "pure Iron". Low grade pure iron offers far lower permeability of 500. But high grade pure iron (one with lowest % C) offers a 1.5T permeability of 5000.

Ultra Low Carbon Steels

Ultra low carbon steels are those with 0.005 to 0.01% C. Since they also have soluble carbon so their magnetic properties also do not degrade with age. They are available as rounds, squares and flats. Some suppliers (e.g. CMI Specialty Steel) sell them in fully annealed condition as specified in ASTM A848. This Folder contains digital B (H) Curves of 2 grades of Ultra Low Carbon Steels, with .005%C or 0.01%C. Depending on their carbon content, their 1.5T permeability varies from 3500 to 5000.

Low Carbon Steels

Also called *mild steels*, they have 0.02 to 0.2%C. Steels with less carbon have higher permeability. But because they contain precipitatable carbon, their magnetic properties degrade with age. Resistivity of most low carbon steels is ~ 12$\mu\Omega$ cm. They are available in grades such as 1002, 1006, 1008, 1010, 1018, 1020 etc. In these, the last two digits express percentage carbon (e.g., 1002 has ~ 0.02%C, 1020 has ~0.2%C). Their yield strength is about 43 ksi. At 1.5 T, the permeability of 1002 steel is 2360.

1010 steel strips are machinable and annealable. (Where free machining is required, one can use SAE 1112 instead). They are available in four degrees of hardness: dead soft, ¼ hard, ½ hard, full hard. The hardness defines their bendability. For best results, the machined part should be annealed, which can double their permeability. For example, annealing of 1010 steel increases the 1.5 T permeability from 585 to 1260.

1020 steel is also machinable, but only heat treatable. It has lower permeability than other grades. Its advantage is easy availability in a variety of sizes and shapes, and ease of machining.

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[24] Sanford, R.L and Bennett, E. G., (1941) Determination of the magnetic saturation induction of iron at room temperature, J. Res. National Beureau of Standards, Vol. 26, Jan. 1941, paper RP 1354, pp. 1-12.

This Folder contains digital B(H) curves of 40 grades of Low Carbon Steels. The 1.5T permeability of 1020 steel is ~ 500.

Medium Carbon Steels (aka structural steels)

They have 0.2 to 0.6%C. They are stronger than mild steels. The 1.5 T permeability of steels with 0.2% C is ~ 600. But in those with 0.6% C, it drops down to 300. This in turn doubles the current required to push 1.5T flux through the material. This Folder also contains digital B(H) curves of 19 Medium Carbon Steels, with about 0.35%C. Of these, 4130, 4140, 4340 steels (with yield strength of 65 ksi) offer 1.5T permeability of 565, 363 and 326 respectively. A high strength steel called D6ac steel (with high yield strength of ~220 ksi) has lower 1.5T permeability of 257.

High Carbon Steels

Steels with 0.6 to 2%C are also called high carbon or *high strength steels.* This Folder contains digital B(H) curves of 19 High Carbon Steels.

Those with 0.6 to 1% C are known as ***spring steels***. The 1.5 T permeability of such steels with ~0.6%C can be ~ 300.

Those with 1 to 2% are known as ***ultra high carbon steels or tool steels***. They are very strong but brittle, and need special heat treatment. Beyond 1.55%C, the permeability degrades sharply. The 1.5T permeability of steels with > 2%C is very low ~ 50 – they act almost like air.

Rotor Forgings

Rotor forgings are medium carbon steels, with 0.15 to 0.35%C. A small percentage of Ni, Cr, V are added to increase strength and hardness. They are used to make very large sized (> 1 m diameter, > 3 m in length) rounds per ASTM A469. They are used as rotors in large power generators that require high strength and hardness. They carry large DC flux close to 2T They are graded by yield strength, which ranges 50 to 110 ksi as listed in the MagWeb database.

The MagWeb database contains digital B(H) curves of 8 grades of Rotor Forgings. Note however, their 2T permeability is poor, ranging only 40 to 70. So they require large (~ 30000 A/m) magnetizing current. This in turn produces significant copper loss in rotors.

Core Loss

The folder also contains hard-to-find core loss curves for mild steel in the 1 -250 Hz range. Applications that carry AC flux will need Low Carbon steels in thin laminations with thickness less than 1 mm. In loud speakers, they are used to carry low level flux at high frequencies.

But they are very lossy at line frequencies. Typically core loss at 0.5 T, 50 Hz is about 8 w/kg. To avoid overheating, most applications use them to carry large flux only at low frequencies (less than 5 Hz, or low flux at high frequencies. Examples include motor shafts, pole pieces, solenoids, actuators etc. Those that carry DC flux can have unlimited thickness. But their thickness is very limited when carrying ac flux as discussed below.

Thickness Limit

The AC flux tends to concentrate in a thin skin near the outer surface. This increases the flux density at the outer surface and decreases that at the central core[25]. The higher flux density at the surface increases core loss.

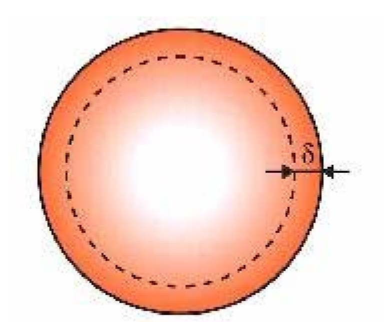

Fig. 15. AC Flux can be carried only upto the Skin Depth δ

[25] http://ecee.colorado.edu/~ecen3400/Textbook/Chapter%2020%20-%20The%20Skin%20Effect.pdf

To limit undue increase in core loss, their thickness must be less than two skin depths (t< 2δ).

Skin depth δ (see Fig. 15) is the distance from the surface at which the flux density reduces to ~ 37% of that at the surface. It is given by[26]

$$\delta = \sqrt{\frac{\rho_T}{\pi \, \mu_0 \, \mu_r \, f}} \quad (1)$$

where
f = frequency of sinusoidal flux wave form, Hz
ρ_T = resistivity at the operating temperature T, ohm m
μ_r = relative permeability at a given flux density B, = μ_r (B, f, T)
$\mu_o = 4\pi \, 10^{-7}$ N/A^2

Thus skin depth δ depends on the frequency and relative permeability μ_r (which itself depends on the flux density B, frequency and temperature). It also depends on the resistivity which varies with temperature. For example a 10000 Hz the flux concentrates in ~0.002 in skin, wasting lot of material. Laminations carry these high frequencies in two skins, one on each flat side.

For example, Fig. 16 shows a 25 mm thick 1020 low carbon steel with resistivity of 12μΩ cm. In an application it attempts to carry 5 Hz flux with relative permeability of 500. Skin effect restricts the 5 Hz flux inside a 4 mm thick skin as shown. Very little flux flows in the 17 mm central core. So skin effect adversely increases flux density and hence core loss!

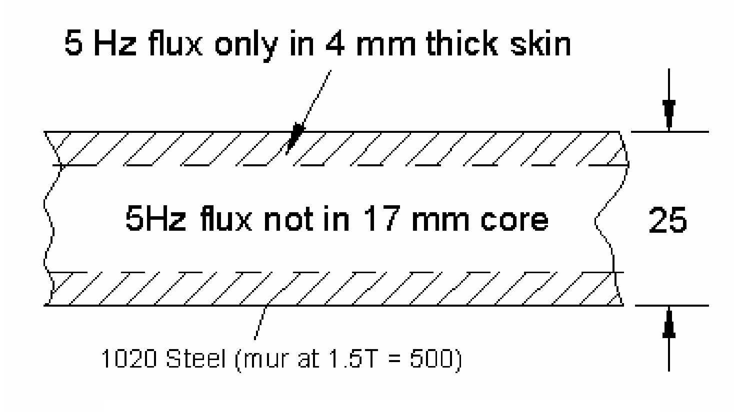

Fig. 16. The central core of solid steels may not carry AC flux

Annealing

The term "Annealing" refers herein to a thermal process in which the material undergoes a specific thermal schedule in order to improve its magnetic properties (e.g., higher permeability, lower core loss etc). A decarburizing anneal is one that reduces the carbon content. A stress relief anneal is one that reduces mechanical stress.

The term "heat treatment" refers to a process that improves mechanical property (e.g., fatigue strength, yield strength, hardness etc). Examples include tempering, hardening, quenching. Hardening produces steels with more austenitic phase (with FCC unit cell) that has high mechanical strength but non-magnetic.

Fig. 17 shows how during annealing, thermal vibrations cause carbon atom to get "squeezed" inside an iron crystal. As a result, crystal structure can change from BCC to FCC, or BCT. This alters the texture and orientation of crystals, its grain size and hence magnetic or mechanical properties.

[26] https://www.allaboutcircuits.com/tools/skin-depth-calculator/

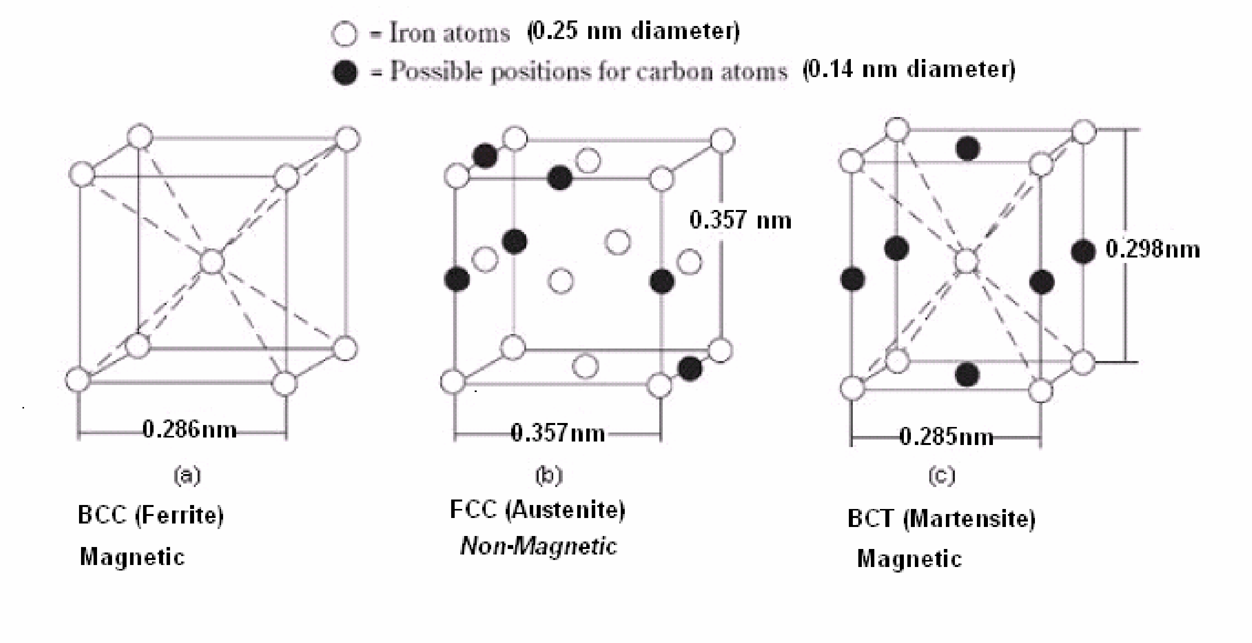

Fig. 17. Annealing squeezes carbon atom inside an iron crystal

For annealing low carbon steels, one can refer to classic papers by Burrows[27] , Cheney[28] or recent investigations by Stokes[29], Ghodsi[30] Zhetvin[31] list annealing schedules and their impact on magnetic properties. Unfortunately, annealing schedule differ with carbon content. Typical annealing schedules for some low carbon steels are given below.

Pure Iron. Anneal below 760 C for 4 hrs, followed by slow cooling.

1005 Steel. Anneal at 843 C for 4 hrs in a closed furnace with 94% Nitrogen, 6% hydrogen, with -68 C dew point atmosphere, flowing at a rate of 5 times the volume of the furnace per hour. Furnace cools at 50 C per hour. Remove from furnace and age at 100 C for 200 hrs in air.

1010 Steel. Heat to 870 to 980^o C. Slow cool in the furnace, stress relief anneal at 1000 F and slow-cool in the furnace to room temperature.

1018 Steel. Heat to 850 -925^o C, ramping at 90^o F per hour. Soak for 3 hours. Slow cool in the furnace to room temperature.

Electrical Steel. The stress relief annealing furnace can use following atmospheres: - Natural endothermic gas, partially combusted under controlled conditions, or Nitrogen exothermic gas (with 0% to 10% Hydrogen, 4.4 C dew point). The furnace load shall be heated to 760+/- 14C at any rate and held at this temperature for 1-2 hour. With natural gas atmosphere, move the load out of furnace into a cooling chamber. Allow to cool at any rate while maintaining the atmosphere to 370C or lower before removing the parts. With Nitrogen atmosphere, maintain the atmosphere and cool at 50 C/hr to 370C or lower. Below 370C, cool at any rate.

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27 Burrows, C.W., (1915) Correlation between magnetic and mechnical properties of steel, Bulletin of Bureau of Standards, vol. 13, pp. 173-209. nvlpubs.nist.gov/nistpubs/bulletin/13/nbsbulletinv13n2p173_A2b.pdf

28 Cheney, W. L. (1922) Magnetic properties of iron-carbon alloys as affected by heat treatment and carbon content, *Scientific Papers of the National Bureau of Standards*, Vol. 18, pp. 609- 635. https://archive.org/stream/magneticproperti18609unse#page/n5/mode/2up

29 Stokes, J. L (1983) Magnetic properties of Iron and low carbon steels for soft magnet application, Naval Weapons Center, TP 6455.

30 Ghodsi, M et al (2011) Effect of forging on ferromagnetic properties of low carbon steel, 4th Int. Conf. on modelling, ICMSAO 2011.

31 Zhetvin,N.P. et al (1960), Heat treatment of low carbon magnetic core steel, Metal Science and Heat Treatment of Metals, Nov. 1960, Vol. 2, Issue 11, Nov. 1960, pp. 595-598

MagWeb
Magnetic Material Data

10. H. CASTINGS

MagWeb's ***Castings Folder*** has 52 excel files listing magnetic properties of these materials. These include cast steel, gray cast iron, wrought iron, malleable iron, ductile iron etc. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database – H. Castings.*

Castings are made by pouring molten iron into molds. Cast iron parts can be intricate and can have even sharp corners and can be large. They are single parts made without additional fabrication and assembly steps. Cast shapes are 3D - unlike 1D thin laminations (as in electrical steels) or 2D flat, rounds or tubes (as in low carbon steels).

Cast Steels

They are steels with carbon ranging 0.1 to 0.5%. Because of low %C, they offer a high saturation induction of 2.14T (compared to cast iron's 1.77T). But low %C reduces their fluidity, making it more difficult to pour into a mold (than cast iron). So cast steel parts should have rounded corners. They also shrink more than cast iron. Since they need more steel, the mold need excess steel reservoirs, called risers. Steel from risers is drawn into the casting as they shrink while cooling. Magweb's Castings Folder contains 5 B(H) files of Cast Steel. They show that unannealed Cast Steel offers a 1.5TDC permeability of about 300; annealing can double its value.

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Cast Iron

It is made of iron with larger carbon ranging 1.7 to 4.5% %. This higher %C causes their magnetic quality to be poorer than cast steel. In 1900's, a highly magnetic form of cast iron, known as mantis was developed, but it is no longer available. Wide range of %C and diverse impurities make their magnetic properties non-reproducible. They are made per EN1561

Cast Iron is used to make high volume (occasionally large) magnetic parts of intricate design at low cost. The ease of casting facilitates mass production. Fig. 18 overviews the magnetic properties of typical cast irons and cast steels32.

Trade Name	Class	Structure	Sat. Induction	Resistivity
			Js Tesla	microohm cm
GJL-250	cast iron	flake graphite	1.76	67
GJS-500-7	cast iron	spherical /ferritic	1.75	45.9
GJS-700-2	cast iron	spherical /ferritic-peralitic	1.69	50.7
GJS-400-15	cast iron	spherical/peralitic	1.77	47.6
GS-52	cast steel		2.03	23.5

Fig. 18. Magnetic Properties of typical Cast Iron and Cast Steel

MagWeb's Castings Folder contains 10 B(H) files of Cast Iron. They show that, because of excessive carbon, their 1.5T permeability is low, ranging 25-100. So, they demand relatively high current (H >10,000 A/m). For example a recent cast iron GJL-250 offers a low permeability of 50 at 1.5T (compared to 300 offered by cast steel).

[32] Prizztech, Magnetic Properties of Cast Irons, www.prizz.fi/sites/default/files/tiedostot/linkki2ID940.pdf

Both Cast iron and Cast Steel produce large core loss at line frequencies. But resistivity of cast iron is thrice that of cast steel, so cast iron's eddy losses are far lower that of cast steel. Since their core loss is higher than electrical steels, they are used at ~ DC.

Their mechanical properties are affected by trace impurities of Si, P, Mn, and S. Si (which can be up to 4%), assists formation of free graphite, and makes cast iron soft and machinable. S (which must be below 1%) makes the cast iron hard and brittle. Mn (which must be below 0.75 %) limits the ill-effect of Sulfur; it makes cast iron white and hard. P (which must be less than 1%) increases fluidity, so facilitates intricate castings, but makes it brittle.

Cast iron is more fluidic than cast steel, so it is relatively easier to pour and make intricate parts. They do not shrink, so do not need risers. But they are brittle. They have high compressive strength. They are available as grey cast iron, malleable cast iron and wrought iron. Malleable cast iron and wrought iron are ductile. Grey Cast Iron is merchantable, but not ductile.

Grey Cast Iron

It is a cast iron whose carbon content ranges 3 to 3.5%. They may also contain 1 to 2.75% Si. Carbon is present in the form of free graphite; hence its color is gray. But they have no ductility.

MagWeb's Castings Folder contains 2 excel files of Grey Cast Iron. They show that at 1T, they offer a permeability of 58. Annealing doubles permeability to about 95.

But they suffer from low tensile strength, which ranges 20 to 60 ksi. As described in Indian Standards IS 210, there are 7 types of Gray Cast Irons, with designations FG150 to FG 400. For example, FG150 means a gray cast iron with tensile strength of 150 N/mm2 (22 ksi).

Wrought Iron

It is a purest form of iron. It contains 99.5 to 99.8% iron. It also contains very minute quantity of carbon (~ 0.02%) and Silicon (0.12%). It also contains trace S (0.018%) and P (0.02%). It is tough, malleable, ductile, forgeable and weldable.

MagWeb's Castings Folder contains 13 B(H) files of Wrought iron. They document the effect of annealing and stress on B(H) curve. They show that a 0.08%C wrought iron has excellent magnetic properties. At 1.5T, it needs H as low as 2440 A/m at permeability of 600. But in poorer grades permeability may degrade to 200.

Malleable Cast Iron

It is a cast iron in which the carbon is present in the form of cementite. That is, its carbon is not in graphitic form. But, unlike gray cast iron, they are ductile and machinable.

MagWeb's Castings Folder contains 3 B(H) files of Malleable Cast Iron. They show that high quality malleable cast irons can offer a permeability of 600 at 1.5T. Poorer grades however offer that permeability only at 1T.

Ductile Iron Castings

MagWeb database contains 3 B(H) files of ductile iron castings. They show that when unannealed they offer a poor permeability of 130 at 12T. Annealing can improve their permeability to about 580.

11. I. IRON POWDER CORES + SMC

MagWeb's ***Iron Powder +SMC Folder*** has 126 excel files listing magnetic properties of these materials, produced by 7 manufacturers. It includes data for Iron Powder Cores and Soft Magnetic Composites. Of these, 65 contain B(H) magnetization curves/permeability curves while 61 contain core loss curves. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database – I. Iron Powder Cores + SMC.*

Iron Powder Cores are fine uninsulated iron powders mixed with insulative resins, molded into a 2D net shape under high pressure. Materials from Fluxtrol, Micrometal, SMP, Hoganas fall into this category. Typical shapes are toroids, E or I cores. They are primarily used to store energy in the distributed gaps formed by insulating medium. They are used as inductor component in a variety of power electronics circuits such as switch mode power supplies, power converters, light dimmers, fly back transformers. (Inductor cores store energy in the distributed gaps) Occasionally they are also used as EMI Filters. Their usable flux density is below 0.2 T, and rarely exceeds 2000 A/m. This keeps copper loss and iron loss in check.

Their magnetic properties are based on initial permeability (measured at less than 0.4A/m) It rarely exceeds 150. Their permeability is less than 100 at .25T. For RF applications, permeability ranges 4 to 40. Such low permeability allows them to store energy. They operate below the peak permeability point. . .

Core loss allows them to operate between 100 Hz to MHz depending on material. Their eddy loss is low because of their high resistivity. All producers express core loss as mW/cc. MagWeb converts them to w/Kg for a better "acceptability feel". For example a 2 w/kg will be acceptable loss, but not 20 w/kg. But if one says it as 1000 mW/cc, one has no idea if it is too low or high.

Because windings cover toroidal cores, it is difficult to remove heat produced by the core. So inductor designs aim at 20-80 split between iron and copper loss.

Soft Magnetic Composites are pre-insulated iron powders, molded into a 3D net shape under high pressure. Materials from Hoganas, PMG, Sintex, Accucore, fall into this category. Unlike powder cores, the intent of SMC is not to store energy, but to transfer flux into an air gap. So they aim to achieve higher permeability. Such 3D flux carrying application targets include electric motor cores, speaker cores, fuel injectors, inductors, sensors etc. Their high cost of tooling limits them to mass-produced parts. But because they are also brittle and mechanically weak, at present their use as motor cores seemed to be at experimental stage.

Their usable frequency ranges 50 to 2000 Hz. For f> 200 Hz, their core loss is claimed to be less than that of a 0.5 mm electrical steel.

Their permeability is less than 400 at 1T. So, operation at more than 1 T will require currents in excess of 2000 A/m. So to keep copper losses in check, they are limited to ~ 1T.

Their mechanical strength is low, primarily because bonding between iron particles is weaker than that between crystal atoms in rolled laminations. This limits their usage in strength-sensitive applications such as motors.

An ideal SMC material should have low core loss. In addition it should have high permeability (to minimize magnetizing current and hence reduce copper loss).

An SMC Material Map displays the SMC materials as points in the Permeability and Core Loss plane. That plot is useful to compare SMC material offerings from different suppliers and select an optimal material that offers highest efficiency.

Fig. 19 shows such SMC material map for a machine operating at 1.5T, 50 Hz. It uses MagWeb data to compare B(H) and Core Loss of SMC materials from firms A and B. It shows some SMC materials from firm A offer lower core loss and higher permeability than those from firm B.

For example, a "best" SMC material 700HR5P from firm A that loses 6.8 w/Kg at 1.5T, 50 Hz has permeability of 140. In contrast, a comparable electrical steel M800-50A that loses 6.6 w/Kg has far superior permeability of 1800. So a comparable electrical steel will require an order of magnitude less magnetizing current.

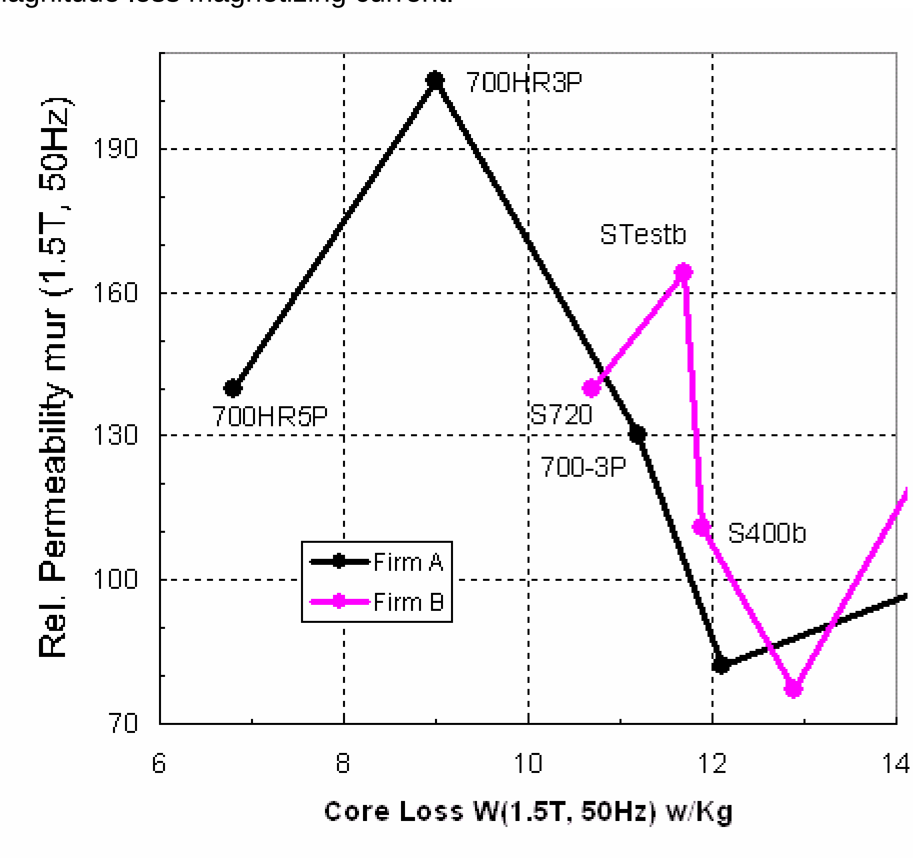

Fig. 19. Magnetic Property Map of SMC at 1.5T, 50 Hz. Firm A offers superior SMC.

Metal Injection Molding (MIM) is a process similar to pressed powder parts. It is used to make extremely small size soft iron parts. Their weight is less than 225 gm (0.5 lb) and size less than 2 cm (1 in). They can be very intricate. They are useful in several applications. They are made by INDO-MIM, India, Sintex, Denmark etc. ***Hot Isostatic Pressing (HIP)*** is another process which is similar to MIM, and is also used to make intricate small size soft material parts. Unfortunately magnetic properties for small intricate parts made by MIM and HIP are not available

12. J. ALLOY POWDER CORES

MagWeb's ***Alloy Powder Core Folder*** has 92 excel files listing magnetic properties of these materials, produced by 3 manufacturers. Of these, 28 files contain B(H) magnetization curves/permeability curves while 62 files contain core loss curves. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database – J. Alloy Powder Cores.*

Alloy Powder Cores are made by pressing uninsulated iron-alloy powders, mixed with epoxy resins. The mixture is compressed at high pressure to form toroids, pot cores etc. Most can operate up to 200 C, except Amoflux which is limited to 155 C. Several firms produce powder cores. Fig. 21 lists trade names, their alloy powders and saturation flux density.

Trade Name	Alloy Powder	Density, gm/cc	Js Tesla
Koolmu	9%Si, 6%Al	7	1
Sendust	9%Si, 6%Al	7	1
MPP	80% Ni	8.7	0.75
Amoflux	Metglas Ribbon	6.7	1.5
HiFlux	50% Ni	8.2	1.5
XFlux	6.5% Si Steel	7.5	1.6

Fig. 21. Trade Names and alloy powders

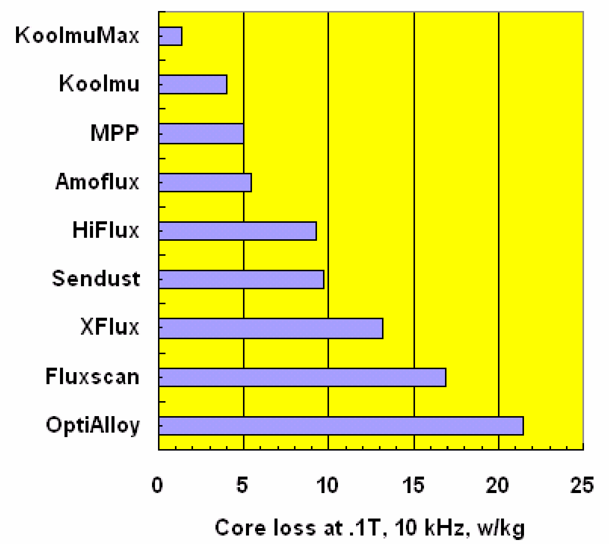

Fig. 22. Core loss of various alloy powders

Trade names also identify its initial permeability. For example HiFlux 125µ refers to one with initial relative permeability of 125. But trace impurities (that control magnetic properties) differ with manufacturers. So MagWeb lists their magnetic properties by trade names and their manufacturer. Example: a) Magnetics' HiFlux 125µ fits the core loss formula $P = 2.687B^{2.59} f^{1.33}$. b) CSC's HiFlux 125µ fits a different formula $P = 0.39B^{2.18} f^{1.69}$.

Applications. They are used as inductor and transformer components in power electronics circuits. They go by special names such as Power Factor Correction Inductors, Flyback transformers, Noise Filters etc. Core loss at design point is a dominant factor in selection of a specific material. A typical application requires the inductor to carry a large dc bias current plus a small high frequency ripple current. The bias current could produce say 0.4TDC. To keep core loss within reasonable limits, the ripple current superposes 0.2T, 100 kHz wave on it. The H required to produce ripple flux density rarely exceeds 2000 A/m.

Saturation induction J_s of alloy powder cores ranges 0.75 to 1.6 T. MPP has the lowest J_s, so it limits DC bias. Their permeability ranges 10 to 200. Such low value let them to store energy in distributed gaps.

Core loss of powder core varies with material in addition to flux density and frequency. So far MPP cores were thought to offer the lowest core loss. Fig. 12 compares core loss of various powder cores at 0.1T, 10 kHz. It shows that ***Koolmu-Max*** has far lower core loss than other powder cores..

13. K. FERRITES

MagWeb's ***Ferrites Folder*** has 164 excel files listing magnetic properties of these materials, produced by 6 manufacturers. Of these, 72 files contain B(H) magnetization curves/permeability curves while 92 files contain core loss curves. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database – K. Ferrites.*

Ferrites are made of iron oxides alloyed with either MnZn ($Mn_xZn_{1-x}Fe_2O_4$) or NiZn ($Ni_xZn_{1-x}Fe_2O_4$). The metallics interact with nonmetallics to produce magnetic properties. Ferroxcube uses "3" to denote MnZn Ferrites and "4" to denote NiZn Ferrites.

They are supplied in solid shapes such as toroids, pot cores, bars etc. Such cores are used in inductors or transformers by power electronics industry. Their loss and high permeability makes them useful at radio frequencies.

Saturation Induction J_s for MnZn ferrites ranges 0.3 to 0.5 T; that for NiZn ferrites is < 0.35T. Ferrites saturate far earlier than alloy powder core, which limits their ability to carry DC bias.

Core Loss of Ferrites is low because of its high resistivity. So they are used below 0.2 T, up to several MHz. Its value at operating flux density and frequency is an important factor in the design of inductors. Unfortunately it also depends on temperature. In fact, there exists an optimal "sweet spot" in the temperature/frequency plane at which core loss attains a minimum.

MnZn ferrites suffer from relatively high core loss, but higher permeability ranging ranges 500 to 20,000 – they are used up to 1 MHz.

NiZn ferrites have lower core loss, but suffer from limited permeability ranging 10 to 2000 - they are used up to 500 MHz.

Ferrite with far lower core loss, for use above 1 GHz are called Broadband Ferrites. They are described in the Broadband Ferrite folder.

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14. L. BROADBAND FERRITES

MagWeb's ***Broadband Ferrite Folder*** has 67 excel files listing magnetic properties of these materials, produced by 3 manufacturers. All files contain core loss curves. They are listed as real and imaginary parts μ',μ", as well as tan δ. For a full list of commercial names of all these materials, please go to the MagWeb.US Website, click on *MagWeb Database – L. Broadband Ferrites.*

Broadband Ferrites (aka microwave ferrites) are non metallic oxides and ferrites that are used at frequencies greater than 1 GHz. Their chemical composition is XFe_yO_z. So, changing values of X, y, z causes their magnetic properties to change, so produce different grades. Their ***Saturation induction*** is less than 0.04T. Their resistivity is higher than that of conventional ferrites.

Above 1GHz, electromagnetic energy is not transmitted via wires. It is not controlled via diodes or IGBT switches. Instead solid disc or squares of less than 25 mm are used to transmit GHz waves. They are used in applications such as waveguides, antennas and filters, and controlled via isolators, phase shifters, circulators. They are used in communication devices, e.g., GPS, Bluetooth, Wi-Fi, cell phone, satellite radio, keyless entry, security systems, tire pressure monitoring in home, auto, and military applications.

Their ***frequency range*** spans 1 to 100 GHz as shown below. Garnet Ferrites - 1-10 GHz Spinnel Ferrites - 3-30 GHz. Hexagonal Ferrites - 1-100 GHz.

Loss Factor tan δ (or its inverse, quality factor Q) defines their magnetic quality. It measures how much energy is lost vs.how much energy is stored. At high frequencies, a magnetic material excited by $H(t) = H_o e^{j\omega t}$ responds by flux density $B(t) = B_o e^{j(\omega t-\delta)}$ where δ defines its phase-lag. Then one can describe a material by *complex permeability* μ*

$$\mu^* = \frac{B}{H} = \frac{B_o}{H_o} e^{-\delta} = \frac{B_o}{H_o}(\cos\delta - j\sin\delta) = \mu' - j\mu''$$

where real and imaginary partsμ' andμ" relates to energy stored vs. energy lost. The loss factor tan δ is defined by

$$\tan\delta = \frac{\mu''}{\mu'} = \frac{1}{Q}$$

If core loss P_{fe} (w/kg) and permeability μ_r are known, then tan δ is calculated from[33]

$$\sin\delta = \frac{\gamma P_{fe}}{\pi J_o H_o f} = [\frac{\gamma}{\mu_o \pi H_o^2 f}]\frac{P_{fe}}{\mu_r}$$

where γ = weight density (g/cc). If tan δ and μ_r are known, the core loss P_{fe} can be calculated from

$$P_{fe} = \frac{\pi J_o H_o f}{\gamma}\sin\delta$$

[33] Fiorello, P., Measurements in bulk magnetic materials, ESM 2013. magnetism.eu/esm/2013/abs/fiorillo-abs.pdf

15. ELECTRICAL MACHINE DESIGN SOFTWARE

Table below lists all **Finite Element Magnetic field software** used to design electric machines. Table **(A)** **l**ists **Free Software (which use mostly 2D FEM)** and Table **(B)** lists **Commercial FEM Software (which use mostly 3D FEM)**. Also listed is custom software for Motors and Inductors (which employ mostly 1D model). Many of these software have only few B(H) curves, or no core loss curves. If you need assistance in choosing software that matches your specific needs, please contact: rao@magweb.us

	(A) FREE SOFTWARE		
No.	**Software**	**Firm**	**Website**
1	**FEMM**	**FEMM, USA**	**femm.info/wiki/Download**
2	**EMETOR**	**Emetor, USA**	**emetor.com**
3	**MotorAnalysis**	**VepcoTech, Russia**	**motoranalysis.com**
4	**KOIL**	**Free Univ, Italy**	**Koil.sourceforge.net**
5	**MAXFEM**	**Univ. Santiago**	**Usc.es/en/proxectos/maxfem/download.html**
6	**FEMAG**	**ETH, Switzerland**	**elmocad.de profemag.ch**
7	**POISSON**	**LANL, USA**	**laacg.lanl.gov/laacg/services/download_sf.phtml**
8	**VIZIMAG**	**VIZIMAG, USA**	**vizimag.software.informer.com/3.1**
9	**ELMER**	**CSC, Finland**	**https://sourceforge.net/projects/elmerfem/**
10	**GETDP**	**GETDP, Finland**	**http://onelab.info/wiki/GetDP**

	(B) COMMERCIAL FEM SOFTWARE		
1	**BIOT**	**Ripplon, Canada**	**ripplon.com/software.html**
2	**COMSOL**	**COMSOL, Sweden**	**comsol.com**
3	**CST**	**CST, Germany**	**cst.com**
4	**EMWORKS**	**EM Works, Canada**	**emworks.com**
5	**FEKO**	**Elec.Mag., South Africa**	**feko.info**
6	**FLUX**	**Altair, France**	**cedrat.com/software/flux/**
7	**Motor Rewind**	**EASA, USA**	**http://www.easa.com/resources/software**
8	**JMAG**	**Jmag Intnl, Japan**	**jmag-international.com/products**
9	**MAGNET**	**Infolytica, Canada**	**infolytica.com**
10	**MAGNETO**	**Integ. Engg , Canada**	**integratedsoft.com**
11	**MAGNUM**	**Field Precision, USA**	**fieldp.com**
12	**MAXWELL**	**Ansys Inc, USA**	**ansys.com/products/electronics/ansys-maxwell**
13	**OPERA**	**Cobham Tech., UK**	**operafea.com**
14	**QUICKFIELD**	**Tera Anal., Denmark**	**quickfield.com**
15	**SAMARIUM**	**Vitatech, India**	**vitatechindia.com/welcome.php**

	(C) MOTOR DESIGN SOFTWARE		
1	BLDC 3.0	Magneforce, USA	magneforcess.com
2	BLDC	Yeadon Energy, USA	yeadoninc.com
3	FLUX	Altair, France	cedrat.com/software/flux/flux-rotating-machines-package/
4	MANATEE	EoMYS, France	eomys.com
5	MotorCAD	Motor Design Ltd, UK	motor-design.com/motor-cad-software
6	Motorsolve	Infolytica, Canada	infolytica.com
7	RMXPRT	ANSYS, USA	ansys.com/products/electronics/ansys-rmxprt
8	SPEED	Siemens/CD-Adapco	speed-emachine-design.com

	(D) INDUCTOR DESIGN SOFTWARE		
1	(FREE)	Micrometals	micrometals.com/software.html
2	(FREE)	Magnetics	mag-inc.com/design/software
3	INTUSOFT	Intusoft	www.intusoft.com/mag.htm
4	PEXPRT	ANSYS	ansys.com/products/electronics/ansys-pexprt
5	Choke	Rale	rale.ch/
6	Power	Ridley Engg	ridleyengineering.com/software.html