SMAG Handbook

Properties of Soft Magnetic Materials

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By

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MagWeb
Magnetic Material Data

ABSTRACT

Whether you are designing a traction motor for the electric vehicle, wind generator, transformer, or loudspeaker, your product is only as good as the soft magnetic material that you employ. For superior designs that gain you a competitive edge, you need to discover a superior Grade that meets your performance requirements. But the problem seems to be the same - experiments are expensive and required magnetic property data is hard to come by.

To manufacture magnetic materials, each manufacturer uses different compositions, processes, and quality control methods. So even if two steel grades are equivalent by international standards, their properties differ subtly with manufacturers. So, searching for a superior grade manufacturer is an amazingly time-consuming and laborious task.

Thus, so far, the lack of a comprehensive magnetic material visualizer has prevented you from identifying the superior grade manufacturer for your specific needs. *MagWeb's Soft Magnetic Material Visualizer* SMAG outlined herein is a curated and encyclopedic compilation of magnetic properties of all grades of soft magnetic materials produced by all manufacturers worldwide. It is the single source of magnetic property information that saves you considerable search time and enables you to make informed decisions on magnetic materials.

The raw measured magnetic property data can be rough (non-smooth) due to measurement or digitization errors. Inputting raw measured data into a design software is known to reduce computational speed or fail to converge. MagWeb has recently developed a proprietary spot-cleaner tool that smooths the rough spots in the raw measured data. Entering such spot-cleaned measured data, contained in MagWeb, will improve computational speed and eliminate any numeric instabilities.

To help design machines operating under near-saturated conditions, MagWeb also uses a proprietary GFrom tool (Generalized Frohlich Model) that extrapolates all magnetization data beyond the last measured data point, close to saturation.

***MagWeb's* SMAG visualizer presents these digital data as excel files. Each file contains B(H) magnetization data and core loss data (at diverse frequencies) for a specific grade made by a specific manufacturer. This version 6 contains ~ 3000 excel files of magnetic properties of diverse materials.**

In summary, *MagWeb's* SMAG visualizer contains spot-cleaned data that is extrapolated close to saturation. It can be inputted directly into your machine design software for convergent solutions, even under severe duty conditions. It will save you hundreds of hours of data search time. You will be able to accelerate the simulation time for assessing how a change in the steel grade impacts the performance of your product. It will help you to quickly discover the Superior Grade that maximizes the efficiency and performance of your machine.

DISCLAIMER

Users are invited to contribute their magnetic properties of magnetic materials by email to rao@magweb.us

TABLE OF CONTENTS

1. INTRODUCTION

1.1. Magnetic Materials

Over the past 30 years, ***MagWeb*** has made an encyclopedic collection of magnetic properties of all magnetic materials that are produced around the world. Its ***SMAG Visualizer*** compares the magnetic property curves of soft magnetic materials while the ***PMAG Visualizer*** compares the demagnetization property curves of hard or permanent magnetic materials. Both visualizers are interactive. They are the right tools you need to discover the best magnetic material for your machine. This Handbook describes the soft material grades in SMAG.

Soft Magnetic Materials are those in which AC magnetic flux flows easily. This unique ability allows designers to reduce the size of electric machines. Modern civilization would not have been possible without them. You are using them all the time - from large multi MW generators that produce electricity, to transformers that bring it to your home, to the car you drive to your office, to the loudspeakers in your favorite TV show– all of them use magnetic materials.

Whether you are designing a traction motor for a hybrid vehicle or a wind power generator - your product is only as good as the magnetic materials that you choose. You might conceivably have few candidate steel grades for your new machine. And you want to find a grade that is best suited for it. You are faced with the awesome task of collecting and compare their magnetic properties[1, 2] The MagWeb Visualizers on the cloud will simplify this task of comparing and discovering the best grade.

In the digital world, the magnetic properties are stored as a table of coordinates (x_i,y_i) of a finite number of points. Thus the B(H) Magnetization Curve is characterized by H, B data columns. The P(B) Core Loss Curve is characterized by a B, P data columns. For each grade, MagWeb contains all these curves in a single 'grade file' in excel format.

The magnetization curve plots the magnetic flux density response of the material (B tesla) vs. applied magnetic field intensity (H A/m). The core loss curve plots the core loss P (w/Kg) while carrying alternating flux of density B at frequency f Hz. The relative permeability curve plots μ_r with H. Here Relative Permeability $\mu_r = B/\mu_o H$ [$\mu_o = 4\pi x10^{-7}$ N/A^2 = permeability of free space].

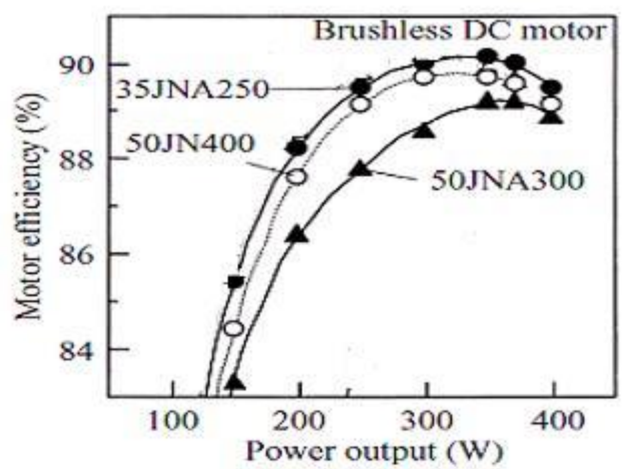

Figure 1. Your machine is only as good as the magnetic material that you use.

Generally, steels with lower core loss produce higher efficiency. ***But the lowest core loss does not guarantee the highest efficiency!*** For example, Fig. 1 compares the results of a study[3] on the effect of core loss of steel on the efficiency of a brushless motor. It shows that steel with lower core loss (grade

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[1] Lee, S., Influence of electrical steel characteristics on efficiency of industrial traction motors, 20th Int. Conf Electric Machines and Systems, Aug. 2017. https://www.researchgate.net/publication/282221620_Core_Loss_Effects_on_Electrical_Steel_Sheet_of_Wound_Rotor_Synchronous_Motor_for_Integrated_Starter_Generator

[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. https://www.sciencedirect.com/science/article/abs/pii/S0304885308005192

[3] 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. http://www.jfe-steel.co.jp/en/research/report/004/pdf/004-12

50JNA300 with maximum specific core loss $W_{15/50}$ = 2.63 w/kg at 1.5T, 50Hz produces an efficiency of 89%. In contrast, this study puzzlingly shows that another steel with higher core loss (grade 50JN400, $W_{15/50}$= 2.86 w/kg) produces higher efficiency of 89.5%. This shows that lower-loss steel does not necessarily produce higher efficiency!

Electrical steels add Silicon to *increase* electrical resistance, thereby ***reduces core loss**.* But this also *increases* its magnetic resistance, (i.e., reduces permeability) which demands more current to produce the same flux. This increases the copper loss. So there is a subtle trade between reduced core loss and increased copper loss[4].

Thus, to maximize efficiency, it is vital to minimize the magnetizing current in addition to minimizing core loss. Experts say that there is an optimal material (with the right %Si that produces optimal core loss and permeability) that maximizes efficiency[5]. So far, the lack of a comprehensive property visualizer has prevented you from discovering such optimal material. The vast visualizer of core loss and B(H) curves available in MagWeb's SMAG visualizers will help you locate such optimal material for your specific application.

1.2. SMAG Visualizer and Visualizers

SMAG visualizer contains magnetic properties of 1289 Grades of soft magnetic materials. They[6] are grouped into 11 Category Folders as shown in Table 1. It also lists the number of B(H) and Core Loss curves in each category. For example, the Electrical Steel (NGO) Folder has 336 Grade Files containing 634 B(H) curves 589 Core Loss curves.

Table 1. *Magnetic Material Property Files in SMAG (1289 Grades)*

Folder	Category Folder Name	B(H) Curves	Core Loss Curves	Grade Files
A	Electrical Steel - Non Grain Oriented	634	589	336
B	Electrical Steel - Grain Oriented	221	190	177
C	Metglas & Nanocrystalline	30	26	28
D	Cobalt Steel	53	192	144
E	Nickel Steel	121	72	68
F	Stainless Steel	52	5	52
G	Carbon Steel	179	3	179
H	Castings	51	2	39
I	Iron Powder Core +SMC	89	85	85
J	Alloy Powder Core	28	64	68
K	Ferrite Core	252	975	113
	Total	1713	2193	1289

[4] Lee C.S et al, Core loss effects of electrical steel of wound rotor synchronous motor for integrated starter generator, J. Magnetics, Vol. 20, No.2, 2015, pp 148-154. https://www.researchgate.net/publication/282221620_Core_Loss_Effects_on_Electrical_Steel_Sheet_of_Wound_Rotor_Synchronous_Motor_for_Integrated_Starter_Generator

[5] Honda, A, Effect of magnetic properties of nonoriented electrical steel sheets on motor efficiency, J. Mat. Engg, Vol. 12, 1990, pp.41-45. https://link.springer.com/article/10.1007%2FBF02834487

[6] *Soft magnetic materials* are those with narrow hysteresis loop (H_c <400 A/m) and easy to magnetize/demagnetize. *Hard magnetic materials* (Permanent Magnets) are those with large loop (H_c >5,000 A/m) and are hard to magnetize/demagnetize.

2. MAGNETIC PROPERTIES

2.1. B(H) Curve

The equation relating the magnetic flux density ***B(H)*** with H is expressed either as proportional to external field H or as the sum of *ferric flux density* J (in the magnetic material) and vacuum flux density $\mu_o H$ (in the "vacuum"),

$$B(H) \equiv \mu H \equiv J(H) + \mu_o H \qquad \text{.. .. (1)}$$

J is also known as Magnetic Polarization, Intrinsic Flux Density B_i, Magnetic Induction[7] , etc.

Fig. 2 shows a typical B(H) curve from ***MagWeb***. This curve is for the M250-35A grade. It is measured by the manufacturer as the locus of tips of a series of hysteresis loops. It has a characteristic *knee*. Its slope permeability (aka differential permeability) $B' \equiv dB/(\mu_o dH)$ increases with H first, reaches a peak at the inflection point Q and then decreases[8]. Magnetic field solvers are fundamentally unstable at this inflection point[9] (see 2.3).

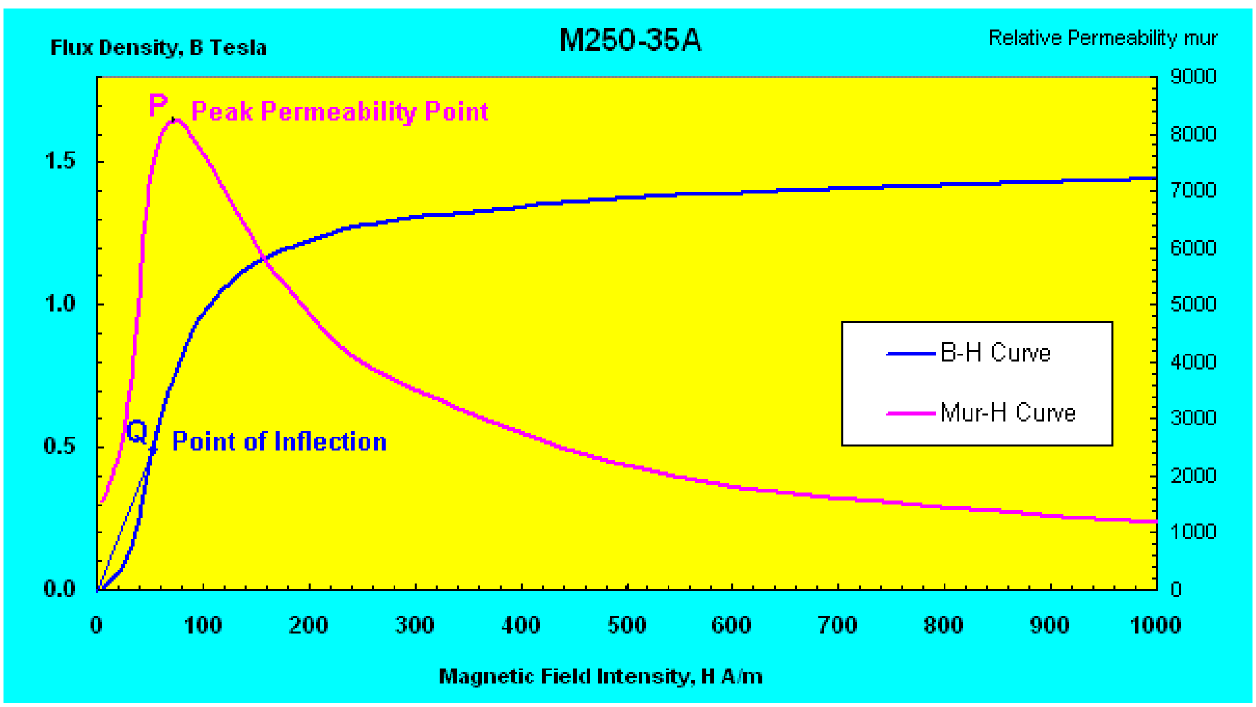

Figure 2. B-H Curve has an inflection point – a source of poor convergence.

B(H) curves are affected by microstructure, which is controlled by careful annealing. For an introduction on this subject, please see section 11, Carbon Steels.

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7 J is related to (volume) magnetization M by $J = \mu_o M$, (or $J = \mu_o \rho M$ if it is *(mass) Magnetization* in Am^2/kg, where ρ = mass density)

8 Spooner, T. *Properties and Testing of Magnetic Materials*, McGraw Hill, 1927, p.10

9 Kis, P. *Jiles-Atherton model implementation to edge FEM*, Ph. D Thesis, Budapest Univ.Tech., 2006, p.2. https://repozitorium.omikk.bme.hu/bitstream/handle/10890/563/ertekezes.pdf;sequence=1

Mislabeling J(H) as B(H)

Historically, the International Standards[10] dictate that an electrical steels' magnetic property be measured as a J(H) ferric flux density curve. But all engineers use the B(H) magnetization curve in solving the Maxwell laws. To add to the confusion, most manufacturers measure J(H) and ***mislabel*** it as ***a Magnetic Flux Density B(H) curve!*** [11].

A design software expects the user to input ***Magnetic Flux Density B(H) - not Ferric Flux Density J(H).*** This leads to a subtle mislabeling error. MagWeb had converted such measured J(H) data into B(H) data thereby avoiding the mislabeling error. So MagWeb visualizers B(H) data can be inputted directly into simulation software.

This depends on whether the software uses B(H) or H(B). 3D FEM software B = B(H), the difference between B and J is often minute and ignorable. For example, when a machine operates at say 1.8T/10,000 A/m, the vacuum carries a small flux density $\mu_o H$ of 0.0125 T. Then the entered ferric flux density J = 1.8T refers to magnetic flux density B = 1.8125 T. The *mislabeling error* ε_{BJ} = (B-J)/J is ~0.7%. Most machines normally operate at H<10000 A/m. So this mislabeling error is small. Ignoring it does not greatly harm the design. (But 2D software uses H(B), the mislabeling error can be substantial).

The mislabeling error also becomes significant in over fluxed machines that operate in severe duty. A machine is said to be over fluxed if it operates far beyond the last measured data point.

One major cause of motor failure is when it delivers large torque for a short duration. Such short-duration overloads can occur in traction motors, starter-generators, current transformers, or core-ends of Multi-MW utility generators [12] , etc. Flux concentration areas such as sharp corners of a tooth, slot, or in core-ends are especially vulnerable. During such overloads, the laminations are nearly 'saturated', and act like air. In such cases, inputting J instead of B causes the mislabeling error to increase to more than 10%. Ignoring it can create faultily designed machines that are susceptible to failure.

2.2. Extrapolation to Saturation

Saturation Induction J_s (*aka Saturation Flux Density)* is the maximum possible flux density a material alone can carry. At that point, *all* the magnetic dipoles in a ferromagnetic solid are fully aligned with an applied field H[13]. It is the most important characteristic of magnetic material. Unfortunately, no software requires it to be inputted as no manufacturer specifies it and this property is rarely available.

Fig. 3 shows the B(H) and J(H) curves. It shows that, as $H \rightarrow \propto$, the ferric flux density $J \rightarrow \boldsymbol{J_s}$. The slope permeability $J'(H) \rightarrow 0$ and $B'(H) \rightarrow 1$. For electrical steels, J_s range 1.95T to 2.16T. But their measured B(H) data end at ~1.8T. In severe duty, machines are *over-fluxed,* i.e. operate close to J_s. This is far from the 1.8T limit. Then the flux will leak from designated paths

[10] See e.g. IEC 60404-2, Magnetic Materials, part 2, Methods for measurement of the magnetic properties of electrical steel strip and sheet by means of an Epstein frame, 2008. https://webstore.iec.ch/preview/info_iec60404-2%7Bed3.1%7Db.pdf

[11] Novoliptesk, Thyssen, Voestelpine correctly label their data as J(H) magnetic polarization curves. Others label add 'induction".

[12] Overfluxing in transformers, https://www.electrical4u.com/over-fluxing-in-transformer/

[13] One cannot measure J_s defined this way as it requires infinite H to reach it. Instead, some standards define J_s as the point where a 10% increase in B demands a 50% increase in H, i.e. J'(H) = 0.2, B'(H)=1.2.

unknowingly into neighboring structures - causing them to overheat. Detecting such over-fluxing therefore requires one to know the saturation flux density J_s of laminations.

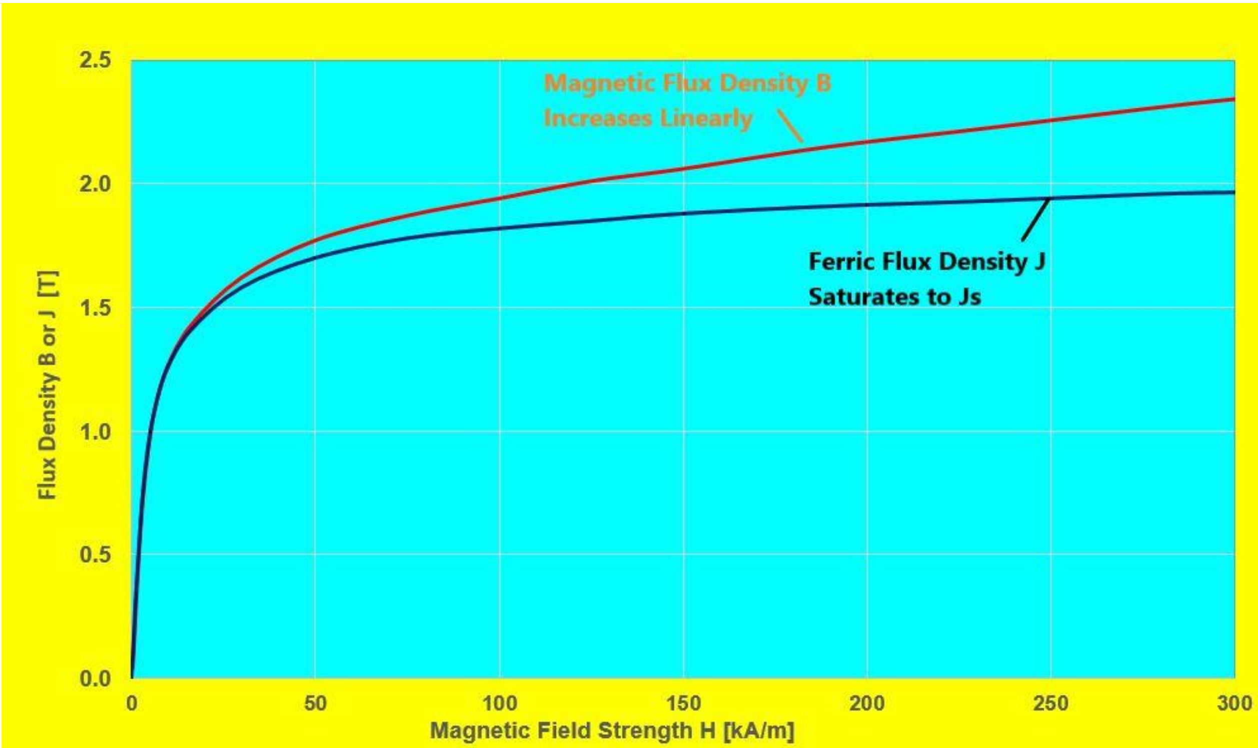

Figure 3. Ferric Flux Density J saturates to J_s. The Visualizers lists J_s for all soft magnetic material grades.

Magweb recently developed an approach called Generalized Frohlich Model (GFrom) which extends the classic Frohlich approach[14]. GFrom extracts J_s from the smoothed measured data. In version 7, MagWeb provides it in its SMAG visualization software to subscribers.

2.3. Permeability Curve

The relative permeability μ_r is as important as B(H) curve. As H increases, the relative permeability increases at first. Around the knee region, it reaches a ***peak*** P. Further increase in H causes permeability to decrease. At very large H, the material saturates: it behaves like air, with μ_r ~1.

Permeability at Rated Point. The permeability at the rated point $\mu_r(B_o, f_o)$ (B_o is the flux density in the tooth at the rated torque and f_o is the electrical frequency) is an important metric to discover a better grade. ***MagWeb*** Visualizers plot the permeability curves from which you can compare the permeability of candidate grades at the rated flux density. Discovering a grade with the highest permeability helps you minimize the current required to get flux density B_o in the teeth.

[14] E.g. Spooner, ibid, p. 24.Bozorth, ibid. p. 488

For example, consider grades carrying the same label of "M250-35A", produced by two different firms A and B for a machine operating at 1.5T, 50 Hz. MagWeb's visualizers showed that the permeability of firm A's grade is 1513 while that of B is 660. So to carry 1.5T, firm A's grade demands 789 A/m, while B's grade demands 1809 A/m. So the firm A's grade requires less current than that in Firm B. (see sec. 3 on discovering a better grade).

Permeability at Peak Point. If you are designing a magnetic shield, GFI, or filter, you need materials with the highest peak permeability. Operating a shield at this point will minimize the thickness of the shield and maximize the shield effectiveness. The permeability curve in the ***MagWeb*** Visualizer will help you estimate the peak permeability produced by a grade. Using MagWeb to compare the peak permeability of two grades will help you discover a better magnetic shield.

2.4. Roughness in B(H) Curve

Due to errors in measurement, digitization, it is not uncommon for measured B(H) data to be rough. It is well known that the B(H) data must not be rough (i.e must be 'smooth') for the solution to converge rapidly[15], or it may fail to converge [16] [17] [18] [19] [20] [21] [22] . To determine roughness in a raw B(H) data, plot its slope permeability B', defined by

$$B' \equiv \frac{1}{\mu_o} \frac{dB}{dH} \qquad (1.1)$$

A smooth B(H) data will have only one Inflection Peak (Fig. 3). On the other hand, a rough B(H) curve may have several rough points where the slope permeability spikes. They can occur if measurement points are too closely spaced.

Rough points confuse the Newton Method used by field software[23]. They increase the number of iterations needed to converge. This increases computer time[24]. The solver may fail to converge or cause numerical instability. To avoid such convergence issues, one needs to remove all rough points from raw measured data [25] before inputting it into a field software.

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[15] Liu, L., How the B-H curve affects a magnetic analysis (and how to improve it) , Nov. 2019 , comsol.com, https://www.comsol.com/blogs/how-the-b-h-curve-affects-a-magnetic-analysis-and-how-to-improve-it/

[16] G.F.T Widger, "Representation of magnetization curves over extensive range by rational-fraction approximations, Proc. Electrical Engineers, Jan. 1969, pp. 156-160.

[17] Fujiwara, K., A proposal of finite element analysis considering two-dimensional properties, IEEE Trans Magnetics Vol. 38, No. 2, Mar 2002.

[18] Kameari, J., FEM Computation of magnetic fields in Anisotropic magnetic materials, IEEJ Trans. Vol. 126, No.2, 2006

[19] Kaido, C., Modeling of magnetization curves in Nonoriented electrical steels, Elect. Engg in Japan, Vol. 180, N0. 3, 2012, pp. 1-8.

[20] Rao,,D. K., Effective use of magnetization data in the design of machines with overfluxed regions, IEEE Trans. Magnetics Vol. 51, No. 7, July 2015. pp 6100709.

[21] Augustvniak, Finite element method applied in electromagnetic NDTE, a review. J, Nondestructive evaluation, Vol.35, 39 (2016) https://link.springer.com/content/pdf/10.1007/s10921-016-0356-6.pdf

[22] Jesenik, Analytical modelling of a magnetization curve obtained by the measurements of magnetic materials' properties using evolutionary algorithms, Applied Soft Computing, Vol. 52, 2017. pp. 387-408

[23] 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 2015, paper no. 6100709. https://www.academia.edu/28570138/Effective_Use_of_Magnetization_Data_in_the_Design_of_Electric_Machines_with_Overfluxed_Regions

[24] Hameyer, *Numerical Modeling and Design of Electric Machines*, WIT Press, 1997, p. 93

[25] Few FEM software simply eliminate the true inflection point (TIP), but this will not eliminate SIPs . They replace B(H) below TIP by data with constant slope. For example, see 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/ In such cases, solutions below TIP are unphysical and erroneous. .

For example, Fig. 4 plots B'(H) of M250-35A grade of two firms A and B.   It reveals that the B'(H) curve for firm A has 4 rough points. One has to correct them. Only non-rough data can be inputted into a field software). Otherwise, the solution may not converge, or converge slowly. In contrast, that from firm B has only one inflection point. So its solution will converge.

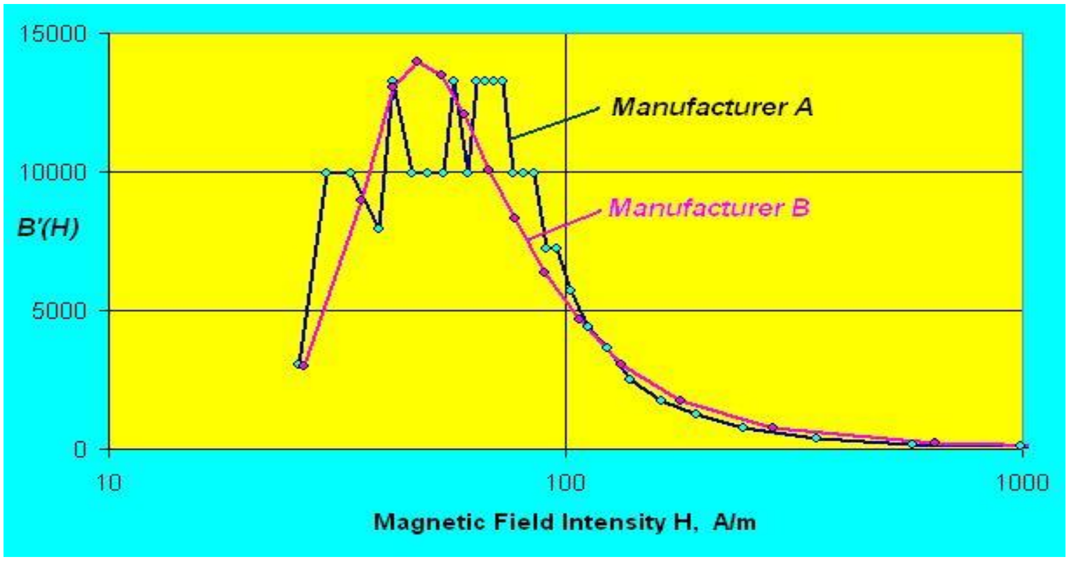

Figure 4. Measured B(H) data can have rough points (i.,e slope permeability spike points)

Unfortunately, it is very hard to correct the rough points from the measured data. Like whack-a-mole, the removal of one rough point causes it to reappear at another point. Until now, that is. So far, one removes them by adjusting decimal digits manually[20]. But such practice is laborious.

MagWeb recently perfected a proprietary *B(H) smoother* software.   It locates and removes the rough points from the raw digitized data automatically. Version 7 presents B(H) data that is free of rough points. Such smooth B(H) data ensures faster convergent solutions. If you suspect that your B(H) data is rough, please email it to rao@magweb.us. Magweb can return smooth B(H) data that is free of rough points.

Effect of Stress. To manufacture a motor, electromagnetic steel sheets have to be converted into laminations using a punching process. Core has to be formed by clamped laminations into place using welding, bolting, bonding, etc., processes. The core has to be fitted into housing using press-fitting or shrink-fitting processes. The electrical steel incurs stress and residual strain as a result of this multitude of processes. This reduces its permeability which in turn increases core losses (see 2.6.3). For accurate analysis, the effect of stress can be expressed in terms of a reduced permeability coefficient which needs to be measured experimentally.

2.5.   Residual Flux Density B_r

When excitation is removed, some of the magnetic domains retain a degree of orientation relative to the applied magnetic field H. So on reversing, at H=0, it intersects B-axis at a residual value. This residual value increases with amplitude H. As H increases indefinitely, it attains a value called residual flux density B_r. Residual flux density is an important parameter for the design of Current Transformers and Solenoids as they will saturate sooner than expected if B_r is excessive. Unfortunately, B_r depends on the internal stress and operating temperature of magnetic materials. For example, hot rolling greatly reduces B_r. In Ferrites B_r is highly sensitive to operating temperature. So when one specifies Br, one had to specify the conditions, viz., temperature and whether annealed, unannealed, or stressed.

Materials with high B_r can act like magnets. They can attract iron dust particles, and the clinging dust dodged between clamped laminations can punch through the insulation locally, causing a short circuit path for eddy currents which increases core loss.

It can range from 30 to 80% of saturation induction J_s. B_r for 1020 is 0.74T[26]. That for 1215 steel is 1T. That for Pure iron and dead soft 1010 steel is 1.25T. That for NGO steels range 0.5 to 0.75T per Spooner. For GO steels it can be as high as 1.5T[27]. For data on other steels, see Spooner and [28] . For stainless steel, please consult section 10.

Normal Coercivity H_{cB} is the point of intersection of the B(H) hysteresis loop with the H-axis. (Point of the intersection of J(H) with H axis is denoted by H_{cJ}; it is a popular metric to characterize the demagnetizability of permanent magnets). It defines the ability of a soft magnetic material to incur core loss. As with B_r, the value corresponding to the saturation hysteresis loop is called H_{cB}. High H_{cB} normally points to a material with high hysteresis loss. Coercivity increases with hardness. H_{cB} is an order of magnitude lower for soft magnetic materials than permanent magnets.

H_{cB} for pure iron and dead soft 1010 steel is 150A/m. For 1020, it is 300 A/m. That for electrical steel ranges 40 to 100 A/m.

2.6. Core Loss Curve

Magnetic materials carrying alternating fluxes incur losses known as *core loss*. It is well known that core loss varies with flux density and frequency. But not so well known is that core loss varies with manufacturer even in equivalent grades. Core loss for same-grade steels varies with the manufacturer because each uses its proprietary composition, purities, and processes to make electrical steel. For example, Si in M270-50A grade is 2.173% in one manufacturer, 1.65%b from another[29]. Their Mn is 0.558%, in the first, 0.177% in the second. This affects their resistivity and grain size, so affects their core loss and B(H) curves. The core loss is also very sensitive to minute impurities. These include Oxygen, Sulphur, Titanium, and Nitrogen[30] , For example, an increase of Sulphur from 20 to 40 ppm can increase core loss by 20%! Different manufacturers use different ways to control impurities. So the core loss varies greatly with the manufacturer, even in equivalent grades.

MagWeb's visualizer contains thousands of core loss curves for all grades made by different manufacturers. Comparing their core loss property curves using the visualizers can help you

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[26] Spooner, T., *Electromagnetic Devices,* John Wiley, 1941, p. 55

[27] Knapek, W. Residual Magnetism, Omicron, https://www.eiseverywhere.com/file_uploads/63356affaf81e30a2410dc337476805b_Residual_Magnetism.pdf

[28] http://depts.washington.edu/mictech/optics/sensors/week2.pdf

[29] Pricop, V. et al, Influence of alloying elements on magnetic properties of electrical steels, 2016 Int. Conf. ICATE, https://www.researchgate.net/publication/310809006_Influence_of_alloy_elements_on_magnetic_properties_of_electrical_steels

[30] Bozorth, *ibid*, p. 52

discover the manufacturer that produces the lowest core loss in your flux density and frequency range.

The maximum frequency at which a magnetic material can be used is dictated by the acceptable core loss at a chosen maximum flux density. For electrical steels, MagWeb offers core loss curves up to10 kHz. For cobalt steels, they are available up to 1000 Hz. For Metglas and Nickel steels, they are available up to 100 kHz. For iron and alloy powder cores, they are available up to 25 kHz. For Ferrite cores, they are available up to ~5MHz. Each file can have core loss curves at several frequencies.

2.6.1. Core Loss Models in the Visualizers

Over the past 100 years, several experts, from Steinmetz[31] (in the 1900s) to Bertotti[32] (in the 1990s) to Ionel[33] (in 2010s) - have developed several core loss ***models.*** They broadly break the core loss into hysteresis loss, eddy loss, and anomalous loss. They fit a known interpolating function to the measured core loss data. These models are then used to calculate the core loss at any flux density and frequency. The SMAG Visualizer can fit the following popular core loss models.

$$1.\ Steinmetz: \qquad P = K_h f^n B^m$$

$$2.\ Steinmetz\ with\ eddy: \qquad P = K_h f^n B^m + K_e (fB)^2$$

$$3.\ Berttoti: \qquad P = K_h f\, B^m + K_e (f\, B)^2 + K_a (f\, B)^{1.5}$$

$$4.\ Maxwell: \qquad P = K_h f\, B^2 + K_e (f\, B)^2 + K_a (f\, B)^{1.5}$$

2.6.2. Eddy Loss vs. Skin Depth

Magnetic materials are configured as either *flux carriers or flux barriers.* Flux carriers circulate the flux loops parallel to their flat faces. Flux Barriers circulate eddy current loops parallel to the flat faces. Motor laminations are flux carriers while shields or induction heaters are flux barriers.

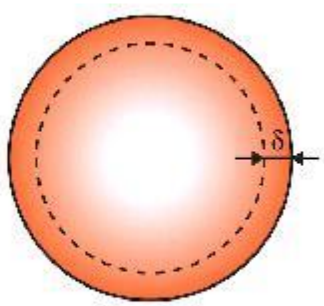
At, at high frequencies, the flux density is non-uniformly distributed, so is the eddy loss. It not only varies spatially but also depends on frequency, thickness, skin depth, resistivity, and temperature. The nonlinearity adds to the complexity. So calculating eddy loss is approximate at best. The following analysis shows that the lamination thickness of a carrier should be less than two skin depths, while that of a barrier should be less than one skin depth.

Carriers

[31] 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) https://ieeexplore.ieee.org/document/1457110

[32] G. Bertotti, "General properties of power losses in soft ferromagnetic materials," *IEEE Trans. Magnetics*, Vol. 24, No. 1, pp. 621-630, Jan. 1988. https://www.researchgate.net/publication/3095090_General_properties_of_power_losses_in_soft_ferromagnetic_materials

[33] D. M. Ionel, Popescu, S. et al, "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. https://www.researchgate.net/publication/3173324_Computation_of_Core_Losses_in_Electrical_Machines_Using_Improved_Models_for_Laminated_Steel



At high frequencies, eddy loss dominates the core loss. In carriers, high-frequency flux concentrate around the outer periphery (Fig. 5). This high-frequency flux decays exponentially[34] from the surface. It falls from a 100% peak value at the surface to 37% after one skin depth δ, to 14 % after two skin depths 2δ, etc. This skin depth δ is given by

$$\delta = \sqrt{\frac{\rho}{\pi \, \mu_0 \, \mu_r \, f}} \quad \text{.. .. (2)}$$

Figure 5. In a flux carrier, most AC flux concentrates in two skin depths (2δ), one on each side.

where

f = frequency of sinusoidal flux waveform, Hz

ρ = resistivity, ohm m

μ_r = relative permeability (assumed to be constant in a linear material)

$\mu_o = 4\pi \; 10^{-7}$ N/A^2

Two walls, each of thickness δ, one from each side, carry most AC flux. The central 'core' carries little flux, so behaves like air, simply wasting the material. So, to fully utilize the material magnetically, the thickness of ***lamination should be less than two skin depths (t < 2δ).***

Eq. (4) shows that the skin depth reduces as frequency increases. So to carry flux at high frequencies, materials with high permeability need to be thin. The users of the MagWeb visualizer should consider the skin effect in choosing a magnetic material. To assess the impact of skin depth or membrane depth on core losses in GO steels, Metglas, Low Carbon, or Stainless steels, see respective sections.

Barriers

Flux barriers are magnetic materials (such as flux shields, induction heater coils) that receive flux from flux sources on one or two sides. The cross-section of a flux barrier is parallel to that of its flux sources. If there is only one flux source on one side, at high frequencies, a flux crowd in a thin "image" of the flux source on one face (called membrane). Inside the membrane, the flux density decays non-exponentially[35] from a100% peak value at the surface to a 0% at one membrane *penetration depth* δ'. Beyond one membrane depth, the flux density is zero. This membrane depth varies from section to section, δ' =δ'(x). Average membrane thickness δ_o is the average membrane depth. FEM software should be used to estimate it. **To fully utilize the material as a flux barrier, its thickness should be less than one membrane thickness (t<δ_o)**

In both barriers and carriers, the crowding of high-frequency flux reduces the effective area where flux flows. Such area reduction increases the effective flux density, which in turn increases eddy loss! Some experts prefer to use the "surface resistance"[36] (ohms per square) to characterize loss in such cases. It is the resistivity divided by membrane depth. One estimates the eddy loss as the average eddy current squared times surface resistance.

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[34] Bozorth, R. M., *Ferromagnetism*, D. Van Nostrand Co., Princeton, 1951, pp. 770

[35] McConnel, H.M., Eddy current phenomenon in ferromagnetic materials, ONR Contract 30306, 1953. http://www.dtic.mil/dtic/tr/fulltext/u2/021116.pdf

[36] Kirtley, J.S., Class Notes 3: Eddy currents, Surface impedances and loss mechanisms, 2005. https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-685-electric-machines-fall-2013/course-notes/MIT6_685F13_chapter3.pdf

2.6.3. Factors Controlling Core Loss

Stress due to shearing, punching, bend-forming, etc degrades magnetic properties, It causes actual core loss to differ from that specified by the manufacturer. Small motors with a tooth width of fewer than 0.5 inches are affected more by stress than larger motors. Careful stress relief annealing of the finished core could greatly reduce the core losses[37]. Other factors that increase the core loss are:

- *Design* (Manufacturer, Flux density B, Frequency f, temperature T, Aging hrs, thickness t, coating thickness, resistivity, bare spots, sharp corners)
- *Manufacturing* (stresses due to cutting techniques such as stamping, punching, laser cutting, water, etc cutting. deburring, welding, shrink fitting, and clamping pressure; VPI and voids; annealing.
- *Operational* (flux wave shape - PWM harmonics, flux direction).

Burrs may short the laminations, thereby increasing core loss. Cutting creates fab affected zones (FAZ) around the cut edge. They may be affected by stress or heat. around the cut edge. The volume of SAZ/HAZ influences degradation. Core loss also depends on the cutting method - EDM, laser, or punching. Sharp cutting edge produces smaller SAZ/HAZ, so is better. Gavrila[38] showed that water-jet cutting produces the lowest core loss, but per Bayratkar[39] it produces the highest core loss. Weld only in areas where flux flows in opposite directions. Note that core loss beneficially *reduces* as temperature increases.

Coating. During its manufacture, they develop a tightly adherent oxide coating (often called C-0). In electrical steels, they apply an additional thin coating (classed C-1 to C-6) that barely covers surface blemishes. This coating increases the surface insulation resistance. This surface resistance is important in high voltage applications and depends on clamping pressure. It determines interlaminar resistance and hence core loss (Un-annealed or uncoated electrical steels can be procured only as a special order.)

[37] Kim, J. "Efficiency improvement of an automotive alternator by heat treatment", J. Magnetics, Vol. 20, No.2, p.155-160, 2015. http://koreascience.or.kr/article/JAKO201520441372297.page

[38] Gavrila, H. et al, Magnetic characteristics of nonoriented Silicon iron strips obtained through mechanical, laser, electrical discharge and water jet cutting technologies, http://www.agir.ro/buletine/2291.pdf

[39] Bayratkar, S. Turgut, Y., Effects of different cutting methods for electrical steel on performance of induction motors, Proc. Inst. Mech Engrs, Part B., J. Engg Mfr. Aug. 2016 https://journals.sagepub.com/doi/abs/10.1177/0954405416666899

3. DISCOVERING A SUPERIOR GRADE

Designers often need a grade whose core loss P(w/kg) does not exceed a specified value at a known design point (B_o, f_o). They often have several 'equivalent'[40] grades from different manufacturers. They then face the daunting task of identifying a grade that is superior to comparable equivalent grades This section explains how to identify such superior grades.

For example, a 50Hz motor requires electrical steel that dissipates at most 2.7 w/kg when 1.5T flux flows through the steel at 50Hz. Following 'equivalent' grades of M270-35A meet this requirement:

- AK Steel (M-19)
- Cogent (M270-35A)
- Voestalpine (Isovac 270-35A).

Overlay of core loss curves (Fig. 6) shows that AK Steel has higher core loss than others.

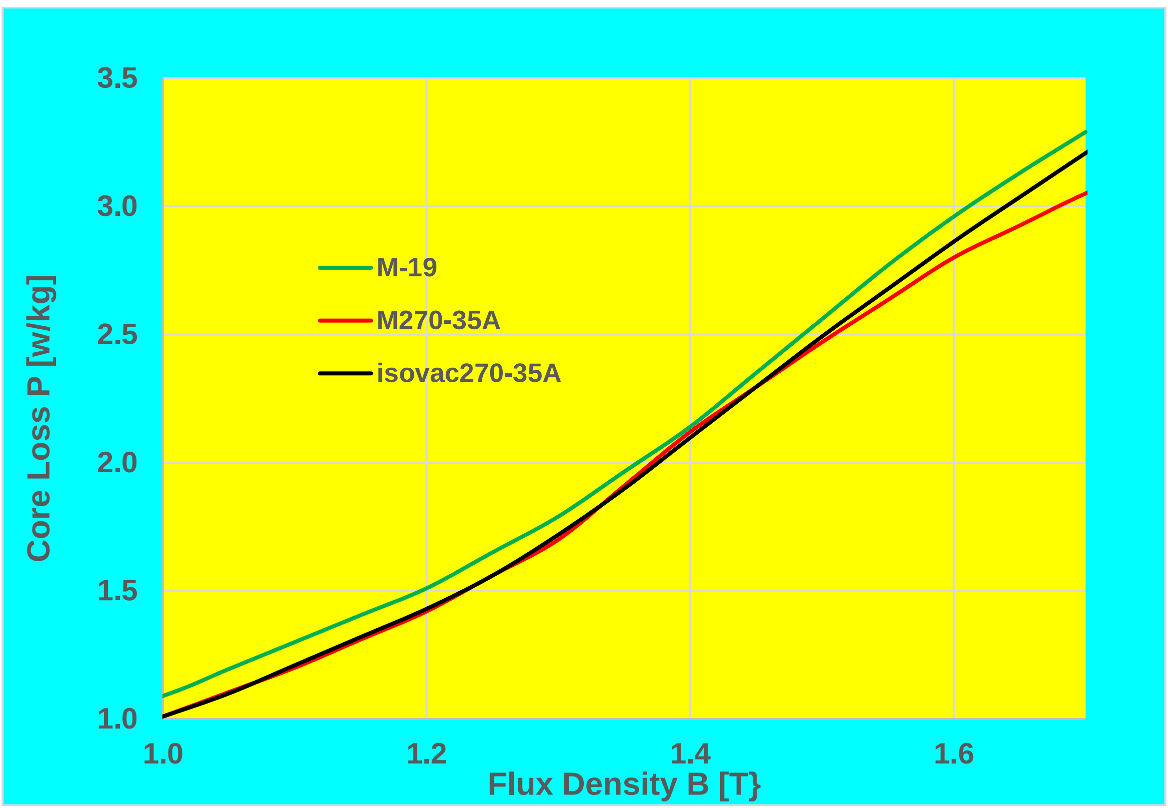

Figure 6. Overlaid Core Loss curve is the starting point to discover a Superior Grade.

At 1.5T, the three steel grades (M-19, M270-35A, and isovac 270-35A) produce a 50Hz core loss of 2.56, 2.47, 2.5 w/kg respectively. So the spread is 3.6%. This spread is marginal, and within an acceptable scatter band of 5%. So all grades dissipate nearly the same heat. So how does one find the superior Grade?

[40] GrandHunt, *Non Grain Oriented Steels*, http://www.grandhunt.com/Product/Product.aspx?language=en-us&cid=1&id=12

It is well known that the permeability of a grade influences the performance of a motor. Higher permeability grades require less magnetizing current[41]. Such reduced currents can increase efficiency. They can increase the torque by allowing more turns of smaller wires to be packed in the coil window. Reduced currents can also reduce the size of an inverter. They can also increase the power factor. So, a superior Grade is the one that offers *the highest permeability,* while meeting core loss requirements.

MagWeb Visualizer can generate core loss and permeability curves for any grade produced by any manufacturer. Such a curve-rich visualizer will help you to discover a Superior *Grade*. The next section presents few examples of how to use the MagWeb visualizer to discover a Superior *Grade*.

3.1. Superior Grade for Motors

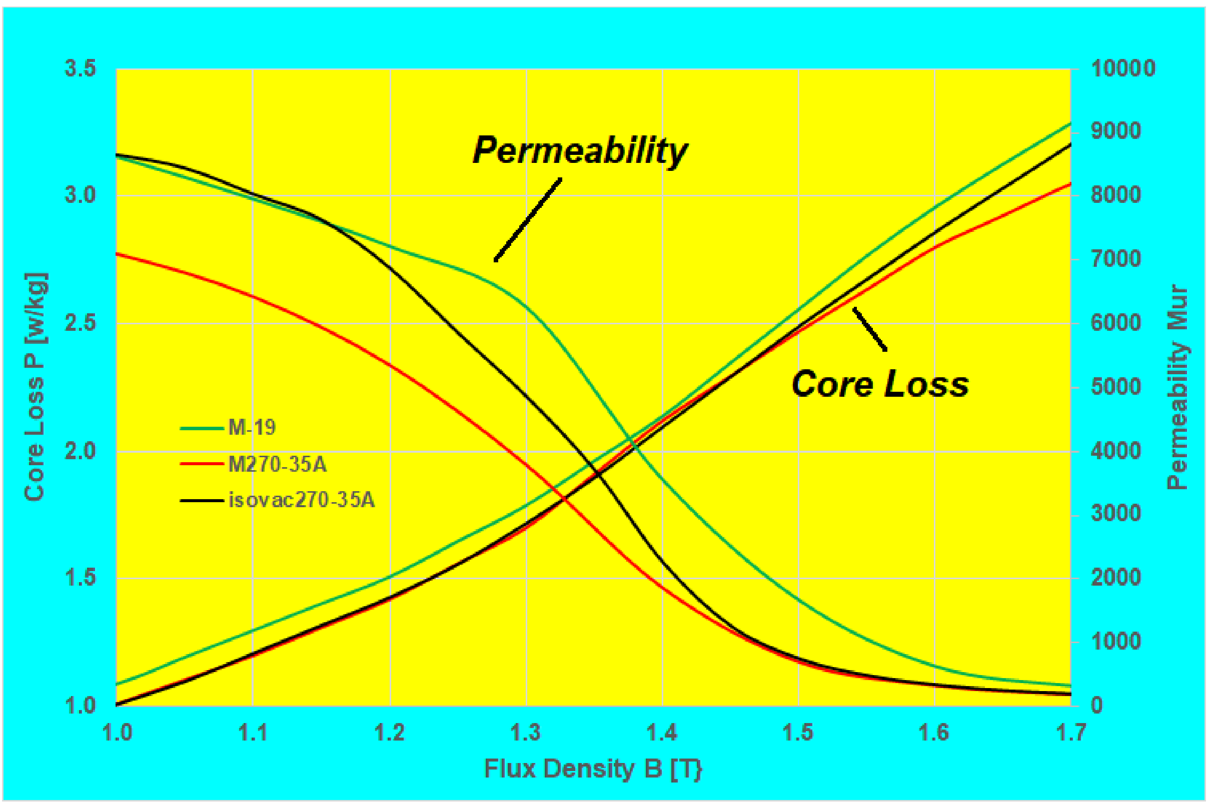

Figure 7. A LossPerm Plot shows core loss and permeability curves on a common flux density axis. It can help one to discover a Superior Grade.

LossPerm Plot is a graph that shows the core loss curve P(B) and the permeability curve μ_r(B) on a common flux density B-axis. Fig. 7 shows a typical LossPerm Plot for all candidate electrical steels discussed in the preceding section. The scale on the left shows core loss P(B) while that on the right shows the permeability μ_r(B). Such LossPerm Plot shows how the performance of steel varies with flux density.

[41] Bavay, J.C. et al, New electrical steel with high permeability, JMEPEG 1993, Vol. 2, pp. 169-172. https://link.springer.com/article/10.1007%2FBF02660282

- At 1.5T, the permeability of AK Steel's M-19 grade is 1680. That for Cogent's M270-35A grade is 702. So M-19 ***is the Superior Grade***.

- At 1.0 T, the permeability of Voestelpine's Isovac 270-35A grade is 8650. That for Cogent's M270-50A is 7105, while that for AK Steel is 8621. So ***Voestelpine's 270-35A is the Superior Grade***

In summary, the ***LossPerm Plot*** can discover a Superior Grade. MagWeb visualizer is useful in preparing LossPerm Plots.

3.2. Superior Grade for Electric Vehicles

Depending on the cooling method, the acceptable core loss in machines can vary from 5 to 15 w/kg. Traction motors typically require an electrical steel grade that dissipates 12 w/kg at 1T, 400 Hz [42]. Following equivalent grades can potentially meet such requirements.

- Cogent (NO20)
- Arcelor (NO20)
- Thyssenkrupps (020-130Y320)

Fig. 8 shows the ***LossPerm Plot*** for these steels around 1T.

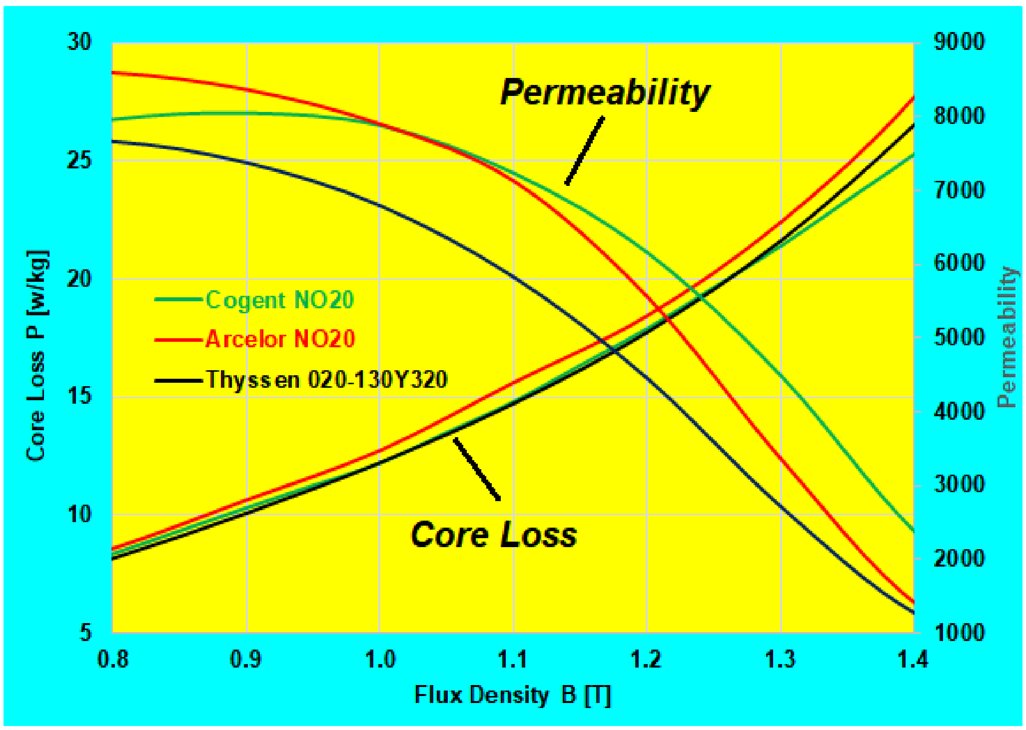

Figure 8. LossPerm Plot for electrical steels for electric vehicle traction motors.

[42] Emadi, A. Advanced Electric Drive Vehicles, p.130. CRC 2015

This plot shows that at 1T, 400Hz, these steels dissipate 12.2, 12.74, 12.21 w/kg. The spread is 4.4%. So all these steel practically dissipate nearly the same heat

But it shows that their permeability at the design point is 7879, 7904, 6802 respectively. This figure shows that, in the 1 to 1.1T range, the steels from Cogent and Arcelor have nearly identical core loss and permeability – so they are Superior.

3.3. Superior Grade for Transformers

Best quality transformers employ Domain Refined Grain Oriented steels for high efficiency. Consider the problem of selecting such steel, 0.27 mm thick, that dissipates at most 0.9 w/kg at 1.7 T, 50 Hz. The following two domain refined steel grades meet this requirement:

- AK Steel (H-1DR)
- Nippon Steel (27ZDKH95)

Fig. 9 shows the LossPerm Plot for these steels in the 0.5 to 1.9T range.

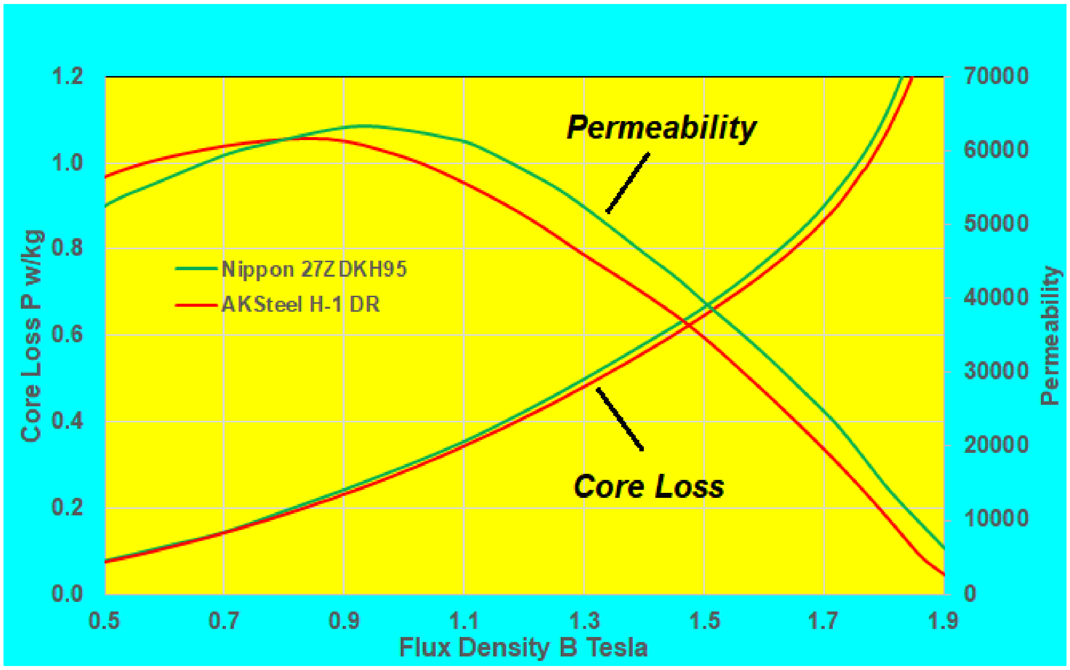

Figure 9. LossPerm plot of Domain Refined Grain Oriented Steels for Transformers.

This plot shows that, at the design point, the core loss of these steels is 0.869, 0.90 w/kg, so dissipate nearly the same heat. But their permeability at the design point is 19530, 24610 respectively. So the grade from Nippon is a Superior Grade.

4. COMPARING EQUIVALENT GRADES

Equivalent grades – International standards consider two grades to be 'equivalent' if they are of the same thickness and produce the same maximum core loss[43]. But they often have different magnetization curves and core loss curves[44]. As a result, switching a manufacturer can and will change the performance of a machine. That is, they are not equivalent grades from a *performance perspective.* The following examples illustrate how grades that are "equivalent" from a standards perspective are not equivalent from a performance perspective.

4.1. Lowest Core Loss (NGO)

Fig. 10 overlays the core loss curves of four M250-35A steel grades listed as *equivalent grades* by Cogent[45]. They are AK Steel (M-15), Cogent (M250-35A), Voestalpine (HP250-35A), and POSCO (35PN250).

This revealed that, above 1.45T, POSCO's grade produces the lowest core loss. But, below 1.45T, Voestalpine's grade produces the lowest core loss. Thus which is a superior grade depends on the operating flux density. MagWeb visualizer can be thus be used to discover the lowest core loss producer of other equivalent grades.

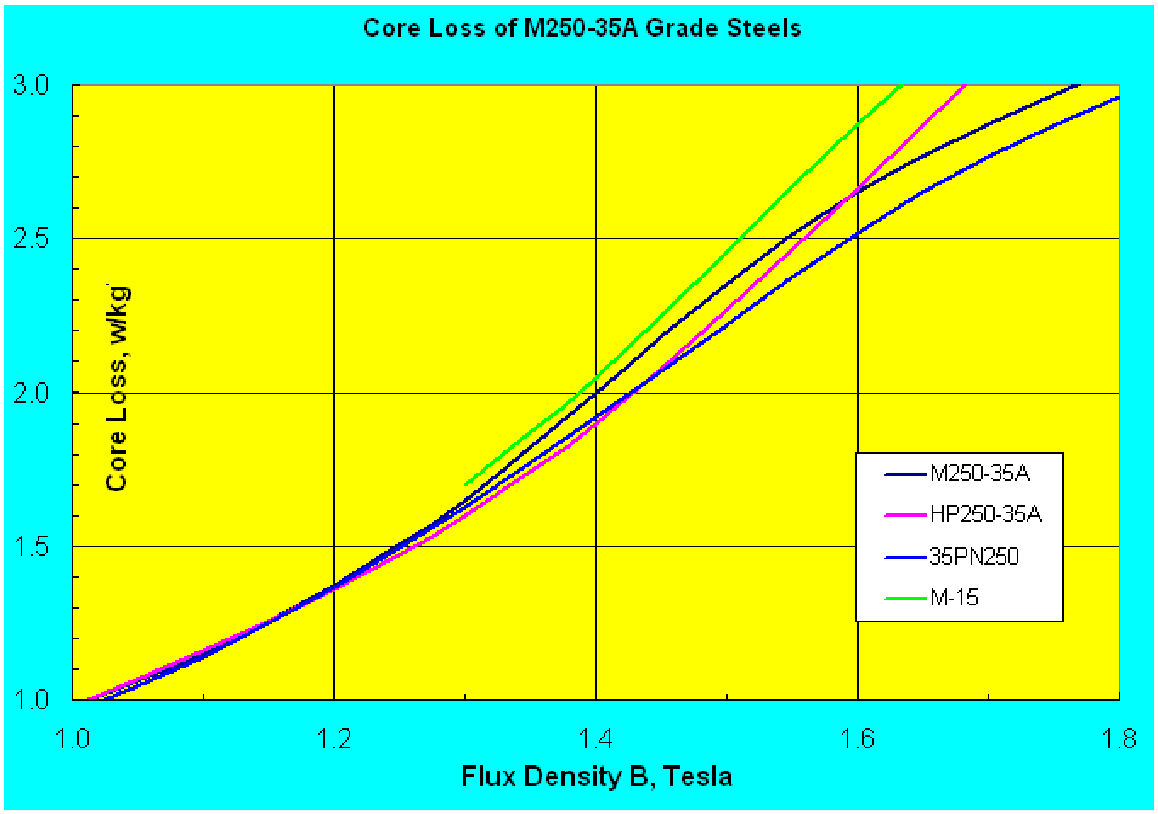

Figure 10. The core loss of equivalent steel grades varies with manufacturers.

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

[44] Heck, C. Magnetic Materials and Their Applications, Butterworths, 1974. p. 350.

[45] Cogent, *Comparison of Grades and Standards*, p. 62 in https://cogent-power.com/downloads

4.2. Lowest Core Loss (GO)

Fig. 11 overlays core loss curves of M-6 grades from 5 manufacturers. These are AK Steel (M-6), ATI (M-6), POSCO (35PG155), Nippon (35Z155), and Cogent (M150-35S). MagWeb's visualizer is used to generate this overlay plot. It shows that, within the same grade, the core loss varies by ***as much as 30%***! Thus MagWeb visualizer found that Cogent's M150-35S produces the lowest core loss – but only below 1.85. But above 1.85T, ATI's M-6 produces lower core loss. *So use the MagWeb visualizer* to discover the lowest core producer *at the operating point of your machine*.

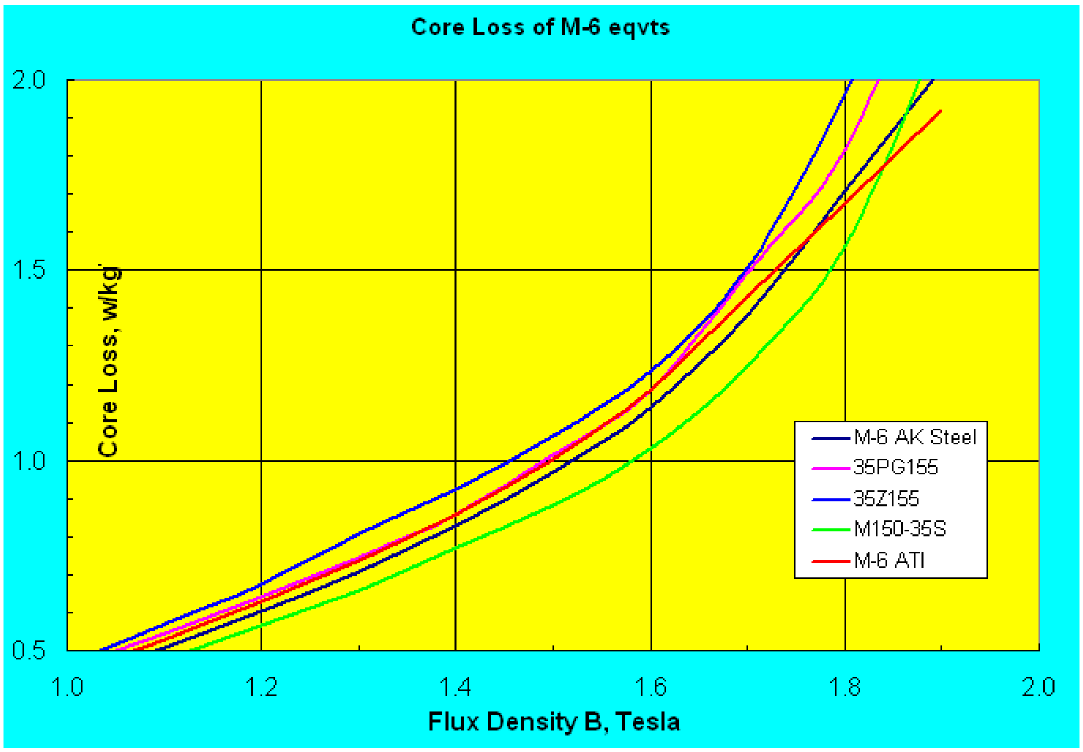

Figure 11. Core Loss of Equivalent Grade GO steels vary with manufacturers.

4.3. Highest Flux Density

Consider 3 grades produced by 3 manufacturers (listed as M310-50A *equivalent grades* by Beckley[46]): AK Steel (M-19), Nippon Steel (50H310), Cogent (M310-50A). Fig. 12 overlays their B(H) curves.

[46] Beckley, P. *Electrical Steels for Rotating Machines,* Inst. Elec. Engrs, 1972. p. 233

MagWeb
Magnetic Material Data

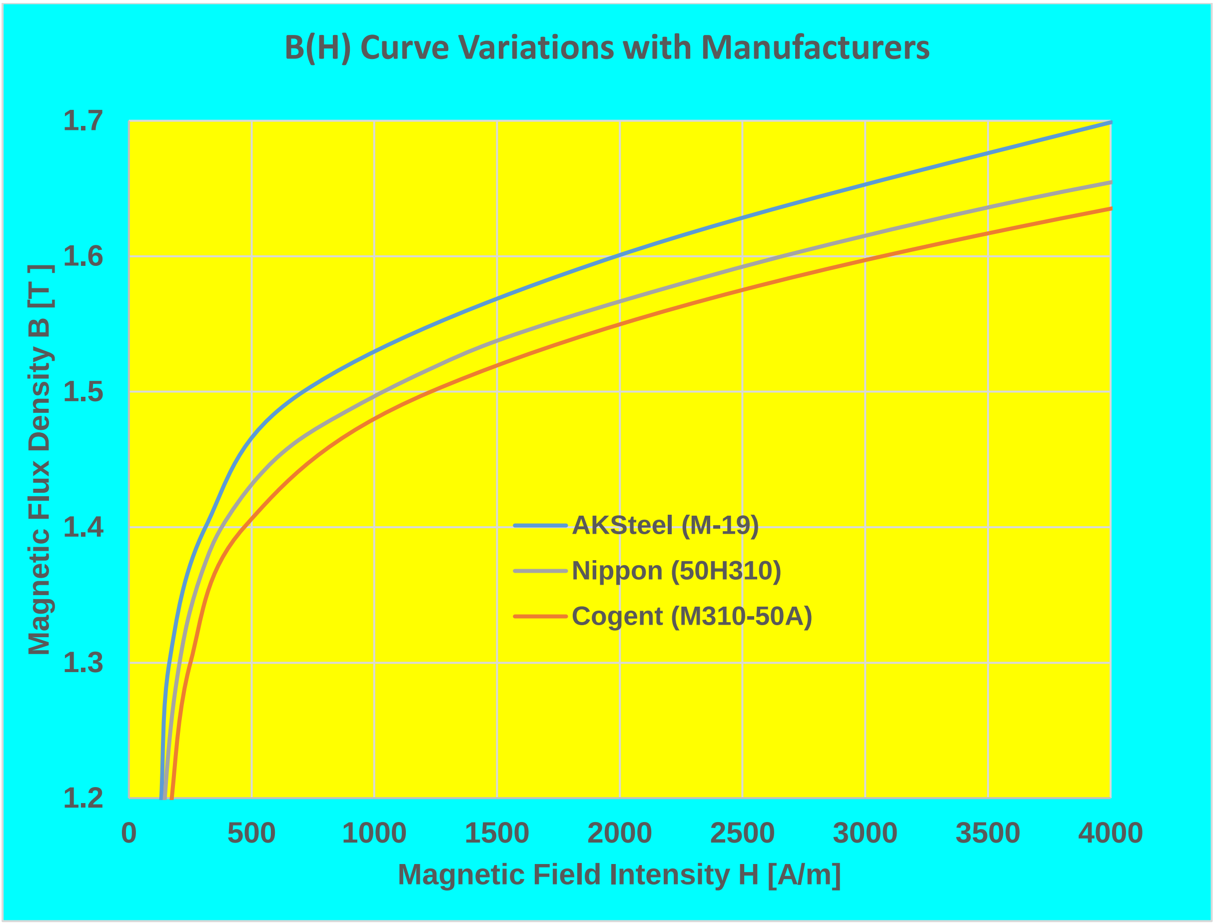

Figure 12. B(H) curves of equivalent grade steels vary with manufacturers.

Thus MagWeb visualizer found that the B(H) curves of these “equivalent” grades are significantly different. It also found that AK Steel’s grade produces the highest flux density. MagWeb visualizer can thus be used to discover the highest flux density producer of other equivalent grades.

4.4. Highest Permeability

Fig. 13 overlays the DC Permeability Curves of M-22 grades, produced by 4 manufacturers. These are AK Steel (M-22), Nippon Steel (50H350), POSCO (50PN350), and Bao Steel (B50A350). All these steels are 0.5 mm thick and produce 3.5 w/kg maximum core loss. So they are listed as equivalent grades by a leading core distributor[47].

It shows that their peak permeability is 8284, 6294,6059, and 6035 respectively. Thus the peak permeability of a Superior Grade is 27 % higher than the poorest one. It found that AK Steel produces steel with the highest permeability.

Example B: Consider NO20 grade electrical steels produced by three European Firms P, Q, R. MagWeb visualizer revealed that, at 1.5T/50 Hz, their permeability is 2150, 1103, 455 respectively. It found that the permeability of equivalent grade steels can vary by as much as

[47] Ibid, *GrandHunt*.

80%. Thus to produce 1.5 T, they require magnetizing currents of 555, 1082, 2620 A/m respectively.

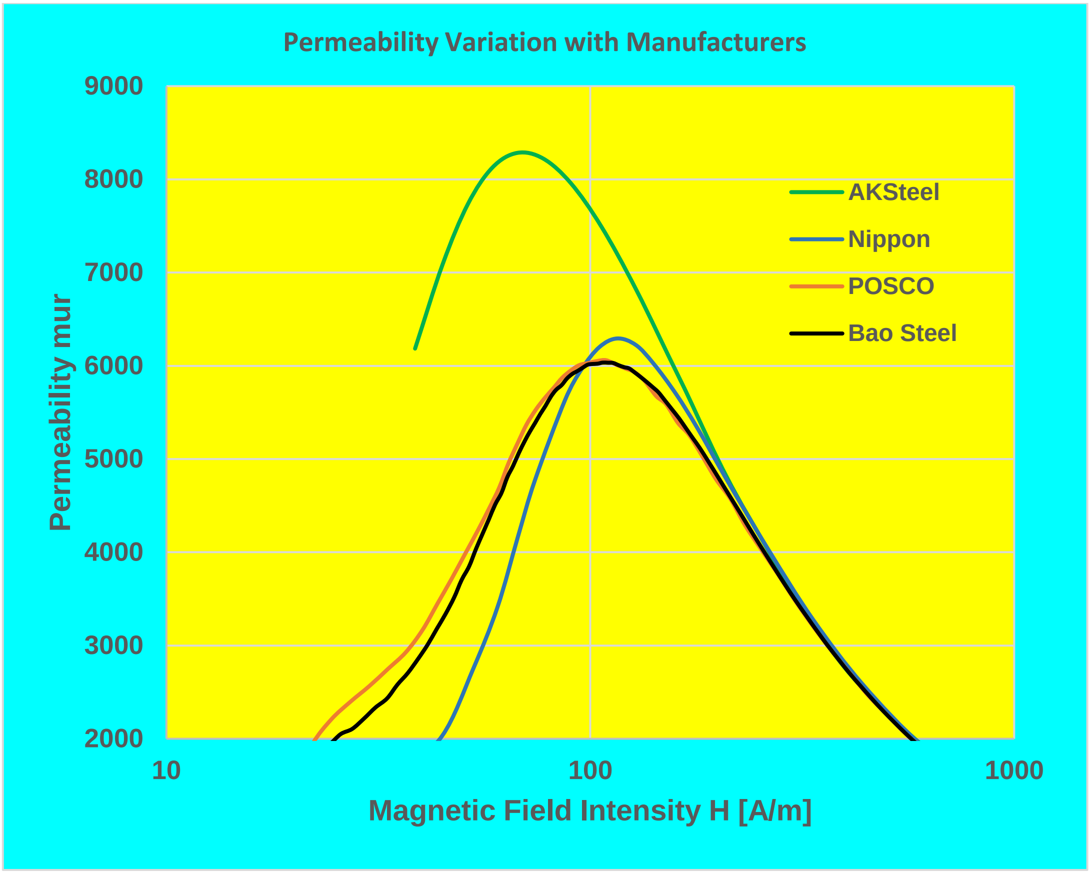

Figure 13. The permeability of Equivalent Grade steels varies with manufacturers.

Thus the MagWeb visualizer found that the NO20 steel produced by firm P requires only 1/5th of H needed by the poorest firm R.

Example C: Consider M250-50A grade electrical steel produced by two manufacturers. The MagWeb visualizer discovered that at (1.5T, 50 Hz), the permeability of Cogent's M250-50A grade is 746 while that for Nippon's 50H250 grade is 1033. Thus Nippon's grade is superior.

All these examples illustrate how to use the MagWeb visualizer to discover a grade that offers the highest flux density, permeability, or core loss.

4.5. Lowest Anisotropy

Orientation Angle α between flux and the Rolling Direction (RD) influences core loss and permeability of all electrical steels. Thinner steels demand more rolling passes, so suffer from higher anisotropy. The deviation is "drastic" in GO steels, but "mild" in NGO steels.

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. Note this definition misleadingly halves the true anisotropy, which is $(P_1-P_2)/P_2$, so true anisotropy is far higher. Unfortunately, even in NGO steels, this anisotropy also ***varies greatly from firm to firm.*** Steel from one manufacturer can have 6% anisotropy while an equivalent grade from another firm can produce as high as 30%. Consult the manufacturer for actual data.

B(H) Anisotropy **–** It depends on the number of rolling passes used by the manufacturer. If a single pass is used, minimum permeability occurs at 45°. If two passes are used, the minimum[48] occurs at 90°. Fig. 14 shows how the angle α affects the B(H) curve of NGO steel.

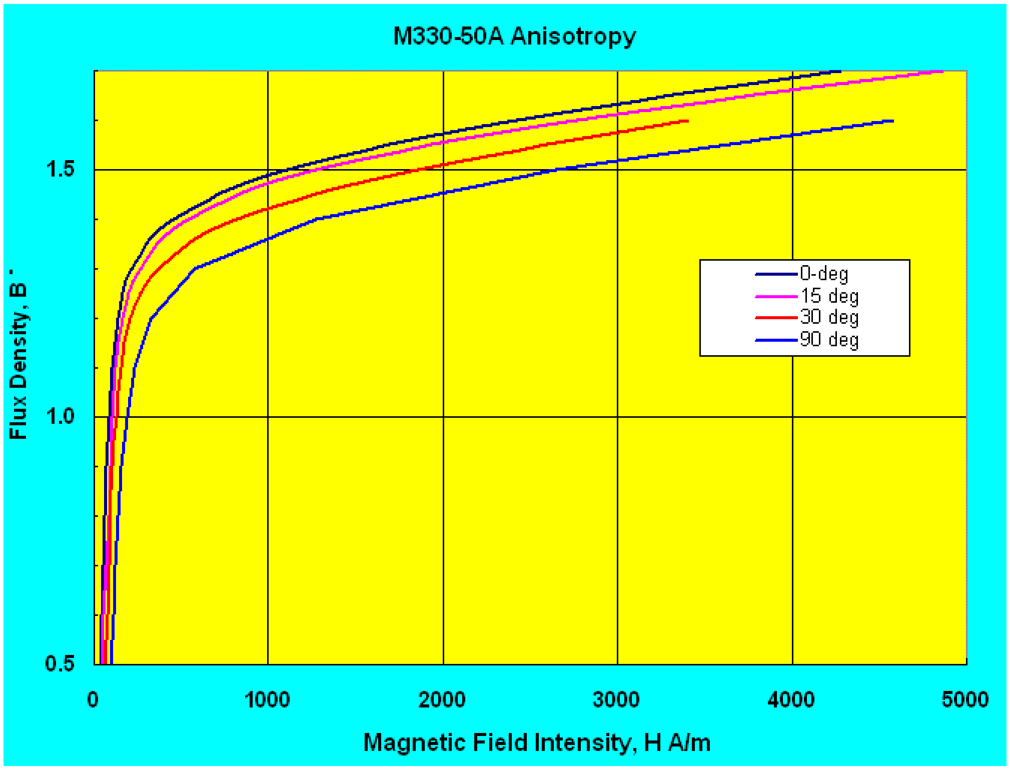

Figure 14. Magnetic Properties of NGO steels do vary with orientation

Countermeasures. To counter the ill-effects of anisotropy,
- use magnetic properties measured in a 50/50 Epstein frame.
- rotate the laminations by 90° along with the stack.
- identify a firm that produces low-anisotropy steels

[48] Honda, A., Effect of Core Material on Efficiency of inverter drive motors, Kawasaki Steel Technical Report, No. 38, Oct. 1998, pp. 36-40.

5. A. ELECTRICAL STEELS – NON-GRAIN ORIENTED

***MagWeb's* Electrical Steel (NGO) Folder** has magnetic properties of 336 grades of NGO electrical steels produced by 16 manufacturers. They contain 634 B(H) magnetization curves and 589 core loss curves. You can compare all these curves to discover the manufacturer that produces the grade that is optimal for your machine. For names of all these grades, please go to MagWeb.US, click on *Steels List*. All electrical steels are supplied in the annealed condition. Manufacturers supply them as coil rolls of 3 to 4 ft. diameter, in widths up to ~ 1.3 m.

Market. Electrical steels form a $9B market, they are used mainly in 50 to 400 Hz applications, spanning motor, generator, power transformer, and inductor segments. NGO steels are used invariably in all-electric motors (greater than .5 kW) in a wide variety of market segments, e.g., industrial motors, fans, pumps, rolling mills, oil/gas, machine tools, etc.

***Electrical Steels* remove** Carbon as much as possible, to improve magnetic properties. (Industrial Steels **add** Carbon as much as possible to improve its mechanical properties, but unwittingly degrade its magnetic properties.) Removal of Carbon reduces core loss and stabilizes it (i.e. prevents the increase of core loss with time, called aging). Carbon is magnetically harmless below its solubility limit of 70 ppm. In electrical steel, carbon is less than 30[49], 50[50,51], 200[52], 800[53] ppm - depending on whom you ask. Electrical steels also add Silicon (up to 4%) and Aluminum (up to 1.25%) to reduce core loss. But it unwittingly degrades permeability, so increases the copper loss. Silicon also causes them to be more brittle.

Grain-Oriented steels (detailed in the next section) have grains as large as 3 to 8 mm. They offer the lowest possible core loss at the highest possible permeability. But their properties are highly directional. Along the Rolling Direction, their core loss is low and permeability high. Typically,

- Core loss ranges 0.5 to 1 w/kg.
- Peak permeability ranges from 40,000 to 80,000
- 1.5 T permeability ranges 5000 to 30000

Non-Grain Oriented steels have grains as small as 0.05 to 0.2 mm. 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. They 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 is higher and permeability lower than that of GO steels. They are less expensive and more isotropic or Omnidirectional. Their properties are measured in a 50/50 Epstein stack. Typically,

- Core loss ranges 2 to 16 w/kg

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49 AK Steel, Selection of Electrical Steel for Magnetic Cores, *Product Data Bulletin*, 2007, p. 7 https://www.aksteel.com/sites/default/files/2018-01/m15-m47201310_Final_0.pdf

50 Electrical steel, https://en.wikipedia.org/wiki/Electrical_steel

51 Dorner, D., Non-Oriented electrical steel sheet for electric vehicle drives, *ThyssenKrupp Techforum*, Issue 1, 2009.

52 ASTM A677, Standard Spec. for NonOriented Electrical Steel.

53 US Govt, Non-Oriented Electrical Steel CVD, http://enforcement.trade.gov/download/factsheets/factsheet-multiple-non-oriented-electrical-steel-cvd-prelime-031914.pdf

- Peak permeability ranges from 4000 to 8000
- 1.5T permeability ranges from 800 to 3000.

Note: Only European manufacturers supply B(H) curves at 50 Hz. **Others supply them at 0 Hz (DC).** ***Reputed firms rightly degrade them to 50 Hz before using them to design their machines.***

Grades

Each manufacturer has his secret recipe composition and method of manufacture of a grade, so their magnetic properties vary even when they carry the same grade label.

European standard (EN10106 and IEC 60404-8-4) grade NGO steels by thickness. They also specify maximum *(guaranteed)* core loss at 1.5T, 50 Hz ($W_{15/50}$), and *minimum (guaranteed)* flux density at 5000 A/m (B_{50}). Standard grades are labeled "Mccc-tt-x". Here, "M" is for electrical steel, "ccc" is for max. core loss (w/kg x 100) at 1.5T/50Hz, "tt" for thickness (mm x 100). "x" is for "type":

- A for fully processed steel
- K, D, or E for semi-processed steel
- PP for semi-processed high permeability steel
- P, HP, or AP for a fully processed high permeability steel
- N for core loss measured at 1.5T/50Hz,
- S for core loss measured at 1.7T/50Hz.

For example, grade M250-50A has $W_{1.5/50}$ = 2.50 w/kg, B_{50} = 1.6T. This means that its core loss is guaranteed to be less than 2.5 w/kg at 1.5T, 50Hz. The flux density is guaranteed to be greater than 1.6T at 5000 A/m. The minimum permeability μ_{50} can be calculated from $\mu_{50} = B_{50}/(5000\mu_o)$. So its μ_{50} = 255, its relative permeability is guaranteed to be greater than 255.

Core Loss. The guaranteed core loss $W_{15/50}$ of electrical steels 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 Fig. 15 shows that typical core loss and permeability of same-grade steels can be significantly different. Such "typical" properties of delivered steels are significantly better than the bounds specified by the grade. MagWeb furnishes these "typical" Core loss and B(H) Curves. MagWeb data can discover Superior Grade as shown in Sec.3.

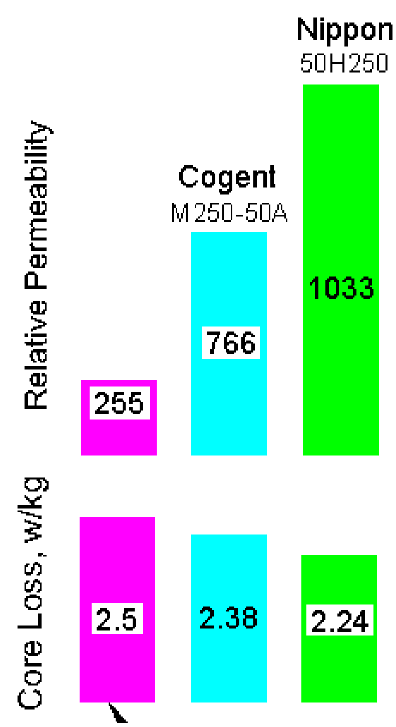

Figure 15. Same-grade steels from diverse firms differ in magnetic quality.

Thermal Conductivity

The thermal conductivity of laminations (hence core) is highly anisotropic. Its in-plane conductivity k_{xy} is high (~ 28 w/mK) but thickness-wise conductivity k_z is low (~0.4 w/mK)[54]. Such anisotropic thermal conductivity data is essential for accurate estimation of temperature rise, but such data is rare and sometimes deceptive.

[54] Cogent, Electrical steels thin nonoriented, https://perso.uclouvain.be/ernest.matagne/ELEC2311/T2006/ThinNOFP.pdf

Most software does not recognize this anisotropy, which only worsens their temperature rise prediction capability.

- k_{xy} (in-plane conductivity) depends mostly on the composition and manufacturer. Pure iron has a thermal conductivity of 72 w/mK, but even minute silicon drastically reduces it. A 1% Si reduces k_{xy} to 40 w/mK. a 3% Si steel degrades it further to 28 w/mK.

- $k_{z,}$ (thickness-wise conductivity) of lamination is different from that of a stack. That for a stack depends on coating class (material and thickness), the number of laminations, and temperature. Besides, it depends on voids that are controlled by clamping pressure and temperature. Tiny voids (air pockets) between the laminations reduce with the clamping pressure, and high temperature could soften the resistive coating. So high clamping pressures and temperatures can significantly reduce voids, so increases k_z. For typical stacks, k_z reportedly increases from 0.6 to 2 w/mK as clamping pressure increases from 20 to 80 psi (0.14 to 0.6 N/mm^2) [55,56].

5.1. Thickness: the USA vs. Rest

MagWeb visualizer contains properties of both US and Non-US electrical steels. For 50/60Hz machines, US manufacturers supply electrical steels in 29, 26, 24 gages i.e., 0.014", 0.0185", and 0.025" thickness. Rest produce in 0.35, 0.5, 0.65 mm thickness (per IEC/EN/JS standards). They are close to inch grade, but not quite the same.

The 0.35 mm (0.01378") IEC steel is 1.6% thinner than its 0.014" US steel. The 0.5 mm (0.0197") IEC steel is 6.4% thicker than its 0.0185" US steel. The 0.65 mm (0.0256") thick IEC steel is 2.4% thicker than its 0.025" US 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 affect the amount of iron in a stack, hence true flux density. What is worse, it affects the cost of a core to attain a given flux density!

Also, for 400 Hz machines (as in hybrid vehicle motors, aviation generators), they supply *thin* electrical steels in 0.2, 0.27, 0.3 mm (0.008, 0.010, 0.012 inches) thickness.

For 1000 – 5000 Hz devices (as in inductors and transformers) they supply *ultra-thin* electrical steels in 0.1, 0.12, 0.18 mm (0.004, 0.005, 0.007 inch) thickness.

[55] Bennion, K, Electric motor thermal management R&D, Report No. NREL/PR-54000-63004, 2014. https://www.ieee-pes.org/presentations/gm2015/PESGM2015P-002837.pdf

[56] Staton, D., et al, Solving the More Difficult Aspects of Electric Motor Thermal Analysis, IEEE Trans. Energy Conversion, Vol. 20, No. 3, pp. 620-628, Oct. 2005. https://www.motor-design.com/wp-content/uploads/2016/12/motor-cad_iemdc_2003.pdf

5.2. CRML (Semi Processed) Steels

CRML ***(Cold Rolled Magnetic Laminations)*** are those that have little or no silicon. They rely on "ultra-low carbon" to reduce core loss. Low grade CRML have carbon <0.06%, high grades < 0.02%, while best (costlier) grades have <0.005%. Unlike electrical steel, they are uncoated and unannealed ("semi-processed") by the steel producer. End-users are expected to perform annealing of the finished part. MagWeb furnishes their properties after such finish annealing.

In the USA they are produced per ASTM 726; different producers grade them as Type 2-6, or Grade Q, CQ, etc. European firms produce them per EN10341. They call them semi-processed steel and identify them by an end code K.

They are characterized by temper-rolling, which produces a rough surface with a mat finish. When stacked, the rough surfaces contact only a 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 end-user should decarburizing anneal after stamping. This greatly reduces core loss and prevents aging. 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.

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

Permeability. Because of the 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 far less expensive than NGO steels, so are preferred in FHP motors. Unannealed CRML also produces very low wear on stamping tools, further reducing tooling costs.

Applications. They are preferred where cost is more important than efficiency or overheating. These include 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.

6. B. ELECTRICAL STEELS - GRAIN-ORIENTED

***MagWeb's* Electrical Steel (GO) Folder** has magnetic properties of 177 grades of GO electrical steels produced by 13 manufacturers worldwide. They contain 221 B(H) magnetization curves and 190 core loss curves. You can compare all these curves to discover the manufacturer that produces the grade that is optimal for your machine. For a full list of commercial names of all these grades, please go to MagWeb.US, click on *Steels List*.

The ***Grain Oriented Electrical Steels*** use ~ 3.25% Silicon to reduce losses. They have ultra-low carbon (< 10 ppm)[57]. But annealing changes the chemical composition, so manufacturers rarely commit to a specific % of C or Si. Their saturation induction J_s ~2.03 T. The grain size of conventional GO steels is ~ 3mm, while that of HiB steels is about 8mm.

Grades. They are available in three grades

- conventional
- high permeability (aka **HiB**)
- domain refined (aka **laser scribed**).

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 max. core loss (w/kg x 100) at 1.5 or 1.7T, 50 Hz. For example, 27ZDKH95 refers to 0.27 mm laser scribed HiB steel with a max 1.7/50Hz core loss of 0.95w/kg. But, just like NGO steel, each manufacturer makes them using his secret recipe and processes. So properties of each steel depend on the manufacturer.

Permeability. They are made by complex annealing that vastly increases permeability and reduces core loss – but only in the rolling direction. If the flux direction deviates by an angle as small as 10^o from the rolling direction, the permeability can drop sharply, by as large as 80%. If the flux flows in Transverse Direction at 90^o (TD or hard axis), its permeability could reduce by an order of magnitude.

Thickness vs Skin Depth. The complex manufacturing process increases the peak permeability of HiB steels to 60,000 or more. However, such high permeability is a ***double-edged sword***. It concentrates magnetic flux on thin skin. At high frequencies, if the lamination is too thick, the mid-core carries very little flux, which wastes material at the central core.

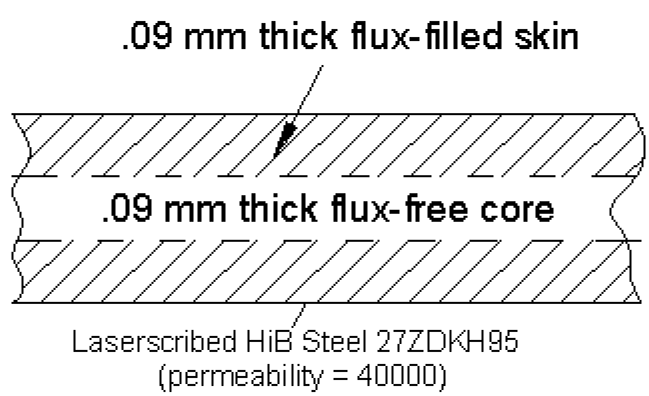

Figure 16. Too high permeability can prevent flux from flowing in a central core of a lamination

Fig. 16 shows a 0.27 mm thick laser scribed Nippon's HiB steel 27ZDKH95 with 50$\mu\Omega$ cm resistivity, used in transformers. At an operating point of 1.5T, 400 Hz, its permeability is 40,000. At this operating point, the skin depth of the 400 Hz flux is only 0.09 mm as shown. *Flux does not flow in the central core* of 0.09 mm thickness. That is, 33% of expensive iron is simply wasted. If

[57] Ramanathan, S., Study of dislocations...on magnetic properties of grain oriented electrical steel, *Ph. D Thesis*, Cardiff University, 2013, p. 2 https://orca.cf.ac.uk/56703/1/2014RamanathanSPhD.pdf

the flux is kept constant, a reduction in the effective area increases actual flux density, which can increase core loss.

Core Loss. At 1.5T, 50 Hz, the core loss of GO steels ranges from 0.5 to 1 w/kg. This core loss is only along the Rolling Direction (RD or easy axis). It could triple along the transverse direction! 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 unidirectional, they are used only in applications where flux flows along the rolling direction. Examples include high-power transformers and low-power 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 are best modeled by separate B(H) and core loss curves for transverse direction, but such a two-curve approach is likely to face convergence issues[58]. Wherever available, MagWeb provides such dual property files, one for rolling and the other for transverse directions. So GO steels should ***never*** be used in radial gap motors since flux flows in all directions.

However, GO steel in tape core form ***can*** be used in axial gap motors since the flux flows only along the rolling direction. They seem to offer significantly higher efficiency than NGO steels. Such axial gap motors can compete with alternative amorphous metal tape core versions recently developed by Hitachi[59]. But apparently, their size is somewhat limited, perhaps to less than 12 ".

[58] Witte, H., FEA Simulation of magnets with Grain Oriented Steel, Brookhaven National Lab, 2012 Rept BNL-98381-2012-IR https://www.bnl.gov/isd/documents/79024.pdf

[59] Hitachi, Development of motor with amorphous metal, http://www.hitachi.com/rd/portal/contents/story/amorphous/index.html

7. C. METGLAS & NANOCRYSTALLINE

MagWeb's ***Metglas & Nano Folder*** has magnetic properties of 28 grades of metglas or nano materials produced by 4 manufacturers. They contain 30 B(H) magnetization curves and 26 core loss curves. You can compare all these curves to discover the manufacturer that produces the grade that is optimal for your machine. For names of all these grades, please go to MagWeb.US, click on *Steels List*.

MagWeb broadly groups them into amorphous and nanocrystalline materials. Both employ a large amount of silicon (9% to 15 %) to reduce core loss but differ in annealing. But high % silicon reduces saturation induction (to less than 1.6T). They also have near-zero magnetostriction.

Cores are also made by powdering the amorphous and nano ribbons and mold-pressing them. Such powder cores are sold under trade names of amoflux, optialloy, and listed in the alloy powder core folder. They have inferior properties.

Many firms, such as Metglas, Hitachi, Vacuumschmelze, Amotech, Toshiba, UAML, Quingdao, Beijing Zang, AT&M, Henan Zhongyue Amorphous, China Amorphous, Usha Amorphous, etc. produce amorphous materials. Magnetec, Arcelor Mecagis, NanoAmor also produce nanoribbon. But only reputed firms provide reproducible B(H) and core loss curves, which are available in the MagWeb visualizer.

Applications. They are used in 10K to 100K Hz frequency 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.

(a) Amorphous

Amorphous ribbons do not have a 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 a crystalline structure. Boron is added for easy flow of molten metal. This process limits the thickness and width of the result, so the resulting materials are called *ribbons*. Speed limits ribbon thickness to 25 μm (1 mil). The drum limits ribbon width to 200 mm (8").

Metglas produces the most amorphous ribbons and cores. So "amorphous" and "Metglas" are often synonymous. It 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 and has higher J_s. 2605SA1 and 2605HB1M are popular in making distribution transformers, with the latter having higher J_s. The price of 2605S3A (which uses less Boron) has drastically reduced recently, allowing its wider usage

But they supply magnetic properties as hysteresis loop (instead of a single-valued B(H) curve). For a given H, such a loop has two values of flux densities. Such multivalued curves are not accepted by most design software. MagWeb converts such multivalued hysteresis loops into a single-valued B(H) curve using the *Elenbass Rule*[60]. This rule states that the flux density B at a given H equals the average of the two flux densities having the same H ordinate.

Manufacturers (and MagWeb) furnish the magnetic properties of raw ribbons (instead of finished toroids). Designers should use them with caution as the magnetic properties of finished cores are inferior to those of ribbons. Manufacturers also supply finished toroidal cores or C-cores made of these ribbons.

Permeability. The permeability can range from 100000 to 300000. It is controlled by the direction of the magnetic field applied during annealing. Nano folks designate cores as follows.

M or NFA	no field annealed
H	peripheral or easy axis annealed
L or LFA	longitudinal or hard axis annealed

H annealed cores will have the highest permeability but relatively high core loss. LFA annealed cores will have low permeability and low core loss.

Skin Depth. One should consider the skin depth at such high frequencies to fully use the material. High-frequency flux concentrates in a thin skin of depth δ. If skin depth is smaller than the thickness of the ribbon, flux avoids the mid-core, thereby wasting the material[61]. For example, consider a tape core made of Metglas 2605SA1 of 25μm thick ribbons. At an operating point of 1.3T,100 kHz, its permeability is 200,000, and its resistivity is 42μΩ cm. The skin depth of 100 kHz flux is 5μm. The high-frequency flux avoids the mid-core of 25–2x5 = 15 μm. This mid-core behaves like air, wasting a lot of costly material (see). If the flux is held constant, such reduction in the effective area increases effective flux density, which can increase core loss!

A simple example of how reduced thickness of a nano material can save core loss was presented by Trupp[62] . He considered a nano ribbon (permeability = 30,000, resistivity = 115 μΩ cm, density = 7.35 gm/cc) operating at (0.3T, 100 kHz). He showed that a 0.02 mm thick ribbon produces an eddy loss of 70 w/kg, while a 0.0164 mm thick material produces a lower loss of 47 w/Kg.

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

Table 2. Metglas Ribbons, graded by core loss

Name	**Base Element**	**Composition**	**J_s, tesla**	**Core Loss w/kg At 0.75T, 50Hz**
2705M	Cobalt	$Fe_4\ Si_{12}\ Co_{69}\ B_{12}Ni_1Mo_2$	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**

60 Bozorth, *ibid*, p. 511

61 Szewczyk, M. et al, Quantitative analysis of high frequency material properties in thin-ribbon magnetic cores, IEEE Trans. Magnetics, Vol. 51, No. 8, 2015. https://ieeexplore.ieee.org/document/7084634

62 Trupp, T., Palanki, Z. "Effect of ribbon thickness on power losses and high frequency behavior of nanocrystalline finemet type cores," http://www.magnetec.de/fileadmin/pdf/smm21_ttr.pdf

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, whereby they develop a tiny crystalline structure. Curve Cu, Nb is added to improve magnetic properties. The ribbons have a thickness of 0.001”, 0.0008” and width less than 4”.

Saturation. Nano ribbons saturate at ~1.2 T, earlier than 1.5 T of amorphous ribbon. For example, Hitachi’s FT-1M saturates at 1.35T, while FT-3M saturates at 1.23T. Its saturation temperature coefficient is 0.1%/C.

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 3. 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 PERM(a)	Carnegie Mellon	$Fe_{67}\,Co_{18}\,Si_1\,B_{14}$	1.8	**-**
HiT PERM(b)	Carnegie Mellon	$Fe_{44}\,Co_{44}\,B_4\,Zr_7\,Cu_1$	1.8	**-**

MagWeb
Magnetic Material Data

8. D. COBALT STEELS

MagWeb's Cobalt Steel Folder has magnetic properties of 142 cobalt steel grades produced by 4 manufacturers. They contain 51 B(H) magnetization curves and 192 core loss curves. You can compare all these curves to discover the manufacturer that produces the grade that is optimal for your machine. For the names of these grades, please go to MagWeb.US, click on *Steels List.*

Cobalt Steels are alloys of cobalt and iron that offer the highest possible saturation induction (J_s~2.45T). 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.

Market. Cobalt steels are used in aerospace generators and motors. The resulting reduction in size and weight overrides the higher cost of these materials. But such expected benefits are sensitive to several factors which are documented in the MagWeb visualizer. Such data helps in the optimal design of aircraft generators.

Saturation Induction J_s of cobalt steels can be as high as ~ 2.45 T (only 14 % higher than iron's 2.158T) - depending on your luck in annealing.

A new 50% Cobalt alloy, made by the hot isostatic press (HIP) claims to offer a J_s of ~ 3 T. But no additional data is available.

Another new alloy called Minnealloy t[63] claims to offer J_s ~2.35T. But, at H = 5000 A/m it yields only 0.15T. In contrast, electrical steels produce ~ 1.6T at the same H. So it is not superior.

***In the USA**,* Carpenter sells 6 Cobalt Steel Grades under the "Hiperco" brand name. They are available as strips of 0.006, 0.010, 0.014-inch thickness. Following Hiperco 50 series have large (48.75%) cobalt. Such a large cobalt % makes them very expensive.

> Hiperco 50A – has ~0% C so offers the 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.

Following other Hiperco alloys have lower cobalt so are less expensive. But their magnetic properties are less attractive as they have a higher %C. They are sold as 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 degrade magnetic properties
> Hiperco 27 – has 27% Co. Is highly ductile. But its .01%C causes higher core loss.

MagWeb has 225 files on both B(H) and core loss of Hiperco cobalt steels, which will be useful in selecting the most appropriate type of Hiperco.

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[63] Mehdi, Md et al. Minnealloy, a new magnetic material with high saturation flux density and low magnetic anisotropy, J. Phys. D: Applied Phy. Vol. 50, 2017.
https://www.researchgate.net/publication/318575768_Minnealloy_A_New_Magnetic_Material_with_High_Saturation_Flux_Density_and_Low_Magnetic_Anisotropy

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 the best magnetic properties. Vacodur has Nb added to improve mechanical properties. MagWeb also has B(H) curves for Arcelor/Imphy's 3 cobalt steel grades under the "Aperam" or "AFK" brand. Others, such as Xian Gangyan Specialty Alloy, China also sell cobalt steels, but their properties are not available.

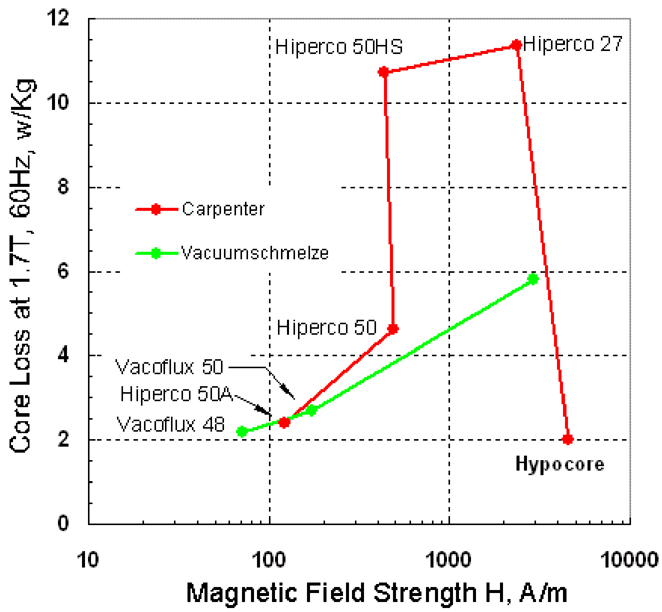

Figure 17. Vacoflux 48 produces least core loss. But Hypocore incurs more copper loss

Core Loss vs. Copper Loss. Fig. 17 compares the core loss of 0.35 mm cobalt steels while carrying 1.7T at 50 Hz. It shows that Vacoflux 48 produces the lowest core loss of 2 w/kg. This cobalt steel also needs a low H = 72 A/m. So its copper loss due to magnetization currents is low. Hypocore also produces low core loss. But it requires 4540 A/m - two orders of magnitude higher than the 72A/m, so produces a lot more copper loss. Hiperco 50A, Vacoflux 50 also produce low core loss but at higher H.

Annealing. Generally, cobalt steel that offers the lowest core loss may not have high strength. 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. Higher strength may require annealing at a lower temperature, but it increases core loss. On the other hand, stator cores may need the lowest-loss steels, so annealing at a higher temperature is recommended.

Anisotropy. MagWeb data shows that the 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. 18 illustrates the 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. The core loss of cobalt steels generally increases with aging. Geist[64] demonstrated that Hiperco 27 is more thermally stable than other cobalt steels.

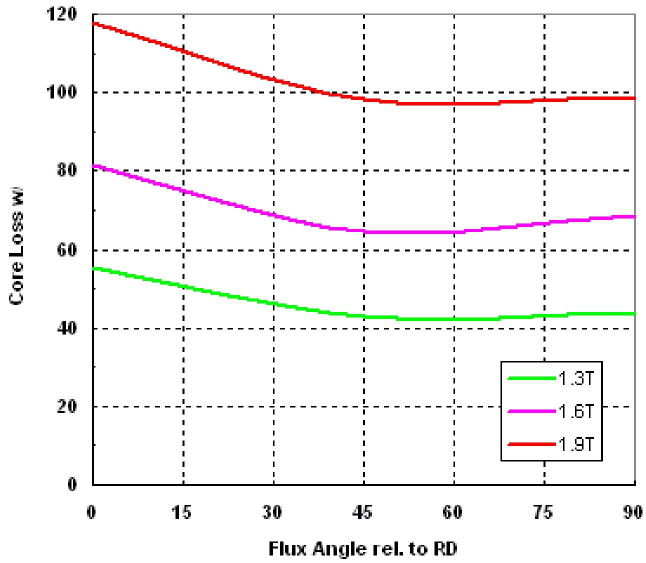

Figure 18. Core Loss of Cobalt Steels varies with direction of flux.

Yield Strength. Yield strength depends on the annealing schedule. Hiperco 50 HS offers the highest yield strength ranging from 70 to 99 ksi while Hiperco 50 offers 60 to 70 ksi (1 ksi = 7MPa). Hiperco 50A offers the lowest at 53 ksi. ***Stress.*** The MagWeb data shows that compressive stress always increases core loss. On the other hand, small tensile stress (~ 50 MPa) seems to minimize the core loss. ***Temperature.*** Only in Hiperco 27 the core loss beneficially decreases with increasing temperature (Fig. 20). Other cobalt steels are not that thermally sensitive.

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[64] 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. https://www.researchgate.net/publication/234873110_Effect_of_high-temperature_aging_on_electrical_properties_of_Hiperco_R_27_Hiperco_R_50_and_Hiperco_R_50_HS_alloys

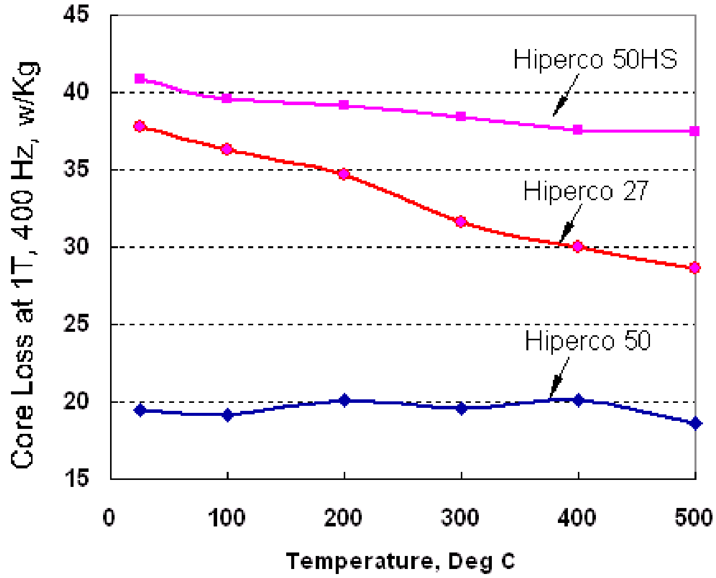

Figure 19. Hiperco 27's Core Loss beneficially decreases with temperature

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Magnetic Material Data

9. E. NICKEL STEELS

MagWeb's Nickel Steel Folder has magnetic properties of 68 grades of Nickel Steels produced by 7 manufacturers. They contain 121 B(H) magnetization curves and 72 core loss curves. You can compare all these curves to discover the manufacturer that produces the grade that is optimal for your machine. For names of all these grades, please go to MagWeb.US, click on *Steels List*.

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 Ni steels are also produced. Even at 10%, 88%. They are available in 0.001 to 0.014-inch thickness, but even 0.040 thick sheets are not uncommon. Most are sold as 1-mil (25μm) thick ribbons, but thinner ones at 0.125 mils (3μm) are also available. They are sold uncoated, but applying an insulation coating can reduce core loss further.

80% Nickel steels offer very high permeability of ~100,000 at 0.5 T DC; its core loss is also low. But its saturation induction is lower (~0.8 to 1.1T). It is sold under various trade names such as Permalloy, Mumetal, Ultraperm, Magnifer 7904, etc. But their properties differ because of differences in manufacturing and impurities. Some have permeability as high as 500,000 but only in a narrow low-tesla range (see the folder for details). 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, the finished product must undergo through careful annealing process as prescribed by the manufacturer.

50% Nickel steels offer lower permeability of ~32,000 at 0.5T DC. Its saturation induction is higher (1.6T). It is sold under 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 these 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 50% Nickel steel is comparable to that of Metglas 2605SC or Nanocrystalline materials. But, as with electrical steels, curve impurities differ with manufacturers, so their magnetic properties vary with the manufacturer, even if the composition is the same.

Applications. They are employed in high frequencies up to 100000 Hz in inductors, transformers in communication, EMI Shielding plus anti-shop lifting devices. To achieve the highest Shielding Effectiveness, the shield must operate at the peak permeability point. You can use MagWeb's permeability curves to synchronize the peak permeability point of the material with the operating point of the shield, thereby maximizing the Shield Effectiveness.

10. F. STAINLESS STEELS

***MagWeb's* Stainless Steel Folder** has magnetic properties of 52 grades of stainless steel produced by diverse manufacturers. You can compare all these curves to discover the manufacturer that produces the grade that is optimal for your machine. For names of all these grades, please go to MagWeb.US, click on *Steels List.*

Stainless Steel here those with chromium (Cr). Unlike carbon steels, they don't 'rust' because of Cr. The chromium works by reacting with oxygen to form a thin, tough, adherent, invisible, passive, and bright layer of chromium oxide film on the steel surface. If damaged mechanically or chemically, this film is self-healing as long as it has enough oxygen. But a minimum chromium content of **10.5%** is needed for continuous protection. Their yield strength is higher than these mild steels - but elongation is lower. As the percentage of Cr increases, their corrosion resistance increases, but their magnetic permeability decreases. Careful control of Cr vs C percentages enables metallurgists to control their magnetic, mechanical, and corrosion properties. They may have "ferritic", "martensitic" or "austenitic" phases. Their permeability depends on the relative distribution of these phases.

"Ferritic" stainless steels (409, 430, 446) are those with BCC structure, so are most easily magnetizable. Annealed ferritic stainless steels behave like soft magnetic materials. But if heavily stressed ('cold worked') they can behave like hard magnetic materials (ie they act like weak permanent magnets). Their magnetic properties also depend on the percentage of carbon. Unfortunately, most producers do not control %C very tightly. So their magnetic properties vary with the manufacturer, that too from batch to batch. Their corrosion resistance depends on %Cr and the additives. They fall into 5 groups.

Group 1 (405, 409, 410, 416, 420, FM grades), with 10 to 14% Cr. They are the least expensive. They are best suited for a light-corrosive environment - where slight spot rusting is acceptable. Their magnetic properties are superior to other grades, but corrosion resistance is just above mild steel.

Group 2 (430 and its derivatives), with 14 to 18% Cr, plus 1.5% Si. Their corrosion resistance is comparable to nonmagnetic grade 304 (so far superior to that of Group 1) and Si lowers core loss. Type 430 often replaces 304 in kitchenware requiring magnetic properties.

Group 3 (430Ti, 439, 441) also has 14 to 18% Cr Ti, Nb is added for weldability. They are also ductile. They are best for outdoor applications such as valves, exhaust systems, and washing machines.

Group 4 (434, 436, 444) also has 14 to 18% Cr. They add Molybdenum for higher corrosion resistance. They are used in highly corrosive environments, such as water tanks, exhaust systems, and outdoor applications.

Group 5 (445, 446, 447) also has 14 to 18% C. Molybdenum is added for higher corrosion resistance. They are comparable to titanium in corrosion and wear resistance. They are ideal for highly corrosive offshore applications, heat exchangers, water heaters, and boilers.

Typical magnetic stainless steels in the MagWeb visualizer are:

8-FM has 8% Cr. It is FM (Free Machinable) and offers high saturation induction (J_s ~ 1.86T) – so suitable for high flux density applications. It is useful for light corrosive applications where alternative 1000 series low carbon alloys may need additional coatings to prevent pitting. But its resistivity is relatively low - so it can carry DC or low-frequency flux without excessive loss.

12-FM and 13-FM have 12 and 13% Cr. They are also Free Machinable. They also have reasonably high saturation induction (Js ~1.7T). Permeability is 12-FM is similar to 8-FM, but that of 13-FM is poor. But its resistivity is 50% higher than that of 8-FM, so its eddy coreless can be smaller. Both have higher corrosion resistance than 8-FM.

18-FM has 18% Cr. It is also Free Machinable. But the high Cr degrades saturation induction to J_s = 1.5T. So its magnetic properties are poorer. But its corrosion resistance is far superior to that of the 8 or 12 % Cr stainless steels, or even 430FR steel.

430 (1.4016) has 17% Chromium. It is magnetically poor. Its saturation induction is low. For example, to conduct 1.5T it demands 13560A/m, i.e. its permeability at 1.5T is 88, which is very poor.

430F (ASTM 838) grade is called "solenoid" quality steel. It has excellent corrosion resistance and low residual magnetism. But its saturation induction is lowest (J_s = 1.42T) among stainless steels. So it is useful in applications that need high corrosion resistance, but do not need high flux densities.

430FR It has higher wear resistance and hardness and lowers residual flux density than 430F. Its higher resistivity 760 μΩ mm reduces eddy losses. So it can conduct AC fluxes. But its higher coercivity (H_c = 200 A/m) discourages AC applications. It suffers from low Saturation Induction (J_s ~ 1.5T). Its permeability at 1T is 1700. Table 5 below compares their magnetic properties.

Table 4 Magnetic Properties of various stainless steels.

Name	% Chr	% C	% Si	Sat. Ind.	Resistivity	Properties at 1.5T	
				Js tesla	μohm cm	A/m	Mur
8-FM	8	0.03	0.50	1.86	50	**2354**	**507**
12-FM	12	0.03	0.50	1.77	57	**2641**	**452**
13-FM	13	0.03	1.25	1.70	78	**6401**	**180**
13-XP	13	0.03	1.50	1.70	82	**23800**	**40**
405	13	0.08	1.00		60	**5670**	**211**
410	11	0.15	1.00	1.60	57	**6395**	**188**
416	13	0.15	1.00		57	**11000**	**110**
430	17	0.12	1.00	1.56	60	**13560**	**88**
Name	**% Chr**	**% C**	**% Si**	**Sat. Ind.**	**Resistivity**	**Properties at 1.2T**	
				Js tesla	**μohm cm**	**A/m**	**Mur**
430F	18	0.07	0.50	1.56	61	**1153**	**828**
430F-RB75	18	0.07	0.50	1.56	60	**1522**	**627**
430F-RB82	18	0.07	0.50	1.42	60	**2190**	**436**
430F-RB87	18	0.07	0.50	1.42	60	**1993**	**479**
430FR	18	0.07	1.25	1.52	76.4	**1478**	**646**
440	18	0.68	1.00		60	**15500**	**62**

444 is Ferritic stainless steel with low carbon, containing 18% chromium, 2% molybdenum. It provides pitting and crevice corrosion resistance superior to other ferritic stainless steels, perhaps as good as 304. Its magnetic properties are similar to stainless steel with 18% chromium, and poor.

Duplex Stainless Steels (2205, S31803, A815, 1.44462) have 50% austenitic phase, 50% ferritic phase. They have poor magnetic properties, with permeability ~ 50 at 0.25 T. They also saturate fast, at 0.7T. Such weak magnetic properties interfere with the ultrasonic testing of pipelines for corrosion crack detection. But they offer high strength, high corrosion resistance, and toughness. Their resistance to pitting, chloride corrosion, stress corrosion, cracking is high. It is better than 317L (which is non-magnetic), so they are used in offshore pipelines.

"Martensitic" stainless steels (410, 416, 420, 440, 17-4 PH, 17-7 PH, 15-5 PH) contain more carbon and can be hardened to attain high strength. They are difficult to magnetize or demagnetize, so are considered "hard" materials. They have poor corrosion resistance. Precipitation hardened versions (17-4 PH, 17-7 PH, 15-5 PH) offer high strength and good corrosion resistance but have low permeability. If they are magnetized in hardened conditions, they may behave like weak magnets. ***440*** comes in grades 440A, 440B, 440C. Their %C is (0.6 to 0.75%), (0.75 to 0.95%), (0.95 to 1.2%) respectively. Its permeability is poor, that for 440C worst. Called razor blade steel, it is valued for high corrosion resistance/ hardness, in surgical instruments, valve seats.

"Austenitic" Stainless Steels (300 series – 302, 304, 316, etc.) have an FCC structure. They are generally nonmagnetic. They contain Nickel in addition to Chromium. The lowest permeability austenitic steels are those with nitrogen: 304LN (1.4311) and 316LN (1.4406) or those with high nickel: 310 (1.4845) and 305 (1.4303). In contrast, low nickel steels such as 301(1.4310), 321 (1.4541) & 347 (1.4550) offer higher permeability. Cold working stresses can transform an austenitic phase to a martensitic phase, increasing permeability, causing it to become magnetic. Magnetization can occur at sharp corners, sheared edges or machined surfaces, or welding. The welded zones can become "magnets" (Such zones can be demagnetized by heating to 1050C followed by rapid cooling.) MagWeb contains core loss data for such magnetized 304 at various stresses.

Applications. Magnetic stainless steels are valued for their corrosive resistance. They are used in solenoids in corrosive fluids pumps (e.g., antilock braking systems, fuel injectors, fuel pumps, solenoids in refrigerators, soda/beer dispensers), rotors, motor shafts, and induction cookware. Some are Free Machinable (FM), some weldable.

The selection of particular stainless steel depends on the application requirement of strength/corrosion vs. permeability. A high corrosive resistance requirement often conflicts with a high permeability requirement. The operating parameters (flux density, frequency) must be compared against material offerings (permeability/saturation induction, coercive force, remnant flux density, electric resistivity). Besides, trading mechanical strength with loss, thermal conductivity, hardness, machinability, weldability, etc and cost plays a critical role.

Core loss data of stainless steel is rarely published. Higher electrical resistivity reduces wasteful eddy currents. It can be inferred from its resistivity. As chromium increases from 8 to 18%, its resistivity increases from 50 to 76 $\mu\Omega$ cm. This reduces the core loss - but only slightly. High Cr steels have lower permeability so demand much more magnetizing current. So switching to high % Cr steel can increase copper loss.

Permeability and Annealing.

Annealing is required in dynamic applications to reduce core loss and increase permeability. *Note: To attain datasheet values of permeability, the finished stainless part must be annealed.* Materials with high permeability require less H so require lighter currents. This leads to smaller and cheaper parts with less power input. A typical annealing schedule is to heat to 1500F in dry hydrogen, cool at 20F per hour to 110F, and air cooling further. Fig. 20 shows the hysteresis loops of stainless steel for the stressed and annealed state. It shows annealing beneficially increases permeability and reduces Hc. However, it dramatically increases residual flux density Br from ~0.5 to ~0.9 T.

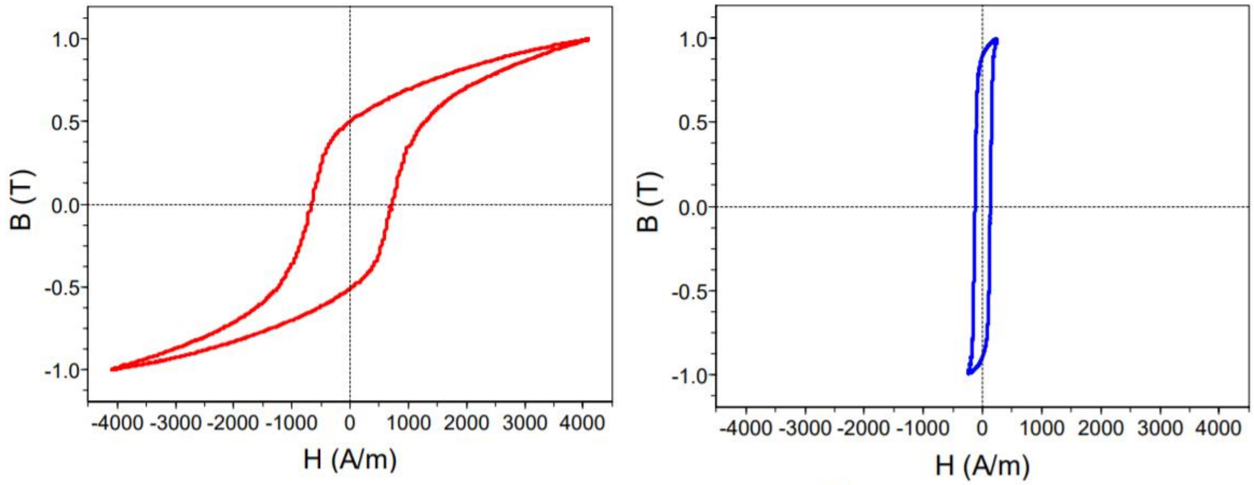

Figure 20. Annealing of stainless steel reduces core loss but increases residual flux density.

Fig. 21 shows that to pass 1.5T flux, an 8% Cr steel may require a low magnetizing current (H ~2400 A/m). But an 18% Cr steel may demand two orders of magnitude higher magnetizing current (H= 240,000 A/m).

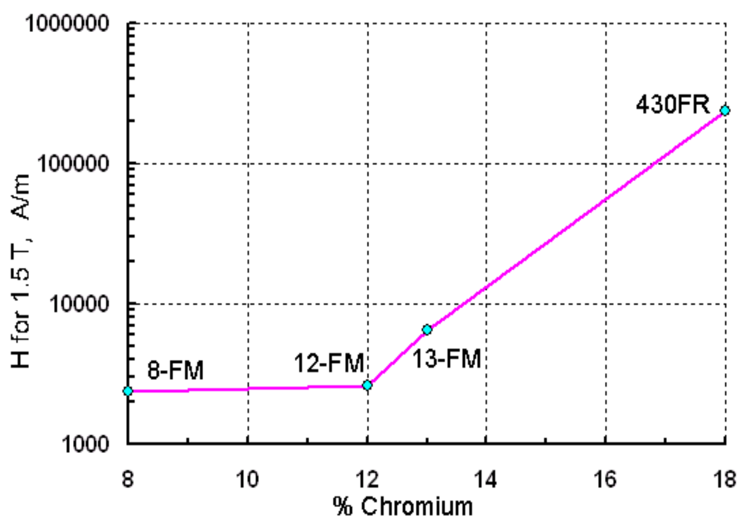

Figure 21. Magnetizing current varies with stainless steel grade.

Saturation Induction J_s Table 5 presents saturation induction and resistivity of various stainless steels. It decreases as p = % Chromium increases according to $J_s = 2.0795 - 0.0302p$. For example, 8%, 12%, 18% chromium steels have saturation induction of 1.84, 1.71, 1.54T respectively. It also depends on the method of annealing and the percentage of carbon. The latter depends on how tightly the manufacturer controls carbon. So saturation induction can vary with the manufacturer. For example annealed 430 from Carpenter's has J_s = 1.626T, while that from Allegheny has J_s = 1.5T per test by Apostolopoulos[65] . Also, expect an 8 to 15% reduction in J_s as temperature increases to 200 C.

Residual Flux Density. It varies from 0.47T to 0.83T, depending on the type of stainless steel. Solenoid manufacturers prefer 430FR as it has a low B_r of 0.48T. For values of residual flux density of other stainless steels, please refer to the MagWeb visualizer.

Coercivity**.** Low coercivity H_c permits rapid demagnetization, reducing the force required to open and close without "sticking", allowing a higher speed solenoid. But as already stated, cold working can increase H_c so it can behave more like a magnet instead of a soft magnetic material.

Skin Depth. Frequency greatly influences skin depth, hence losses. The thickness of magnetic stainless steel must be less than twice skin depth to fully utilize costly magnetic material.

For example, consider a motor for a hybrid electric vehicle that uses a 430 steel rotor with a 14 mm wall to mount magnets to resist corrosion (its resistivity is 60 $\mu\Omega$ cm). This motor has two operating points: a max torque point (1.2T, 200 Hz), a max speed point (0.6T, 400 Hz). The relative permeability of 430 steel is 327, 663 at these points. Respective skin depths are 1.5, 0.76 mm. So the thickest skin is 1.5 mm. The mid-core of 14–2x1.5 = 11 mm is devoid of flux. Such mid-core effectively behaves like air! So using 430 steel at 200 Hz wastes a lot of costly material. If the flux is kept constant, this increases the effective flux density, which increases core loss!

Induction cooktops are made of aluminum housing brazed to a stainless steel disc bottom. It is placed over an induction coil which is essentially a spiral-shaped air-cored Litz coil. The coil carries the current at 24 kHz, so radiates the HF flux pattern into the air. This flux enters the stainless steel bottom axially at the outer periphery, flows radially inwards, and exits axially at the center. The changing flux induces eddy voltage that creates eddy currents. They create eddy heating of the stainless steel bottom which cooks the food inside the cooktop.

The stainless steel bottom must be made of low-resistivity steel to increase eddy heat loss. The primary issues are what magnetic circuit/configuration will increase heating efficiency, whether the pot bottom is heated uniformly, and whether leakage flux is controlled to prevent messing surrounding metals.

Consider a 430 steel bottom with (60 $\mu\Omega$ cm at 400 C, 477 μ_r). A (1T, 24kHz) flux impinging concentrates the eddy currents in a 0.18 mm skin. Alternatively consider 8-FM steel with (50 $\mu\Omega$ cm, 2338μ_r). A (1.2T, 24kHz) flux impinging reduces skin to 0.074 mm. This significantly increases flux density, hence eddy heat.

[65] Apostolopolous, Magnetization, resistivity, structure of AISI 430 ferritic steel after heat treatment, 2013.

11. G. CARBON STEELS

***MagWeb's* Carbon Steel Folder** has magnetic properties of 143 grades of Carbon Steel. 87 of them contain B(H) curves for *Low Carbon Steel* (0.02% to 0.2 % C), which have better magnetic properties but have lower tensile strength. 93 of them contain B(H) curves for *Industrial Steels* (0.2% to 2%C), which have poorer magnetic properties but are stronger. You can compare all these curves to discover the manufacturer that produces the grade that is optimal for your machine. For names of all grades, please go to the magweb.us, click on *Steels List*. Steels with more than 2%C are called cast iron, wrought iron, malleable iron, etc. Their properties are listed in the "Cast Iron" folder.). These steels are further subcategorized as follows

Low Carbon Steels (87)

- Pure Iron (< 0.005% C)
- Ultra Low Carbon (ULC) Steels (0.005 to 0.03%C)
- Mild Steels (0.02 to 0.2%C)

Industrial Steels (93)

- Medium Carbon Steels (0.2 to 0.6%C)
- Plain Carbon Steels (0.6 to 2%C)
- Tungsten Steels
- Rotor Forgings
- Tool Steels
- API Grade Pipeline Steels

LOW CARBON STEELS (87)

MagWeb visualizer has B(H) curves for 87 low carbon steel grades. They are available in several forms, such as rounds, flats, tubes, pipes, etc. in several thicknesses. They are usually thicker than electrical steel grades. They are also more ductile and machinable.

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 a 1.5T permeability of 5000 will require a low magnetizing current of 240 A/m. That with 500 needs 2400 A/m - an order of magnitude higher current (hence more copper loss) to produce the same flux density.

Fig. 22 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 the flow of flux. It can be countered somewhat by annealing. But annealing can increase the permeability only by a factor of 2 at most, not by an order of magnitude. That is, even after annealing, the 1020 steel cannot reach the permeability of pure iron.

Mild steels or soft steels have 0.02 to 0.2%C. Lesser the carbon, the higher the permeability. But because they contain precipitable carbon, their magnetic properties degrade with age. The 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 % carbon/100 (e.g., 1002 has ~ 0.02%C, 1020 has ~0.2%C). Their yield strength is about 43 ksi. (1 ksi=7Mpa). At 1.5 T, the permeability of 1002 steel is 2360. Their tensile strength is less than 400 N/mm^2 (60 ksi)

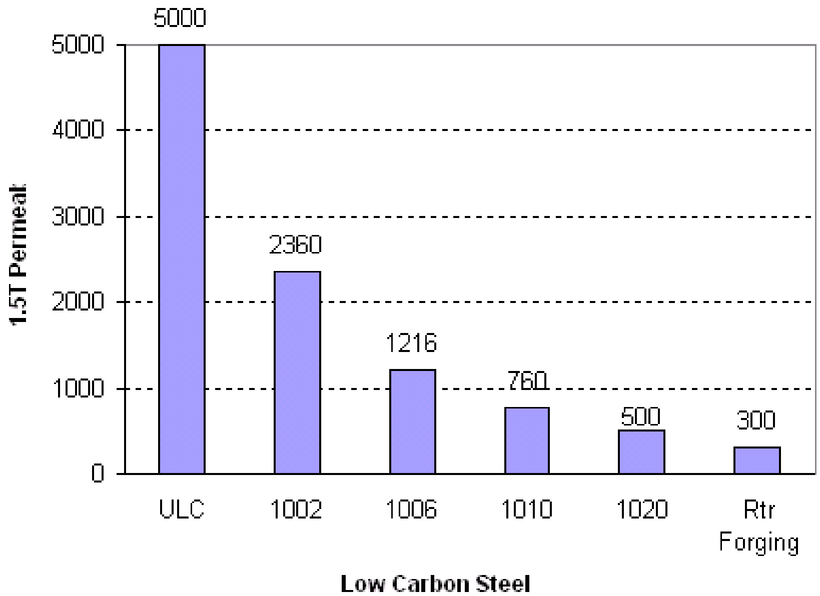

Figure 22. Permeability of Low Carbon Steel reduces as %C increases.

Pure Iron (9)

Pure iron has less than .003% C (and no Si). It has high permeability and saturation induction of 2.158 T[66] (all other steels saturate earlier). This high permeability feature makes it attractive for DC electromagnets. Its extremely low carbon content prevents an increase of core loss with time (aging). The absence of Si makes it ductile but pitifully degrades its ability to carry alternating flux.

This folder contains B(H) Curves for 9 Pure Iron grades produced by various manufacturers. Pure Iron is originally developed a century ago as ARMCO, OH. Currently, AK Steel sells it in 4 grades.

Several other manufacturers produce similar material, but with different carbon and curve impurities and different annealing schedules. The total impurities can range from 0.02% to 0.5%. Out of this, carbon can range from 0.003 to 0.02%. Unfortunately, all label their product as “pure Iron”. But minute differences in %C impurity cause their permeability to differ with the manufacturer. Low-grade pure iron offers a 1.5T permeability of 500. High grades (those with the lowest % C) offer a 1.5T permeability of 5000.

Pure iron is available in sheets, bars, plates, and wire. But to attain datasheet values, it must be annealed after machining. It is also available as a hydrogen annealed sheet which has much higher permeability. ARMCO’s pure iron can be annealed per Schedule A or B. That with

[66] 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. https://nvlpubs.nist.gov/nistpubs/jres/26/jresv26n1p1_a1b.pdf

schedule B offers a peak permeability of 7000 at 1.32T. This folder also contains B(H) curves of ARMCO pure iron annealed at different temperatures.

1002 Ultra-Low Carbon Steel Grades (7)

Steels with 0.005 to 0.03% C (and without Si) are called 1002 Ultra low carbon steel grades herein. This Folder contains digital B(H) Curves of 7 grades of Ultra-Low Carbon Steels. Since they have carbon in soluble form, their magnetic properties do not degrade with age. Depending on their carbon content, their 1.5T permeability varies from 3500 to 5000. 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.

1006 to 1020 Steel Grades (aka Mild Steels, Soft Steels) (57)

They have good magnetic properties and are fairly strong. This folder contains the magnetic properties of 57 of these steels. **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, fully hard. The hardness defines their bendability. For best results, the machined part should be annealed, which can double its permeability. For example, the annealing of 1010 steel can increase its 1.5 T permeability from 585 to 1260.

Their B(H) curves are quite sensitive to annealing temperatures. MagWeb folder contains B(H) curves of 1010 steel annealed at 700, 760, and 815 C. For example, their permeability at 1.5T, when annealed at 700C is 951; annealing at 815C increases it to 1260 – you save 30% magnetizing current. Please see the annealing section for more details.

1020 steel is also machinable, but only heat treatable. It has lower permeability than other grades. Its advantage is the easy availability in a variety of sizes and shapes and ease of machining. The 1.5T permeability of 1020 steel is ~ 500.

INDUSTRIAL STEELS (93)

MagWeb visualizer has B(H) curves for 93 Industrial steel grades (aka structural steels). Their magnetic properties depend on manufacturers. They do not tightly control % C. So their magnetic properties can vary from firm to firm, and within a firm, they can vary from batch to batch. They can also vary in form and size. Other factors include: rolling (cold, hot), annealing (annealed, unannealed), stress (stressed or unstressed), temperatures (high, low). MagWeb visualizer describes several of these effects and assists in the selection of appropriate carbon steels.

Medium Carbon Steels (aka industrial steels)

They have 0.2 to 0.6%C. They are stronger than mild steel grades. The 1.5 T permeability of steels with 0.2% C is ~ 500. But in those with 0.6% C, it drops down to 300. This in turn nearly doubles the current required to push 1.5T flux through the material. This Folder also contains digital B(H) curves of 19 Medium Carbon Steel grades, with about 0.35%C. Of these, 4130, 4140, 4340 steel grades (with the yield strength of 65 ksi) offer 1.5T permeability of 565, 363, and 326 respectively. High strength steel called D6ac steel (with a high yield strength of ~220 ksi) has lower 1.5T permeability of 257.

API Pipeline Steels (10)

These are medium carbon steel pipes (~0.24%C) that carry oil and gas. This folder contains B(H) curves for 10 grades of API Pipeline steels. API specifies their grades as X52, X56, X120, with numerals referring to their minimum yield strength in ksi. They do not have unique chemical composition, so magnetic properties can vary significantly. In these pipe grades, magnetic flux flows easier along the axis than around the periphery. MagWeb lists magnetic properties in both directions; it also documents the impact of stress on their magnetic properties.

MFL (Magnetic Field Leakage) devices are popularly used to detect corrosion cracks in pipelines. They operate by sensing the fringe flux around cracks. To reduce the size of the DC field source and maximize detection sensitivity, they must operate just above the peak permeability point[67]. For example, the MagWeb visualizer shows that the peak permeability point of X52 is ~700 at 0.7T. MagWeb's permeability curves can locate the peak permeability point of other pipeline steels. (In contrast, High Field MFL saturates pipeline steel, reducing its permeability to ~200. This is not far from that of crack (~1), so could reduce its detection sensitivity.

Plain Carbon Steels (aka high strength steels)

Steels with 0.6 to 2%C are also called high carbon *steels.* This Folder contains digital B(H) curves of 19 High Carbon Steel. 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. MagWeb has B(H) curve of a tool steel.

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) large forgings 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, so permeability at 2 T is critical. Their yield strength ranges from 50 to 110 ksi (350 to 770 MPa).

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

Core Loss

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. This folder also contains hard-to-find core loss curves for mild steel in the 1 -250 Hz range.

Skin Depth vs. Thickness

These steels can have unlimited thickness when carrying DC flux. But their thickness should preferably be less than 10 mm when carrying ac flux. (In loudspeakers, they are used to carry low-level flux at high frequencies).

[67] Shi, Y. et al, *Theory and application of magnetic flux leakage pipeline detection*, ***Sensors***, Vol. No. 15, No. 12, Dec. 2015, pp. 31036-31055. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4721765/

Fig. 23 shows a 25 mm diameter motor shaft of low carbon steel 1020 carrying flux axially. At its operating point of 1.5T, 5 Hz, its permeability is 500 and its resistivity is 12$\mu\Omega$ cm. The 5Hz flux flows only in the 4 mm thick skin as shown. Very little flux flows in the 17 mm mid-core. This simply wastes a lot of material and increases eddy core loss.

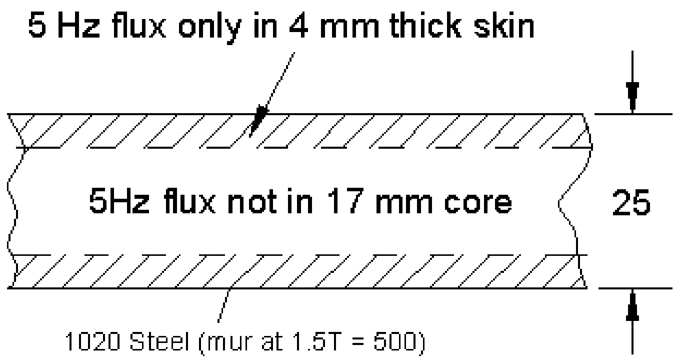

Figure 23. The central core of a thick steel may not carry AC flux

Annealing

The term "Annealing" refers to a process to control microstructure, aiming to improve magnetic properties such as higher permeability or lower core loss. For an introduction on how annealing affects the microstructure and magnetic properties, see Powers[68]. A decarburizing anneal reduces the carbon content. A stress relief anneal reduces mechanical stress. In contrast, "heat treatment" (e.g., tempering, hardening, quenching) aims to improve mechanical properties such as higher mechanical strength or hardness.

Fig. 24 shows how during annealing, thermal vibrations cause carbon atoms to get "squeezed" inside an iron crystal. As a result, crystal structure can change from BCC to FCC or BCT. This alters the microstructure (grain size, texture, orientation of crystals) and hence magnetic and For annealing low carbon steels, one can refer to classic papers by Burrows[69] , Cheney[70] or recent investigations by Stokes[71], Ghodsi[72] Zhetvin[73] list annealing schedules and their impact on magnetic properties. Unfortunately, the annealing schedule differs 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.

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68 Powers, M., Principles for Understanding Heat Treating Materials – Annealing of Ferromagnetic Alloys, https://www.nevadaheattreating.com/principles-understanding-heat-treating-materials-annealing-ferromagnetic-alloys-part-1/

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

70 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

71 Stokes, J. L (1983) Magnetic properties of Iron and low carbon steels for soft magnet application, Naval Weapons Center, TP 6455. https://books.google.com/books/about/Magnetic_Properties_of_Iron_and_Low_Carb.html?id=6FgjOAAACAAJ

72 Ghodsi, M et al (2011) Effect of forging on ferromagnetic properties of low carbon steel, 4th Int. Conf. on modelling, ICMSAO 2011. https://www.researchgate.net/publication/261169945_Effect_of_forging_on_ferromagnetic_properties_of_low-carbon_steel

73 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 https://link.springer.com/article/10.1007/BF00651930

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 980º C. Slow cool in the furnace, stress relief anneal at 537ºC and slow-cool in the furnace to room temperature. MagWeb visualizer contains info on how annealing affects B(H) curves

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

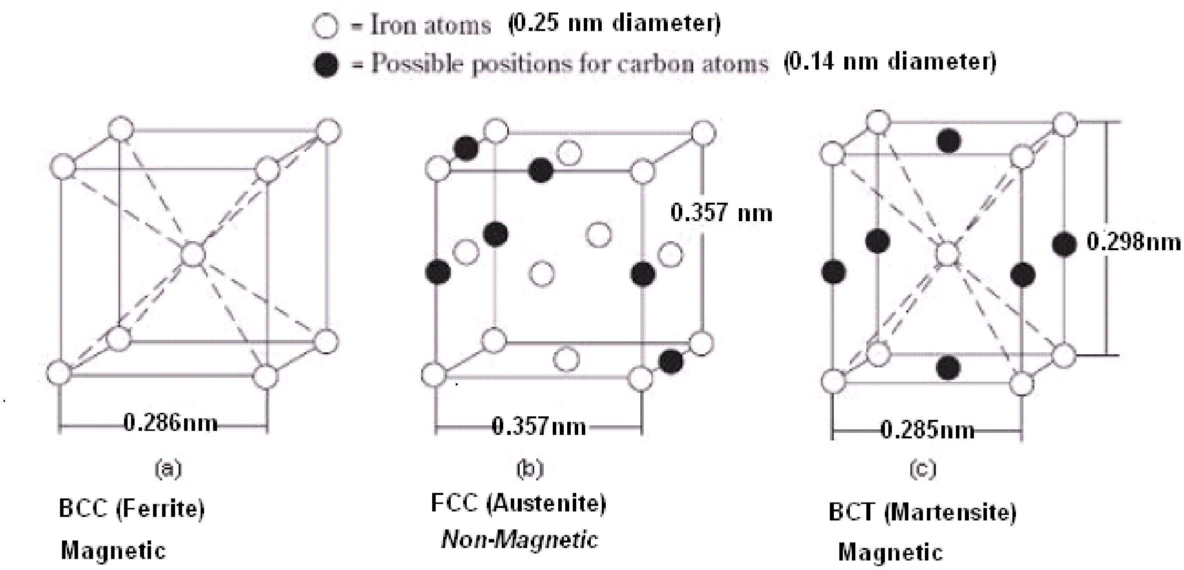

Figure 24. Annealing squeezes carbon atom inside an iron crystal

Electrical Steel. The stress relief annealing furnace can use the 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 hours. With natural gas atmosphere, move the load out of the furnace into a cooling chamber. Allow to cool at any rate while maintaining the atmosphere to 370C or lower before removing the parts. With a Nitrogen atmosphere, maintain the atmosphere and cool at 50 C/hr. to 370C or lower. Below 370C, cool at any rate.

12. H. CASTINGS

***MagWeb's* Castings Folder** has magnetic properties of 39 grades of casting, containing 51 B(H) curves and 2 core loss curves. These include cast steel, gray cast iron, wrought iron, malleable iron, ductile iron, etc. You can compare all curves to discover the manufacturer that produces the grade that is optimal for your machine. For names of all these grades, please go to MagWeb.US, click on *Steels List*.

Castings are made by pouring molten iron into molds. Casting is used to make high-volume large-size parts at a low cost. Casting can make intricate parts with sharp corners 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). Typical applications are engine blocks, machine tool beds, pump bodies, cookware, etc.

Cast Steels

Cast Steels have 0.1 to 0.5%C. 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 with sharp corners. So cast steel parts should have rounded corners.

Further, they also shrink more than cast iron. Since they need more steel, the mold needs 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

Cast Iron has 1.7 to 4.5%C. The most popular version with 2.5 to 4% C and 1 to 3%Si is called Gray Iron, or Gray Cast Iron. This higher %C makes its magnetic properties poorer than cast steel. A wide range of %C and diverse impurities cause considerable scatter in its magnetic properties. In Europe, they are made per EN1561, in the USA per ASTM A48, in Automotives per SAE J431. Fig. 25 overviews the magnetic properties of typical cast irons and cast steels[74].

Trade Name	Class	Structure	Sat. Induction Js Tesla	Resistivity 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

Figure 25. 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 from 25-100. For example, cast iron GJL-250 offers a low permeability of 50 at 1.5T (compared to 300 offered by cast steel). So, they demand a relatively high current (H >10,000 A/m).

[74] 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 than that of cast steel. Since their core loss is higher than electrical steels, they are used at ~ DC.

Their mechanical properties are affected by curve impurities of Si, P, Mn, and S. Si (which can be up to 4%) assists the 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 from 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 from 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 a tensile strength of 150 N/mm2 (22 ksi).

Wrought Iron

It is close to pure iron. Unlike cast iron, wrought iron has only minute carbon (0.08%) and Silicon (0.12%). It also contains curve 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 the 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 the permeability of 600. But in poorer grades permeability may degrade to 200.

Malleable Cast Iron

It is a cast iron in which 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 visualizer 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.

13. I. IRON POWDER CORES + SMC

MagWeb's* *Iron Powder Cores +SMC Folder has magnetic properties of 85 grades of iron powder/SMC cores, produced by 7 manufacturers. It includes both Iron Powder Cores (which use uninsulated iron particles) and Soft Magnetic Composites (which use insulated iron particles). They contain 89 B(H) magnetization curves and 85 core loss curves. You can compare all curves to discover the manufacturer that produces the grade that is optimal for your machine. For the names of these grades, please go to MagWeb.US, click on *Steels List*.

Powder Cores are solids made of fine magnetic powder particles compacted with resin binders. They get rid of the headache of annealing to attain good magnetic properties. But in return, they suffer from lower permeability (usually less than 500 at 1T). Their low core loss at low flux density allows them to operate between 100Hz to 1MHz.

Iron Powder Cores

They use uninsulated iron powders mixed with insulative resins, molded into 2D net shapes under high pressure. They intend to store energy in the distributed gaps formed by an insulative medium. Materials from Fluxtrol, Micrometal, SMP, Hoganas fall into this category. Typical shapes are toroids, E, or I cores. Applications include inductors in power electronics circuits such as switch-mode power supplies, power converters, light dimmers, flyback transformers. Occasionally they are also used as EMI Filters. Their usable flux density is below 0.2 tesla and rarely exceeds 2000 A/m. This keeps copper loss and iron loss in check.

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

Core loss Producers tend to express core loss as mW/cc. MagWeb converts them to w/Kg for a better "feel" for the core loss. For example, a 2 w/kg will be an acceptable loss, and 20 w/kg is simply unacceptable. But if expressed as 1000 mW/cc, one has no idea if it is acceptable or unacceptably high. Their eddy loss is low because of their high resistivity. 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 (SMC)

They use insulated iron powders mixed with resins, molded into 3D net shapes under high pressure. They fall into two types, Low-Frequency SMC and High-Frequency SMC.

Low-Frequency SMC. Their usable frequency ranges from 50 to 2000 Hz for use in electric motors. They intend to transmit flux with low loss, store energy in an air gap. They aim to achieve higher permeability (~400). Such higher permeability hopefully minimizes magnetizing current and hence reduces copper loss. But they do store energy in the gaps between insulated particles anyway. Materials from Hoganas, PMG, Sintex, Accucore fall into this category. They are also brittle and mechanically weak. Manufacturers claim that their core loss is less than that of a 0.5 mm electrical steel at 1T, 50Hz. At present their use as motor cores seemed to be at an experimental stage.

A Material Map displays the materials as points in the Permeability and Core Loss plane. That plot is useful to compare SMC material offerings from different suppliers and select a Superior Grade that offers the highest efficiency for specified performance.

Fig. 26 shows such an 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 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 loses 6.8 w/Kg at 1.5T, 50 Hz, and has a permeability of 140. In contrast, M800-50A loses 6.6 w/Kg but has far superior permeability of 1800. So comparable electrical steel will require an order of magnitude less magnetizing current.

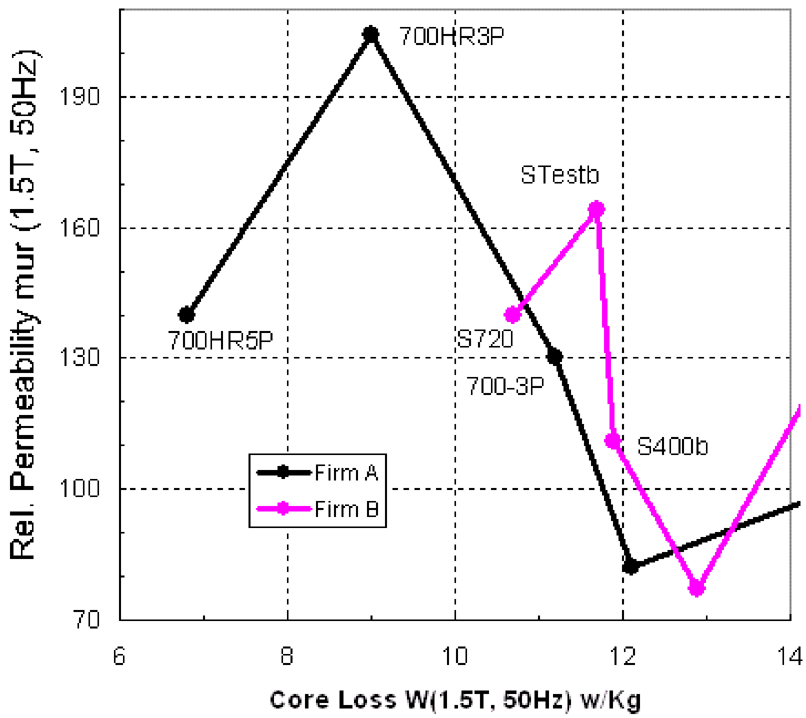

Figure 26. Property Map of SMC at 1.5T, 50 Hz. Firm A offers superior SMC.

High-frequency SMC. They are used in the heat treatment of steels by induction heating. They intend to achieve a higher depth of penetration by low permeability (10 to 30) materials from Fluxtrol fall into this category. Other application targets include speaker cores, fuel injectors, inductors, sensors, etc. Their high cost of tooling limits them to mass-produced parts.

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 is 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 that is similar to MIM, and is also used to make intricate small size soft material parts. Unfortunately, methods to measure magnetic properties for such mall intricate parts are not yet developed. So their properties are not available, so not yet documented in MagWeb.

14. J. ALLOY POWDER CORES

MagWeb's Alloy Powder Core Folder has magnetic properties of 92 grades of alloy powder cores, produced by 3 manufacturers. They contain 28 B(H) magnetization curves and 64 core loss curves. You can compare all curves to discover the manufacturer that produces the grade that is optimal for your machine. For names of all these grades, please go to MagWeb.US, click on *Steels List*.

Alloy Powder Cores are made by pulverizing uninsulated iron-alloy powders, mixing them with epoxy resins, and compressing them 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 them with a variety of alloys. For example, MPP (Moly Permalloy Powder) alloy consists of ~ 2% Molybdenum, 81% Nickel, and 17% iron. It has low core loss up to a few hundred kHz (at low flux densities), but is expensive. Fig. 28 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

Figure 28. Trade Names and alloy powders

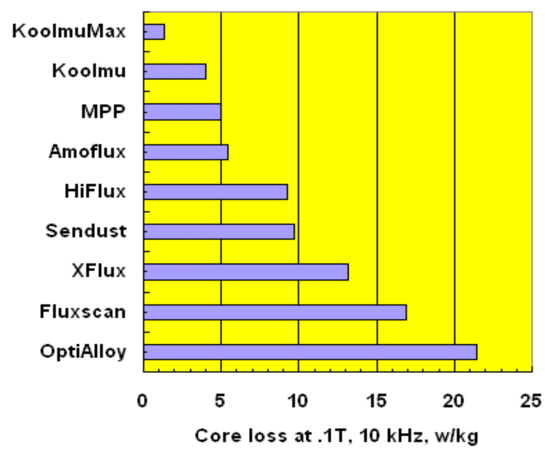

Figure 27. Core loss of various alloy powders

Their trade names also identify initial permeability. For example, HiFlux 125µ refers to one with an initial relative permeability of 125. But curve impurities cause losses to differ with manufacturers, even if they carry the same label. 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 $P = 0.39B^{2.18} f^{1.69}$.

Core loss. Their core loss restricts their use to below 10 kHz, but Sendust can go to 25 kHz. Fig. 27 compares core loss of various powder cores at 0.1T, 10 kHz. The common belief is that MPP cores offer the lowest core loss. But it shows that ***Koolmu-Max*** produces a far lower loss.

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

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

15. K. FERRITE CORES

***MagWeb's* Ferrite Cores Folder** has magnetic properties of 113 grades of ferrites produced by 16 manufacturers. They contain 252 B(H) magnetization curves and 975 core loss curves. You can compare all the curves to discover the manufacturer that produces the grade that is optimal for your machine. For names of all these grades, please go to MagWeb.US, click on Steels List.

Market. Soft Ferrites is a $1.7 B market comprising communication, automotive, LED, and consumer segments. They are used in high-frequency transformers and inductors for diverse circuits such as SMPS, voltage multipliers, etc. Conflicting requirements for a specific application make their sizing fairly complex[75].

Ferrite cores are made of metallic iron oxides (Fe_2O_4) alloyed with non-metallic - either MnZn (Mn_xZn_{1-x}) or NiZn (Ni_xZn_{1-x}). The metallic oxides interact with the non-metallic to produce magnetic properties. Manufacturers press the mixture and fire them in a kiln at very high temperatures. They then machine them to a specific shape. Ferrites are brittle – so have poor mechanical strength. Ferroxcube uses "3" to denote MnZn Ferrites and "4" to denote NiZn Ferrites. They operate in 10-1000 A/m, 0.1-0.5T, 10 kHz to 5 MHz range. Manufacturers report their magnetic properties measured per IEC 62044.

Forms. Ferrites are supplied in several shapes such as toroids, pot cores, bars, squares, rectangles, etc. But they cannot form complex shapes due to shrinkage while sintering. Most cores come in standardized sizes They are generally limited to < 500w, < 100 mm, < 2kg.

Core Loss

MagWeb visualizer displays core loss P in [w/kg]. To convert it into the traditional P_v [mW/cc], multiply P by the density of ferrite γ in gm/cc (typically γ = 4.8 gm/cc). $P_v = \gamma P$.

- **Frequency.** Ferrite is non-metallic. Its high resistivity limits core losses at high frequencies. So they are suited for low power applications at frequencies above 10 kHz. ***MnZn*** ferrites have lower resistivity (0.1 to 10 Ωm), so are used below 1MHz. ***NiZn*** ferrites have higher resistivity (10^4 to 10^6 Ωm), so can be used between 1 to 500MHz.

- **Temperature.** Their resistivity varies with temperature, hence core loss varies with temperature[76]. A "sweet spot" temperature/frequency exists where the core loss attains a minimum. Unfortunately, only a few vendors furnish P (B, f, T) core loss curves, so it is tricky to find such a sweet spot.

- **Duty Cycle.** In SMPS applications, loss in ferrite core depends significantly on duty cycle, limiting flux density to generally below 0.3 T.

- **Saturation Induction J_s.** For ferrites, it is defined as the flux density at H = 1200 A/m per IEC 60401-3. But it is difficult to compare J_s published by different manufacturers use diverse H to measure it[77]. J_s for MnZn ferrites ranges 0.3 to 0.5 T. That for NiZn ferrites is < 0.35T.

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75 Williams A, *Fundamentals of Magnetics Design*, https://www.ieee.li/pdf/viewgraphs/fundamentals_magnetics_design.pdf

76 Ferroxcube, *Soft Ferrites, Introduction,* http://ferroxcube.home.pl/prod/assets/sfintro.pdf

77 Orenchak,G. *Specify saturation properties of ferrite cores to prevent field failure*, http://www.tscinternational.com/tech13.pdf

It reduces significantly with temperature. For example saturation induction of 3C8 reduces from 0.42T at 25C to 0.34T at 100C As a result, one expert[78] suggests that maximum operational flux density B_{max} be $0.5J_s$ below 50kHz, 0.1 J_s above 1 MHz. Ferrites saturate far earlier than alloy powder core, which limits their ability to carry DC bias. J_s can differ greatly in two ferrite cores of the same inductance.

- **Permeability.** MnZn Ferrites offer relatively higher permeability, ranging from 500 to 20,000; they also have higher initial permeability. NiZn Ferrites suffer from a lower range of 10 to 2000. But it changes with temperature, sees above.

- **Complex Permeability**. Some vendors express core loss in terms of *complex permeability* μ^*

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

Here real part μ' relates to stored energy and the imaginary part μ" relates to lost energy. It assumes that when a magnetic material is excited by a harmonic $H(t) = H_o\, e^{j\omega t}$ its response flux density $B(t) = B_o\, e^{j(\omega t-\delta)}$ lags by phase lag δ.

They express core loss as the *loss factor or loss tangent* tan δ is defined by

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

It is the ratio of energy lost vs. vs energy is stored. The inverse of tan δ is called quality factor Q. MagWeb shows such permeability data shaded yellow. The index file shows tan δ shaded yellow.

They furnish complex permeability μ'(f), μ"(f) curves (instead of traditional P(B, f) core loss curves). You can convert these curves into the core loss P_{fe} (w/kg) by using [79]

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

where γ = weight density (kg/m^3) and H_o, J_o denote the operating point at which they are measured. But μ'(f), μ"(f) curves supplied by the vendor are valid only for a fixed flux density J_o, usually 0.25mT. *Using these complex permeability curves to estimate core loss at other flux densities is not recommended.*

- **Stresses**. The magnetic properties of ferrite cores are very sensitive to stresses or shocks. Excessive stresses degrade their permeability. Ferrites are also brittle. So one must ensure that they are not subjected to severe thermal or mechanical stresses.

-

[78] See http://www.engr.colostate.edu/ECE562/98lectures/l27.pdf

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

- **Models.**
  A model fits the core loss P [w/kg] at a given frequency f [Hz], magnetic flux density B [T], and temperature T [C] with a physically feasible interpolating function. Magweb fits core loss with several well-known models. The Steinmetz model

$$P = K_h f^x B^y$$

  is popular in fitting ferrite core loss data. MagWeb software can calculate the resulting Steinmetz coefficients:
  K_h = Hysteresis Loss Coefficient,
  x = frequency index,
  y = flux density index.

  In SMPS, core loss depends on several variables, such as B, f, T, D, μ, σ etc. MagWeb software can also be custom-programmed to calculate coefficients for refined models which include them[80].

Ferrite used above 1 GHz is known as *microwave ferrites.* The chemical composition of microwave ferrites is XFe_yO_z. So, changing values of X, y, z causes their magnetic properties to change, so produce different grades. Garnet Ferrites are used in 1-10 GHz, Spinnel Ferrites in 3-30 GHz, and Hexagonal Ferrites in 1-100 GHz.

Some of these are saturated at 0.04T, others at 0.4T when annealed[81]. Their resistivity is higher than that of conventional ferrites.

Above 1GHz, electromagnetic energy is not transmitted via wires or cores. It is not controlled via switching components such as MOSFETs, diodes, or IGBT nor programmed via software. 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 are 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 the home, auto, and military applications.

[80] Ridley, R. Magnetic Core Loss, APEC 2016, http://www.apec-conf.org/Portals/0/Industry%20Session%20Presentations/2016/1124.pdf

[81] Harris, V.G., *Advances in Microwave Ferrites*, IEEE Trans. Magnetics, Vol. 48, No.3, Mar. 2012, pp. 1075-1104.

16. APPENDIX A. FORMAT OF SMAG VISUALIZER

16.1. Manufacturer Subfolders

Each Category Folder comprises several Manufacturer Subfolders. Its label refers to a specific manufacturer. Example: ‘Hitachi’ subfolder contains data files of all the grades produced by Hitachi Metals Ltd.

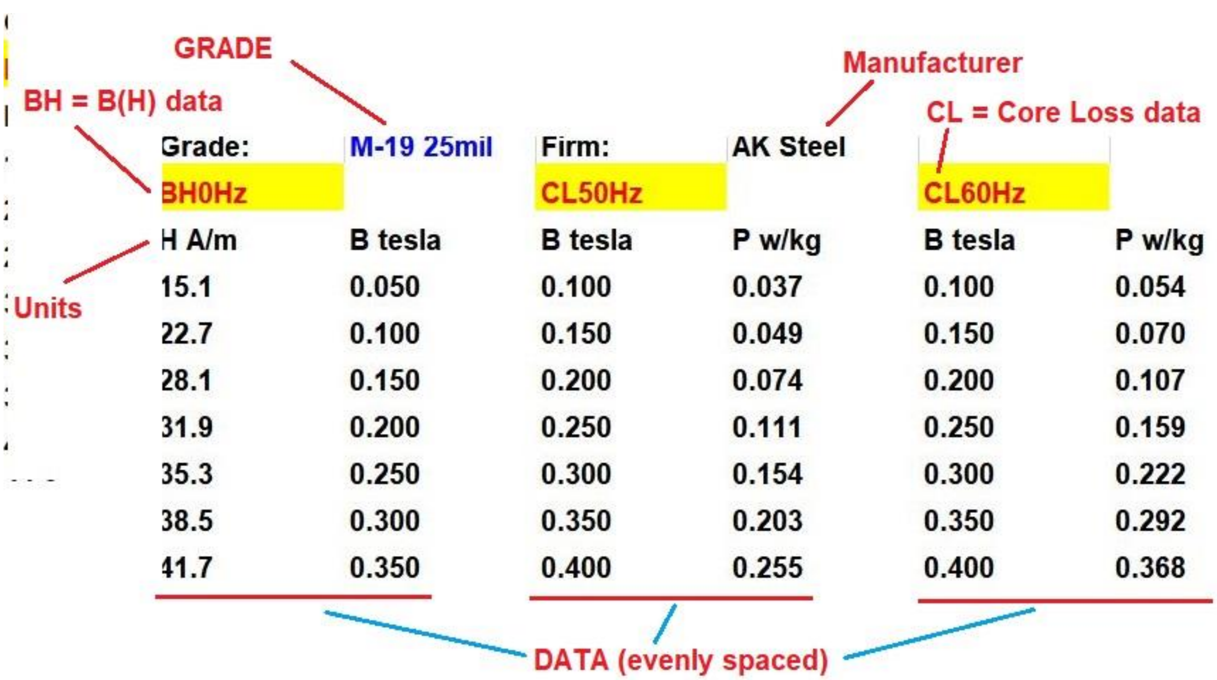
16.2. Grade Files

Each Manufacturer subfolder comprises several Grade Files. Each Grade File is a .xlsx excel file that contains the B(H) and Core Loss curves (at several frequencies and temperatures) for a particular Grade. For example, ‘M-19 14 mil’ contains magnetic properties of M-19 grade produced by AK Steel that is 0.014 inches thick.

Format of Grade Files

Fig. 29 shows the format of curves in a Grade File. In each Grade File,

- Header Row 1: Grade in col. 2, its Manufacturer in col. 4.
- Header Row 2 contains the Data Labels,
- Header Row 3 lists their units. H A/m, B tesla, P w/kg.



Grade:	M-19 25mil	Firm:	AK Steel		
BH0Hz		CL50Hz		CL60Hz	
H A/m	B tesla	B tesla	P w/kg	B tesla	P w/kg
15.1	0.050	0.100	0.037	0.100	0.054
22.7	0.100	0.150	0.049	0.150	0.070
28.1	0.150	0.200	0.074	0.200	0.107
31.9	0.200	0.250	0.111	0.250	0.159
35.3	0.250	0.300	0.154	0.300	0.222
38.5	0.300	0.350	0.203	0.350	0.292
41.7	0.350	0.400	0.255	0.400	0.368

Figure 29. *Format of SMAG visualizer. Header Row1 Lists Grade and Firm. Row2 lists Data Labels. Row 3 lists Units. The remaining rows list data. BH denotes B(H) Data, CL denotes Core Loss Data. Both labels are followed by frequency and/or temperature numerals.*

MagWeb
Magnetic Material Data

Data Labels

The Data Label, highlighted in yellow, defines the type of curve. It also identifies frequencies and temperatures at which it is measured. Its format is:

CVffHzttC

where
CV = type of curve. CV = BH for B(H) Curve ; CV = CL for Core Loss Curve
fffHz = frequency numerals followed by 'Hz'
ttC = Temperature numerals followed by ' C'

Example: **BH50Hz**- B(H) Data at 50Hz.

Data

All data are spaced at intervals of 0.05T. T**he last point of measured data is shown** with 4 decimals. It displays other (H, B) points to 3 decimals.

16.3. DIGEST File

The DIGEST Is a single searchable excel file. It lists magnetic properties for all grades (in a category) at a single data point in 13 columns A to M.

A to D: Material Descriptors (manufacturer, country, material category, and material name).
E to I: Test Conditions (thickness, units, annealing, frequency, and temperature).
J to M: Magnetic Property Data Point:

For Core Loss:
Flux Density B, Core loss P(B, f), Resistivity, Density.
For B(H) Curves:
Magnetic Field H, Flux density B(H, f, T), Permeability and Saturation Induction.

17. ELECTRICAL MACHINE DESIGN SOFTWARE

The table below lists all **Finite Element Magnetic field software** used to design electric machines. Table **(A) l**ists **Free Software (which uses mostly 2D FEM)** and Table **(B)** lists **Commercial FEM Software (which uses mostly 3D FEM)**. It also lists Motor-specific and Inductor-specific software. Many have only a few B(H) or core loss curves. If you need assistance in choosing software, please contact: rao@magweb.us

MagWeb
Magnetic Material Data

	(A) FREE SOFTWARE		
	Software	Firm	Website
1	FEMM, XFEMM	FEMM, USA	femm.info/wiki/Download
2	JMAG express	JMAG	Express.jmag-international.com
3	EMETOR	Emetor, USA	emetor.com
4	MotorAnalysis	VepcoTech, Russia	motoranalysis.com
5	KOIL	Free Univ, Italy	Koil.sourceforge.net
6	MAXFEM	Univ. Santiago	usc.es/en/proxectos/maxfem/download.html
7	FEMAG	ETH, Switzerland	elmocad.de profemag.ch
8	POISSON	LANL, USA	laacg.lanl.gov/laacg/services/download_sf.phtml
9	VIZIMAG	VIZIMAG, USA	vizimag.software.informer.com/3.1
10	ELMER	CSC, Finland	https://sourceforge.net/projects/elmerfem/
11	GETDP	GETDP, Finland	http://onelab.info/wiki/GetDP
12	SYRE	C. Lu	https://sourceforge.net/projects/syr-e/
13	SMEKLIB	Antti Lehikoinen	https://www.linkedin.com/pulse/smeklib-released-antti-le
	(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	FEMTET	Murata, Japan	https://www.muratasoftware.com/en/
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