ABSTRACT

Whether you are designing a traction motor for electric vehicle, wind generator, transformer or loudspeaker, your product is only as good as the soft magnetic material that you employ. For optimal design, you need to identify the top grade that best suits your specific product requirements. Choosing the right top grade gives you the competitive edge.

A magnetic material is like a cake. It is made by each factory with its own secret recipe ingredients and method of manufacture. So even if two magnetic materials carry the same name, their properties differ with manufacturers. So, searching for the best-quality manufacturer is an amazingly non-trivial task.

So far, lack of a comprehensive magnetic material database prevented you from identifying the top grade and its manufacturer. MagWeb’s encyclopedic Soft Magnetic Material Database compiles the properties of all grades of magnetic materials produced by all manufacturers worldwide. Such single source places data of all magnetic materials at your finger tip, saving you considerable search time.

Till now, the magnetic properties were available only as continuous curves in pdf or picture files. They need to be digitized before inputting into electric machine design software. MagWeb has developed proprietary tools to digitize them with minimal digitization noise. Entering this data will eliminate any numeric instabilities that can be caused by digitization noise.

MagWeb database presents these digital data as excel files. Each file contains digital magnetization curve, permeability curve or core loss curves. This version 5 contains ~ 3000 excel files of digital magnetic properties of diverse materials.

In summary, the noise-free digitized data from MagWeb can be inputted directly into your machine design software. It will save you hundreds of hours of data search time. You will be able to accelerate the simulation time for assess how a change in the steel grade impacts the performance of your product. It will help you to quickly discover the top grade that maximizes the performance.

DISCLAIMER

The MagWeb handbooks are the result of multi-decade effort to compile hard-to-find magnetic property data from open source publications. They include scientific literature, manuals, handbooks, textbooks, websites, federal databases, university records, old archives, manufacturer's catalogs etc. MagWeb believes the data to be accurate and reliable. It is intended to support the user in making informed decisions on magnetic materials. MagWeb does not provide any warranty or support. MagWeb is not liable, for any damages caused by using its database, whether explicitly or implicitly. The sources and methods used to derive/digitize the MagWeb data are confidential and proprietary. MagWeb reserves the right to change the data without notice.

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1. INTRODUCTION

1.1. What is MagWeb?

Soft Magnetic Materials are those which permit large AC magnetic flux to flow easily with acceptable heat dissipation. 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 multiMW generators that produce electricity, to transformers that bring it to your home, to the car you drive to your office – all of them use magnetic materials.

But whether you are designing a traction motor for hybrid vehicle, a wind power generator or a loud speaker - your product is only as good as the magnetic materials that you choose. MagWeb database will help you in making the right choice.

From your past experience, you might have in mind few candidate steels. Then you face the daunting task of comparing their magnetic properties\textsuperscript{1,2}.

Properties of magnetic material are characterized by three curves – Magnetization Curve, Permeability Curve and Core Loss Curve. They are called B(H), \( \mu_r(H) \), \( P(B, f) \) curves respectively. All of them need to be considered simultaneously. MagWeb contains all these curves at one place, simplifying the selection process.

The B(H) magnetization curve plots magnetic flux density response B (Tesla) of the material vs. applied magnetic field intensity H (A/m). Here H is the amp turns (mmf) per unit length of the magnetic circuit. Relative Permeability \( \mu_r = B/\mu_0 H \) characterizes how the material multiplies the vacuum flux density \( \mu_0 H \) (i.e. if it is replaced by air), \( \mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2 \). The \( \mu_r(H) \) relative permeability curve plots relative permeability \( \mu_r \) with H. The core loss curve \( P(B, f) \) plots the core loss or heat P (w/kg) dissipated by the material while carrying alternating flux of density B at frequency f Hz.

Generally, steels with lower core loss produce higher efficiency. \textbf{But lowest core loss does not guarantee highest efficiency!} For example, Fig. 1 compares the results of a study\textsuperscript{3} on effect of core loss of a steel on efficiency of a brushless motor. It shows that a steel with lower core loss (grade 50JNA300 with maximum specific core loss \( W_{15/50} = 2.63 \text{ w/kg at } 1.5T, 50\text{Hz} \) produces efficiency of 89%. In contrast, this study puzzlingly shows that another steel with higher core loss (grade 50JN400, \( W_{15/50} = 2.86 \text{ w/kg} \)) produces higher efficiency of 89.5%. This shows that a lower loss steel does not necessarily produce higher efficiency!

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


Electrical steels add Silicon. This increases its electrical resistance, thereby reduces core loss. Instead, the act of adding Silicon also increases its magnetic resistance. This reduces permeability, hence demands more current to produce same flux. So steels with more silicon reduce core loss, but demand more current (to attain same flux) which increase the copper loss\(^4\).

Thus, to maximize efficiency, it is vital to minimize the magnetizing current in addition to minimizing core loss. In fact, experts say that there is a sweet combo of core loss and permeability (i.e. optimal Si content) that maximizes efficiency\(^5\).

So far, absence of a comprehensive property database has prevented one from discovering such sweet combo. MagWeb’s exhaustive listing of core loss curves, permeability curves and B(H) curves will help you locate such sweet combo material for your specific application.

1.2. MagWeb Database Files (2963)

MagWeb groups all soft magnetic materials\(^6\) into 11 Material Categories. Table 1 lists the 11 folders and the number of B(H) and Core Loss files they contain. For example, the Electrical Steel (NGO) Folder has 1223 files, of which 634 carry B(H) curves, 589 have Core Loss Files.

Table 1. Soft Magnetic Material Files in MagWeb (2963)

<table>
<thead>
<tr>
<th>Category</th>
<th>MagWeb Folder</th>
<th>B(H) Curves</th>
<th>Core Loss Curves</th>
<th>Total Files</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Electrical Steel - Non Grain Oriented</td>
<td>634</td>
<td>589</td>
<td>1223</td>
</tr>
<tr>
<td>B</td>
<td>Electrical Steel - Grain Oriented</td>
<td>221</td>
<td>190</td>
<td>411</td>
</tr>
<tr>
<td>C</td>
<td>Metglas &amp; Nanocrystalline</td>
<td>30</td>
<td>26</td>
<td>56</td>
</tr>
<tr>
<td>D</td>
<td>Cobalt Steel</td>
<td>51</td>
<td>192</td>
<td>243</td>
</tr>
<tr>
<td>E</td>
<td>Nickel Steel</td>
<td>121</td>
<td>72</td>
<td>193</td>
</tr>
<tr>
<td>F</td>
<td>Stainless Steel</td>
<td>49</td>
<td>0</td>
<td>49</td>
</tr>
<tr>
<td>G</td>
<td>Carbon Steel</td>
<td>179</td>
<td>3</td>
<td>182</td>
</tr>
<tr>
<td>H</td>
<td>Castings</td>
<td>51</td>
<td>1</td>
<td>52</td>
</tr>
<tr>
<td>I</td>
<td>Iron Powder Core +SMC</td>
<td>89</td>
<td>85</td>
<td>174</td>
</tr>
<tr>
<td>J</td>
<td>Alloy Powder Core</td>
<td>28</td>
<td>64</td>
<td>92</td>
</tr>
<tr>
<td>K</td>
<td>Ferrite</td>
<td>88</td>
<td>200</td>
<td>288</td>
</tr>
<tr>
<td></td>
<td>Total Files in MagWeb</td>
<td>1541</td>
<td>1412</td>
<td>2963</td>
</tr>
</tbody>
</table>

\(^6\) 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

In the MagWeb database, a Folder Symbol (A to K) identifies a material category. Each material category folder contains a B(H) Magnetization Curve subfolder and a P(B) Core Loss Curve subfolder. Each of them contain several manufacturer subfolders. Each manufacturer subfolder contain hundreds excel files. Each excel file contains properties of a material grade produced by that manufacturer.

A B(H) file contains both B(H) magnetization curve and \( \mu_r(H) \) Permeability Curve of one grade. A Core Loss File contains up to six P(B) Core Loss Curves at various frequencies for one grade. Each curve is digitized by up to 200 data points.

2.1. **B(H) Curves**

Fig. 2 shows a typical B(H) curve from MagWeb. This curve is for M250-35A grade. It is measured by the manufacturer as locus of tips of a series of hysteresis loops. It has a characteristic knee. Its slope permeability (aka differential permeability) \( B' = dB/(\mu_0 dH) \) increases with H first, reaches a peak at a point of inflection Q and then decreases\(^7\). This point is a source of computational instability\(^8\) (see 2.3). MagWeb’s B(H) data can identify such sore point. Its digital data can allow you to overlay B(H) curves of several candidate materials, so you can spot a better grade.

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2.2. Permeability Curves

The relative permeability $\mu_r$ is as important as $B(H)$ curve. It is reciprocal of magnetic resistance. In a highly magnetically resistive material $\mu_r$ can be close to 1. In a magnetically conductive material it can be as high as 100,000. MagWeb plots also show permeability curve (pink). It shows that, as $H$ increases, the relative permeability also increases first. It then reaches a peak $P$ (around the knee region). Further increase in $H$ causes permeability to decrease. A very large value of $H$ saturates the material, and it behaves more like air.

**Permeability at Rated Point.** The permeability at the operating point $\mu_r(B_o,f_o)$ ($B_o$ is the average flux density in tooth and $f_o$ is the electrical frequency) is an important metric to discover a better grade. *MagWeb* lists permeability data, so you can compare this permeability for several candidate grades. Discovering a grade with highest permeability helps you get your flux density $B_o$ with least current.

For example, consider grades carrying same label of “M250-35A”, produced by two different firms A and B for a machine operating at 1.5T, 50 Hz. MagWeb’s database showed that 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 produces 1/5th of respective copper loss! So MagWeb’s database helps you to discover that firm A’s grade is a preferable choice, in spite of both grades carrying the same label (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 highest peak permeability. Operating a shield at this point will minimize the thickness of shield and maximize the shield effectiveness. The permeability table in the *MagWeb* database will help you estimate the peak permeability produced by a grade. Using Magweb to compare peak permeability of two grades will help you discover a better magnetic shield.

2.3. Slope Permeability Curves

The slope permeability is the local slope of $B(H)$ or $J(H)$ curve,

$$B' \equiv \frac{1}{\mu_r} \frac{dB}{dH}, \quad J' \equiv \frac{1}{\mu_r} \frac{dJ}{dH}$$  \hspace{1cm} (1.1)

It is listed in col. 4 of the MagWeb database. This column can reveal the point of inflection $Q$ (it correspond to peak point on $B'(H)$ curve). It can be used to avoid computational instability (caused by an inflection point). It also can indicate as to how far a point is from saturation.

Digitization represents a curve by a set of discrete digital data points. But during manual digitization by eyeballing, one can pick points that are slightly offset from the midline of a $B(H)$ curve. This introduces sharp changes in its slope, called digitization noise.

To detect digitization noise, one needs to plot the slope permeability curve $B'(H)$. The $B'(H)$ curve for a digital $B(H)$ data that is free of digitization noise will have only one peak, corresponding to point of inflection. That for a digital $B(H)$ data that is corrupted by digitization noise will contain multiple peaks. For example, Fig. 5 plots $B'(H)$ of M250-35A grade of two firms A and B. The digital $B(H)$ data furnished by them is used to create this plot. It reveals that the $B'(H)$ curve for firm A has multiple peaks, while that from firm B has only one peak. From this, one discovers that that the digital $B(H)$ data from firm A suffers from digitization noise, while that from A has none.
A B(H) data corrupted by digitization noise confuses the Newton method used by FEM software to interpolate data. The computer struggles to find the real peak point that is buried within multiple peaks created by digitization noise. This slows convergence, increasing computer time. The solver may fail to converge, or cause numerical instability. To avoid such convergence issues, one obviously should input noise-free B(H) data into software.

Over past several years, MagWeb developed several proprietary tools that create noise-free B(H) data. Such noise-free B(H) data will prevent computational instability issues.

2.4. Core Loss Curves

It is well known that core loss varies with flux density and frequency. But not so well known is that it also varies with manufacturer. Each firm has its own secret recipe composition and method of manufacture, so their properties are different (see section 3) - even though they carry similar sounding grade labels. MagWeb database contains thousands of core loss files for all grades made by different manufacturers. By comparing their core loss property curves, it can help you discover the manufacturer that produces 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. Depending on the cooling method, the acceptable core loss can vary from 5 to 15 w/kg. From this perspective, for electrical steels, MagWeb offers core loss curves up to 10 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

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10 To avoid inflection-related convergence issues, some FEM software simply eliminate the inflection point. They modify measured B(H) data by one with constant slope below inflection point. But obviously it leads to large errors for machines operating below inflection point. See e.g. https://www.imag-international.com/library/imag_atoz/03.html or https://www.emetor.com/blog/post/influence-b-h-curve-convergence-finite-element-solution/
available up to 25 kHz. For Ferrites they are available up to ~1GHz or more. Each file can have core loss curves at several frequencies.

Typically, HEV traction motors require an electrical steel that can carry 1T at 400 Hz and dissipates lowest possible heat\(^{11}\). Assume that the designer is looking for a steel that produce less than 5w/kg at this operating point. A quick scan shows that MagWeb’s DIGEST has about 90 electrical steels with properties at 400 Hz. It discovered that the top grade (from Japan) offers lowest core loss of 5.5w/kg while a poorest steel from China produces 62 w/kg. But this top grade is only 0.1 mm thick, which is considered too thin. Re-scanning the DIGEST for 0.2mm thick steels narrows the search to six 0.2mm thick steel offerings from USA, Europe, Japan and China - but the core loss doubles to 11 w/kg. One can download the NGO folder to discover the top grade meeting your requirements in this fashion.

2.4.1. Inflection Point in Core Loss Curves

Review of the MagWeb database discovered that, for electrical steels at line frequencies, the core loss curves have an inflection point. In them, as the flux density B increases, the slope \(P'(B) = \frac{dP}{dB}\) increases at first. But it attains a peak at a certain flux density. Then the slope falls as flux density increases further. The flux density point P at which the slope reaches a peak is the inflection point.

For example, Fig. 3 shows the core loss curve \(P(B)\) and core loss slope curve \(P'(B)\) for M-19 steel at 50 Hz. It indicates that as flux density increases the slope initially increases. But it reaches a peak at the inflection point P as shown. **Beyond this inflection point P, the slope \(P'(B)\) decreases as flux density B increases.**

MagWeb’s database reveals that this inflection point ranges 1.3 to 1.9T, depending on manufacturer and grade. For M-19, the inflection point is at 1.5 T.

\(^{11}\) Emadi, A. Advanced Electric Drive Vehicles, p.130. CRC 2015

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**Figure 4. Core Loss Curve also have an Inflection Point**
Over past 100 years, fertile minds - from Steinmetz\textsuperscript{12} (in 1900’s) to Bertotti\textsuperscript{13} (in 1990’s) to Ionel\textsuperscript{14} (in 2010’s) - have struggled to develop core loss models that can calculate core loss at any point, by fitting a physics-based interpolating function to the measured core loss data. For example, a popular Bertotti’s model expresses the core loss as sum of hysteresis loss, eddy loss and “excess or anomalous loss” components,

\[ P = K_h f B^m + K_e (f B)^2 + K_a (f B)^{1.5} \ldots \quad (1) \]

Its slope \( P'(B) \) is,

\[ P'(B) = mK_h f B^{m-1} + 2K_e f^2 B + 1.5K_a f^{1.5} B^{0.5} \ldots \quad (2) \]

The Bertotti model expects that all coefficients \( K_h, K_e, K_a \) and, \( m \) to be positive. But if all are positive, its slope \( P'(B) \) will increase \textit{monotonically} as flux density \( B \) increases. Thus the Bertotti model did not foresee the point of inflection. In a similar fashion, other core loss models proposed so far are not “perfect” in the sense that they do not expect an inflection point\textsuperscript{15}.

As a result, their predictions beyond inflection point might be in error. But just like the mislabeling error, this inflection error can be small and ignorable for most cases.

\subsection*{2.4.2. Other Limiting Factors}

Actual core loss in a machine is affected by following factors

- \textit{Design} (Flux density \( B \), Frequency \( f \), thickness, sharp corners, coating material/thickness, steel manufacturer)
- \textit{Manufacturing} (annealing, stresses, VPI, cutting, burrs, welding, voids, bare spots, clamping pressure)
- \textit{Operational} (temperature, flux direction, pwm harmonics).

Burrs may short the laminations, thereby increasing core loss. Cutting creates residual stress affected zones (SAZ) or heat affected zones (HAZ) around the cut edge. The volume of SAZ/HAZ influences degradation. Core loss also depends on cutting method - EDM, laser, or punching. Sharp cutting edge produces smaller SAZ/HAZ, so are better. Gavrila\textsuperscript{16} showed that water-jet cutting produces lowest core loss, but per Bayratkar\textsuperscript{17} it produces highest core loss. Weld only in areas where flux flows in opposite directions.

\textsuperscript{15} An exception is the Fractional Polynomial model developed by Armco in 60’s, which does predict the inflection point.
\textsuperscript{16} Gavrila, H. et al, Magnetic characteristics of nonoriented Silicon iron strips obtained through mechanical, laser, electrical discharge and water jet cutting technologies, \url{http://www.agir.ro/buletine/2291.pdf}
MagWeb database documents the impact of design factors (manufacturer, thickness, flux density, frequency, thickness) on core loss mostly. It also documents the effect of manufacturing and operational factors wherever available.

**Coating.** All electrical steels develop a tightly adherent oxide coating (often called as C-0) during manufacture. In addition, they apply a thin coating (classed C-1 to C-6) that barely covers surface blemishes. This coating increases surface resistance but really is not insulative. 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 special order).

### 2.5. Saturation Induction

The magnetic flux density $B(H)$ is often split into a ferric flux density $J$ (that is carried by the “magnetic material” alone) plus vacuum flux density $\mu_0 H$ (that is carried by “vacuum” alone),

$$B(H) = J(H) + \mu_0 H \quad .. \quad (3)$$

J is also known as Intrinsic Flux Density $B_i$, Magnetic Induction, Magnetic Polarization etc.

![Graph showing Magnetic Flux Density B and Ferric Flux Density J](image)

**Figure 5. Magnetic Flux Density B increases linearly with H. But Ferric Flux Density J saturates to $J_s$. MagWeb lists $J_s$ whenever available.**

Fig. 4 shows the difference between $B(H)$ and $J(H)$ curves. Intuitively, as one increases H, more and more grains get “saturated”. As H tends to infinity, ferric flux density $J$ converge to a theoretical limit, called **Saturation Induction $J_s$**. Saturation is characterized by the slope of the magnetization curves. At very large H,
• The J'(H) slope permeability tends to 0.
• The B'(H) slope permeability tends to 1.
• The ferric flux density J(H) curve tends to J_s.
• The magnetic flux density B(H) curve increases linearly, B(H) = J_s + \mu_o H.

MagWeb lists the saturation induction J_s in its B(H) Property Digest file when it is available. Some designers consider a material to saturate if a 10% increase in B demands a 50% increase in H, i.e. J'(H) = 0.2. The data in J'(H) column allows one to judge if the material saturated by examining if J'(H) > 0.2 point is reached. Also, J_s degrades with temperature. Magweb supplies the temperature degradation profile J_s(T) whenever it is available.

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

International standards require\(^\text{18}\) magnetic properties to be measured as J(H) curve. All Electrical Steel Manufacturers supply such Ferric Flux Density J(H) curve. Unfortunately, most mislabel their J(H) curve as B(H) curve. Some (e.g. Nippon, Bao) add ‘B-H” label to the curve to clarify this. Even the legendary Steinmetz, Froelich and ASTM use “B” when they meant “J”. Such mislabeling has oft-ignored consequences.

Thus design software needs B(H) curve to be inputted. But most manufacturers supply J(H) curve instead. When designers enter the mislabeled J(H) data as B(H) data into their design software, a mislabeling error occurs.

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 actually refers to magnetic flux density B = 1.8125 T. The mislabeling error \(\varepsilon_{BJ} = (B-J)/J\) is ~0.7%.

Most machines normally operate at H<10000 A/m. So this mislabeling error is small and ignoring it does not greatly harm the design. But it becomes significant if it operates in overflxed mode. When overflxed (aka near-saturated), the machine operates beyond the last measured data point where \(H > 100 \text{ kA/m} \) or \(B > 2.1\text{T}\).

Overflxing can occur in traction motors in electric vehicles during short duration peak torqueing, or in multiMW generators\(^\text{19}\). Then the mislabeling error can be 10% or more. Then inputting J instead of B leads to erroneous flux density predictions. In improperly designed machines, core failure can occur in flux concentration areas such as sharp corners of tooth or slot, or in core-ends. So, to design against core failure one should convert the measured J to B, and enter such B(H) data.

Each software uses its own secret algorithm to extrapolate B beyond the measured data. True extrapolation needs J_s - but no software requires it to be inputted! So a software’s ability to calculate accurately the flux density during overflxing depends on its ability to hit J_s, without knowing what it is. This holy grail issue of extrapolation to saturation can best be conquered by inputting a Large-H measured data point \((B_{so}, H_{so})\) with \(H_{so} >100 \text{ kA/m}\). Corresponding J_{so} should be as close to J_s as possible.

\(^{18}\) J is related to magnetization \(M\) by \(J = \mu_o M\), (or \(J = \mu_o \rho M\) if \(M\) is in Am\(^2\)/kg, where \(\rho = \text{mass density}\).

2.7. Other Properties

**Residual Flux Density** $B_r$. When excitation is remove, some of the magnetic domains retain a degree of orientation relative to the applied magnetic field $H$. $B_r$ is the point of intersection of $B$-axis in a hysteresis loop generated when a material is subjected to a field with amplitude $H$. $B_r$ increases with amplitude $H$. It "saturates" to a specific value. This value at saturation is usually called $B_r$.

Materials with high $B_r$ can act like magnets and attract iron dust particles, and the clinging dust is known to increase core loss. Current transformers will saturate sooner than expected if $B_r$ is excessive (Typically it is $\sim$30% of Saturation). For Pure iron and dead soft 1010 steel, $B_r = 1.25$T; for 1020, it can be 0.74T.

**Normal Coercivity** $H_c$ is the point of intersection of hysteresis loop with the H-axis. 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 $H_c$. High $H_c$ normally points to a material with high hysteresis loss.

Both $B_r$ and $H_c$ are an order of magnitude lower for soft magnetic materials than permanent magnets. For pure iron and dead soft 1010 steel, $H_c = 150$A/m. For 1020, it can double to 300 A/m. For electrical steel, coercivity $H_c$ ranges 40 to 100 A/m at 0Hz.

2.8. Format of MagWeb Database

A BH file of MagWeb database contains BH curve, permeability curve or Core Loss data. B(H) data is listed in $H$ [A/m], $B$ [tesla], $\mu$, [ ]. $B'$ format. This format will be transitioned to one with $J$ [Tesla] added for clarity. MagWeb stores data with 8-decimal digits, but displays only 2 or 3 decimal digits. If greater accuracy is needed, one can display the hidden decimal digits using excel.

Each file name contains following information: The commercial name, thickness. The test parameters at which data is measured (flux density, frequency, temperature, time, stress etc.). For example, the file “Hiperco50 @500C for 2000 Hr; 300 to 2000 Hz” presents 6 core loss curves for Hiperco 50A material (that is kept at 500 C for 2000 Hr age), spread over 300 to 2000 Hz range.

In addition, Top two rows contain material descriptors that lists manufacturer, brand name, thickness, and annealing condition. Their format is shown below.

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

<table>
<thead>
<tr>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>C9</th>
<th>C10</th>
<th>C11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Steel GO</td>
<td>Posco, South Korea</td>
<td>Posco</td>
<td>0.009</td>
<td>0.25</td>
<td>Fully Processed</td>
<td>DC</td>
<td>2.020</td>
<td>2.083</td>
<td>B002</td>
<td></td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Brand</td>
<td>gage</td>
<td>inch</td>
<td>mm</td>
<td>Annealing</td>
<td>Hz</td>
<td>BsatMS/m</td>
<td>Curve</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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2.9. **DIGEST File lists all materials**

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.
3. DISCOVERING A TOP GRADE

Most manufacturers and distributors furnish *cross-index tables* of equivalent grades\(^{21}\) from other firms. A grade is said to be “equivalent” (from *standards perspective*) if they are of same thickness and produce same maximum core loss. This may give you the impression that all equivalent grades (produced by different manufacturers) are interchangeable. They are not!

It is well known that the core loss and permeability characteristics of a grade influence the efficiency and performance (torque capacity) of a machine. But MagWeb database found that these characteristics of “equivalent” grades vary with manufacturer\(^{22}\). As a result, even if two grades are equivalent (from standards perspective), a machine’s efficiency and performance will vary with the manufacturer of the grade. That is, they are not equivalent from *performance perspective*.

In fact, next section presents few examples of how MagWeb database can be used to find (within equivalent grades) the top grade that offer lowest core loss, highest flux density or permeability. It will show that there is no manufacturer produces a steel with highest flux density and lowest core loss. It shows that ranking of a grade depends on the machines’ operating range of flux density and frequency.

MagWeb lists the property curves for all grades produced by each manufacturer. Such firm-based database will help you to evaluate how “equivalent” grades from different manufacturers change the efficiency and performance of your machine. The exhaustive Magweb database helps you to identify the top grade (and its manufacturer) which can yield the best efficiency/performance of your machine.

### 3.1. Lowest Core Loss (NGO)

Fig. 7 overlays the core loss curves of M-15 grades at 50Hz, produced by 4 manufacturers. These are AK Steel (M-15), Cogent (M250-35A), Voestalpine (HP250-35A) and POSCO (35PN250). All these steels are 0.35 mm thick and produce same maximum core loss of 2.5 w/kg. They are listed as *equivalent grades* by Cogent\(^{23}\). MagWeb’s database is used to generate this overlay plot.

From this, MagWeb database found that the core loss of a top grade can be 30% lower than that from a “worst” grade. It revealed that POSCO’s grade produces lowest core loss above 1.45T. It also found that, below 1.45T, Voestalpine’s grade produces lowest core loss. Thus It can be seen that the that produces lowest core loss depends on the operating flux density. The MagWeb database discovered that AK Steel’s grade might offer highest core loss, hence lower the efficiency. But this may not be valid for all grades. MagWeb database can be used in this fashion to discover the lowest core loss producer of other equivalent grades.

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\(^{21}\) example: Cold Rolled Grain Oriented Electrical Steel produced by Bao Steel, China for international market, mmriii.com


\(^{23}\) Cogent, *Comparison of Grades and Standards*, p. 62 in https://cogent-power.com/downloads
3.2. Lowest Core Loss (GO)

Fig. 8 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 database is used to generate this overlay plot. It shows that, within same grade, the core loss varies by as much as 30%! This in turn causes a grade from one firm to offer higher efficiency than others.

Thus MagWeb database found that Cogent produces lowest core loss below 1.85T. But above 1.85T, it found that ATI’s M-6 produces lower core loss. So use the MagWeb database at the rated operating point of your machine to discover lowest core producer.
3.3. Highest Flux Density

Fig. 6 overlays the B(H) curves of steels of M-19 grades, produced by 3 manufacturers. These are AK Steel (M-19), Nippon Steel (50H310), Cogent (M310-50A). All these steels are 0.5 mm thick and guaranteed to produce same maximum core loss of 3.1 w/kg at 50 Hz. So they are listed as equivalent grades by Beckley. MagWeb’s database is used to generate this overlay plot.

Thus MagWeb database found that B(H) curves of these “equivalent” grades are significantly different. It found that the variance in B increases with H. It also found that AK Steel’s grade produces highest flux density. But this may not be true for all grades. MagWeb database can be used in this fashion to discover the highest flux density producer of other equivalent grades.

### 3.4. Highest Permeability

Fig. 9 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. The data from MagWeb database is used to superimpose them on the same scale.

It shows that their peak permeabilities are 8284, 6294,6059 and 6035 respectively. Thus the peak permeability of the top grade is 27% higher than the poorest one. MagWeb database found that peak permeability occurs at different flux densities. It also found that AK Steel produces steel with highest permeability.

Example B: Consider NO20 grade electrical steels produced by three European Firms P, Q, R. MagWeb database revealed that, at 1.5T/50 Hz, their permeability is 2150, 1103, 455 respectively. It found that permeability of equivalent grade steels can vary by as much as 80%. Thus to produce 1.5 T, they require magnetizing currents of 555, 1082, 2620 A/m respectively.

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Thus the MagWeb database found that the NO20 steel produced by firm P requires only 1/5th of the magnetization current needed by the poorest firm R. So corresponding copper loss will be 1/25th of firm R. So steel from this manufacturer can produce higher efficiency than others.

Example C: Consider M250-50A grade electrical steel produced by two manufacturers. The MagWeb database 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 grade needs ~40% lower magnetizing current.

All these examples illustrate how to use the MagWeb database to discover a grade that offers highest flux density, permeability or core loss. Such due diligence investigation can improve the performance or efficiency of your machine.

3.5. Lowest Anisotropy

Orientation Angle $\alpha$ between flux and the Rolling Direction (RD) influence 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. Unfortunately, even in NGO steels, this anisotropy also varies greatly from firm to firm.

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

Figure 9. Permeability of Equivalent Grade steels vary with manufacturers.
\[ T = \frac{P_1 - P_2}{P_1 + P_2} \]

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, anisotropy varies greatly with manufacturer. Steel from one manufacturer can have 6\% anisotropy while equivalent grade from other 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, minimum\(^{26}\) occurs at 90\°.

Fig. 10 (reproduced from MagWeb database) shows how the angle \( \alpha \) affects B(H) curve of NGO steel. For similar data, see “M-6 and M-19 Effect of Angle” excel file.

![M330-50A Anisotropy](image)

**Figure 10. Magnetic Properties of NGO steels do vary with orientation**

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

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One reason for these wide variation of magnetic properties with manufacturer is that each has his own secret recipe to make an electrical steel. They differ in chemical composition, purity and method of manufacture. For example, Si in M270-50A grade is 2.173% in one manufacturer, 1.65% from another\(^\text{27}\). Their Mn is also different: 0.558%, 0.177%. This affects their resistivity and grain size, so affects their core loss and B(H) curves.

Another reason is that the core loss depends on trace impurities. These include, Oxygen, Sulphur, Titanium and Nitrogen\(^\text{28}\). 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 if they have same composition.


\(^{28}\) Bozorth, ibid, p. 52
4. A. ELECTRICAL STEELS – NON-GRAIN ORIENTED

MagWeb’s Electrical Steel (NGO) Folder has 1223 excel files listing magnetic properties of these materials, produced by 16 manufacturers. Of these, 634 files contain B(H) magnetization curves/permeability curves while 589 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

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.

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 stabilize it (i.e. prevents increase of core loss with time, called aging). Carbon is magnetically harmless below its solubility limit of 70 ppm. In electrical steels, carbon is less than 30\text{ppm}, 50\text{ppm}, 300\text{ppm}, 200\text{ppm}, 800\text{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 copper loss. Silicon also causes them to be more brittle. All electrical steels are supplied in annealed condition. Manufacturers supply them as coil rolls of 3 to 4 ft. diameter, in widths up to ~ 1.3 m.

Grain-Oriented steels (detailed in the next section) have grains as large as 3 to 8 mm. They offer lowest possible core loss at 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 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 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 omni-directional. Their properties are measured in a 50/50 Epstein stack. Typically,

- Core loss ranges 2 to 16 w/kg
- Peak permeability ranges 4000 to 8000
- 1.5T permeability ranges 800 to 3000.

MagWeb database indicates that only European manufacturers supply their B(H) curves at 50 Hz; rest supply them at 0 Hz (DC). They are used mostly in electric motors (greater than .25 kW) in a wide variety of market segments, e.g., industrial motors, fans, pumps, rolling mills, oil/gas, machine tools etc. They contain up to 3.5% silicon to reduce core losses. “Relay steels” are those with 1.5 to 2.5% Si steels that are thicker than 1 mm.

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31 Dorner, D., Non-Oriented electrical steel sheet for electric vehicle drives, ThyssenKrupp Techforum, Issue 1, 2009.
32 ASTM A677, Standard Spec. for NonOriented Electrical Steel.
Grades
Each manufacturer has his own secret recipe composition and method of manufacture of a grade, so their magnetic properties vary even when they carry same grade label.

European standard (EN10106 and IEC 60404-8-4) grade 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 carry the label “Mccc-tt-x”. Here, “M” is for electrical steel, “ccc” 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 NGO steel,
- K for semi-processed steel NGO steel,
- P for a high permeability material,
- N for core loss measured at 1.5T/50Hz,
- S for core loss measured at 1.7T/50Hz.

For example, 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 $\mu_{50}$ can be calculated from $\mu_{50} = B_{50}/(5000\mu_0)$. So its $\mu_{50} = 255$, 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 to 16 w/kg

But “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.

The “typical” core loss of a grade is closer to the “guaranteed” core loss of the next lower grade. Example: For M250-50A grade, “maximum” core loss (at 1.5T, 50Hz) $W_{15/50}$ is 2.5 w/Kg. But Fig. 11 shows that Cogent’s M250-50A “typical” core loss is 2.38 w/kg. That for Nippon’s 50H250 is 2.24 w/Kg. These are closer to the “maximum” core loss (2.3 w/kg) of next lower grade M230-50A.

HP grade. Some producers offer “High Permeability” (HP grade) steels, which are supposed to have higher permeability at the same core loss. For example, Cogent offers M530-50A and M530-50HP. The former offers $B_{50}$ of 1.65 T while the HP version offers a higher $B_{50}$ of 1.71 T. This one may perceive that HP stands for higher permeability.

But MagWeb database discovered that, at 1.5T, 50 Hz, typical permeability of M530-50A is 2083 while that of M530-50HP is 1721. So the HP label might be a misnomer.

In addition, some firms also offer a “High Strength” (HS) grade steel which is useful in machines where strength is critical (e.g. hybrid vehicle motors with bridges).

Figure 11. Same-grade steels from diverse firms differ in magnetic quality.

Thermal Conductivity
Thermal conductivity of laminations (hence core) is highly anisotropic. Its in-plane conductivity $k_{xy}$ is high ($\sim 28 \text{ w/mK}$) but thickness-wise conductivity $k_z$ is low ($\sim 0.4 \text{ w/mK}$)$^{34}$. Such anisotropic thermal conductivity data is essential for accurate estimation of temperature rise, but such data is rare and sometimes deceptive. 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 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 a lamination is different from that of a stack. That for a stack depends on coating class (material and thickness), number of laminations and temperature. In addition, 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$^2$)$^{35,36}$.

### 4.1. Thickness: USA vs. Rest

MagWeb database 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 apparently 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!

In addition, 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 inch) 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.

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4.2. Thickness vs. Skin Depth

The users of MagWeb database should consider the skin effect in choosing a magnetic material. Generally, they are used as flux carriers and flux barriers. Carriers transmit flux lines normal to the cross-section, so eddy currents loop within the cross section. Barriers transmit flux lines normal to a flat face, so eddy currents loop in the flat face. In motors they act as flux carriers. Shields act like flux barriers. Following analysis shows that lamination thickness of a carrier should be less than two skin depths, while that of a barrier should be less than one skin depth.

In carriers, high frequency flux concentrate around the outer periphery (Fig. 12). Some engineers model a magnetic material as one with constant permeability. In such model, the high frequency flux decays exponentially\(^\text{37}\) from the surface. It falls from a 100% peak value at the surface to 37\% after one skin depth \(\delta\), to 14 \% after two skin depths \(2\delta\) etc. This skin depth \(\delta\) is given by

\[
\delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f}} \quad \ldots \quad (4)
\]

where
- \(f\) = frequency of sinusoidal flux wave form, Hz
- \(\rho\) = resistivity, ohm m
- \(\mu_r\) = relative permeability (assumed to be constant in a linear material)
- \(\mu_0 = 4\pi \times 10^{-7}\) N/A\(^2\)

In flux carriers, two walls of thickness \(\delta\), 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 a lamination should be less than two skin depths \((t < 2\delta)\).

Soft magnetic materials are non-linear. That is their permeability varies with flux density, \(\mu = \mu(B(H), f, T)\). Then high frequency flux crowds in a thin membrane. Inside the membrane, the flux density decays non-exponentially\(^\text{38}\) from a 100\% peak value at the surface to 0\% at one membrane penetration depth \(\delta'\). Beyond one membrane depth, the flux density is zero. This membrane depth varies from section to section, \(\delta' = \delta'(x)\). Average membrane thickness \(\delta_o\) is the average membrane depth. FEM software should be used to estimate it.

Flux barriers are magnetic materials (such as flux shields, induction heater coils) which receive flux from one or two sides from flux sources. The cross-section of a flux barrier is parallel to that of its flux sources. At high frequencies, a flux barrier develops an “image” of the flux source. To fully utilize the material as a flux barrier, its thickness should be less than one membrane thickness \((t < \delta_o)\).

In any case, crowding of AC flux reduces the effective area where flux flows. Such area reduction increases the effective flux density, which in turn increases eddy loss! Some experts use “surface resistance”\(^\text{39}\) (ohms per square) to characterize loss in such cases. It is the resistivity

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\(^{38}\) McConnel, H.M., Eddy current phenomenon in ferromagnetic materials, ONR Contract 30306, 1953.

\(^{39}\) Kirtley, J.S., Class Notes 3: Eddy currents, Surface impedances and loss mechanisms, 2005.
divided by membrane depth. Eddy loss is then estimated as average eddy current squared times surface resistance.

Skin depth also reduces inversely with frequency. So to carry flux at high frequencies, materials with high permeability need to be thin. 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.

4.3. CRML (Semi Processed) Steels

**CRML (Cold Rolled Magnetic Laminations)** refer to “ultra-low carbon” steel sheets. They differ from electrical steel in that they are uncoated and unannealed (“semiprocessed”) by the steel producer. They expect the end-user to perform annealing of finished part. MagWeb furnishes their properties after such finish annealing. Low grade CRML have carbon <0.06%, high grades < 0.02%, while best (costlier) grades have <0.005%. They usually have little or no silicon.

In USA they are produced per ASTM 726; different producers grade them as Type 2-6, or Grade Q, CQ etc. In Europe, they are produced per EN10341 and are called semi processed steel, identified by an end code K.

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

**Core Loss.** To reduce carbon to <0.005%, the 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 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 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 the NGO steels, so are preferred in FHP motors. Unannealed CRML also produces very low wear on stamping tool, further reducing tooling cost.

**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.
5. B. ELECTRICAL STEELS - GRAIN-ORIENTED

*MagWeb’s Electrical Steel (GO) Folder* has 401 excel files listing magnetic properties of these materials, produced by 13 manufacturers worldwide. Of these, 221 files contain B(H) magnetization curves/permeability curves while 180 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

The *Grain Oriented Electrical Steels* use ~ 3.25% Silicon to reduce losses. They have ultra-low carbon (< 10 ppm)\(^\text{40}\). But annealing changes the chemical composition, so manufacturers rarely commit to specific % of C or Si. Their saturation induction \(J_s \approx 2.03 \text{ T}\). 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 max 1.7/50Hz core loss of 0.95w/kg. But, just like NGO steel, each manufacturer makes them using his own secret recipe and processes. So properties of each steel depend on manufacturer.

**Permeability.** They are made by a 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\(^\circ\) from the rolling direction, the permeability can drop sharply, by as large as 80%. If the flux flows in Transverse Direction at 90\(^\circ\) (TD or hard axis), its permeability could reduce by an order of magnitude.

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

Fig. 13 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 a lamination**

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\(^{40}\) 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](https://orca.cf.ac.uk/56703/1/2014RamanathanSPhD.pdf)
simply wasted. If flux is kept constant, reduction in the effective area increases actual flux density, which can increase core loss.

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

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

**Applications.** Because they are more or less unidirectional, they are used only in applications where flux flows along 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. Wherever available, MagWeb provides such dual property files, one for rolling and 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 rolling direction. In fact, 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 Hitachi41. But apparently their size is somewhat limited, perhaps to less than 12 ".
6. C. METGLAS & NANOCRYSTALLINE

*MagWeb’s Metglas & Nano Folder* has 56 excel files listing magnetic properties of these materials, produced by 4 manufacturers. Of these, 30 files contain B(H) magnetization curves/permeability curves while 26 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

MagWeb broadly groups them into amorphous and nanocrystalline materials. Both employ 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 magnetostiction.

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. Obviously they have inferior properties.

Many firms, such as Metglas, Hitachi, Vacuumschmelze, Amotech, Toshiba, UAML, Quingdao, Beizing 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 database.

**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 grain or domain structure. They are produced by cooling a molten metal over a rotating copper drum. The drum rotates at such high speed that the melt does not have time to form crystalline structure. Boron is added for easy flow of molten metal. This process limits thickness and width of the result, so 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 most of 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 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 loop has two values of flux densities. Such multivalued curves are not accepted by most design software. MagWeb converts such multivalued hysteresis loops into single valued B(H) curve using the *Elenbass Rule*\(^{42}\). This rule states that the flux density B at a given H equals average of the two flux densities having same H ordinate.

Manufacturers (and MagWeb) furnish the magnetic properties of raw ribbons (instead of finished toroids). Designers should use them with caution as magnetic properties of finished cores are

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\(^{42}\) Bozorth, *ibid*, p. 511
inferior to those of ribbons. Manufacturers also supply finished toroidal cores or C-cores made of these ribbons.

*Permeability.* Their permeability is high and ranges 100000 to 300000. But one should consider the skin depth at such high frequencies in order to fully use the material.

*Skin Depth.* High frequency flux concentrates in a thin skin of depth $\delta$. If skin depth is smaller than thickness of the ribbon, flux avoids the mid-core, thereby wasting the material$^{43}$. For example, consider a tape core made of Metglas 2605SA1 of 25 $\mu$m thick ribbon. At an operating point of 1.3T, 100 kHz, its permeability is 200,000, and its resistivity is 42 $\mu\Omega$ cm. The skin depth of 100 kHz flux is 5 $\mu$m. The high frequency flux avoids the mid-core of 25–2x5 = 15 $\mu$m. This mid-core behaves like air, wasting lot of costly material (see). If flux is held constant, such reduction in effective area increases effective flux density, which can increase core loss!

A simple example as to how reduced thickness of a nano material can save core loss was presented by Trupp$^{44}$. He considered a nano ribbon (permeability = 30,000, resistivity = 115 $\mu\Omega$ cm, density = 7.35 gm/cc) operating at (0.3T, 100 kHz). He showed that a 0.02 mm thick ribbon produces 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 1000 Hz to 100,000 Hz. Typically, the core loss at 0.75T, 50 Hz ranges 0.01 to 0.06 w/Kg as shown in Table 3.

**Table 3. Metglas Ribbons, graded by core loss**

<table>
<thead>
<tr>
<th>Name</th>
<th>Base Element</th>
<th>Composition</th>
<th>$J_s$, Tesla</th>
<th>Core Loss w/kg At 0.75T, 50Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2705M</td>
<td>Cobalt</td>
<td>Fe$<em>4$ Si$</em>{12}$ Co$<em>{69}$ B$</em>{12}$Ni$_1$Mo$_2$</td>
<td>0.77</td>
<td>-</td>
</tr>
<tr>
<td>2714A</td>
<td>Cobalt</td>
<td>Fe$<em>4$ Si$</em>{15}$ Co$<em>{68}$ B$</em>{14}$ Ni$_1$</td>
<td>0.57</td>
<td>-</td>
</tr>
<tr>
<td>2605SSC</td>
<td>Iron</td>
<td>Fe$<em>{81}$ Si$</em>{13.5}$ B$_{13.5}$ C$_2$</td>
<td>1.61</td>
<td>0.011</td>
</tr>
<tr>
<td>2605HB1M</td>
<td>Iron</td>
<td>Fe$_{90}$ Si$_5$ B$_5$</td>
<td>1.63</td>
<td>0.028</td>
</tr>
<tr>
<td>2605S3A</td>
<td>Iron</td>
<td>Fe$_{90}$ Si$_5$ B$_3$ Cr$_3$</td>
<td>1.4</td>
<td>0.036</td>
</tr>
<tr>
<td>2605SA1</td>
<td>Iron</td>
<td>Fe$_{78}$ Si$<em>8$ B$</em>{13}$</td>
<td>1.56</td>
<td>0.055</td>
</tr>
<tr>
<td>2826MB</td>
<td>Nickel</td>
<td>Fe$<em>{40}$ Ni$</em>{38}$ Mo$<em>4$ B$</em>{18}$</td>
<td>0.88</td>
<td>0.057</td>
</tr>
<tr>
<td>2605CO</td>
<td>Iron</td>
<td>Fe$<em>{66}$ Co$</em>{18}$ Si$<em>1$ B$</em>{15}$</td>
<td>1.8</td>
<td>0.178</td>
</tr>
</tbody>
</table>

**(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. Trace Cu, Nb is added to improve magnetic properties. The ribbons have thickness of 0.001", 0.0008" and width less than 4". But they saturate earlier (at ~1.2 T instead of ~ 1.5 T of amorphous ribbon).

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

Table 4. NanoCrystalline Ribbons, graded by core loss

<table>
<thead>
<tr>
<th>Name</th>
<th>Firm</th>
<th>Composition</th>
<th>$J_s$, Tesla</th>
<th>Core Loss w/Kg At 0.2T, 100kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>VITROPERM</td>
<td>Vacuumschmelze</td>
<td>Fe$<em>{73.5}$ Si$</em>{15.5}$ B$_7$ Cu$_1$ Nb$_3$</td>
<td>1.23</td>
<td>35</td>
</tr>
<tr>
<td>FINEMET</td>
<td>Hitachi</td>
<td>Fe$<em>{73.5}$ Si$</em>{13.5}$ B$_9$ Cu$_1$ Nb$_3$</td>
<td>1.24</td>
<td>38</td>
</tr>
<tr>
<td>NANOPHY</td>
<td>ArcelorAperam</td>
<td>Fe$<em>{74.1}$Si$</em>{15.7}$ B$_{6.1}$ Cu$<em>1$ Nb$</em>{3.1}$</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td>NANOPERM</td>
<td>Magnetec</td>
<td>Fe$_{86}$ B$_8$ Cu$_1$ Zr$_7$</td>
<td>1.52</td>
<td>116</td>
</tr>
<tr>
<td>HIT PERMA</td>
<td>Carnegie Mellon</td>
<td>Fe$<em>{67}$ Co$</em>{18}$ Si$<em>1$ B$</em>{14}$</td>
<td>1.8</td>
<td>-</td>
</tr>
<tr>
<td>HIT PERMb</td>
<td>Carnegie Mellon</td>
<td>Fe$<em>{44}$ Co$</em>{44}$ B$_4$ Zr$_7$ Cu$_1$</td>
<td>1.8</td>
<td>-</td>
</tr>
</tbody>
</table>
7. D. COBALT STEELS

_MagWeb’s Cobalt Steel Folder_ has 243 excel files listing B(H) and Core loss curves of these materials, produced by 4 manufacturers. Of these, 51 files contain B(H) magnetization curves/permeability curves while 192 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

_Cobalt Steels_ are alloys of cobalt and iron that offer highest possible saturation induction ($J_s \approx 2.45$T). 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. Resulting reduction in size and weight override the higher cost of these materials. But such expected benefits are sensitive several factors which are documented in the MagWeb database. Such data helps in optimal design of aircraft generators.

_Saturation Induction_ $J_s$ of cobalt steels can be as high as $\sim 2.45$ T (only 14 % higher than iron’s 2.158T) - depending on your luck in annealing.

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

Another new alloy called Minnealloy $t^{45}$ claims to offer $J_s \sim 2.35T$. But, at $H = 5000$ A/m it yields only 0.15T. In contrast, electrical steels produce $\sim 1.6T$ at same H. So it is not superior.

_In USA_, Carpenter sells 6 Cobalt Steels under “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 large cobalt % makes them very expensive.

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

Following other Hiperco alloys have lower cobalt so are less expensive. But their magnetic properties are less attractive as they have 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 degrades 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.

_In Europe_, Vacuumschmelze sells 9 Cobalt Steels under brand names of “Vacoflux”, “Vacodur”. MagWeb has 12 files on these steels. Of these, Vacoflux 48, 50 have 49% Co, 2% V, and so offer best magnetic properties. Vacodur has Nb added to improve mechanical properties. MagWeb also has B(H) curves for Arcelor/Imphy’s 3 cobalt steels under “Aperam” or “AFK”

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https://www.researchgate.net/publication/318575768_Minnealloy_A_New_Magnetic_Material_with_High_Saturation_Flux_Density_an d_Low_Magnetic_Anisotropy
brand. Others, such as Xian Gangyan Specialty Alloy, China also sell cobalt steels, but their properties are not available.

![Core Loss vs. Copper Loss](Figure 14)

**Figure 14. Vacoflux 48 produces least core loss. But Hypocore incurs more copper loss**

**Core Loss vs. Copper Loss.** Fig. 14 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 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 lot more copper loss. Hiperco 50A, Vacoflux 50 also produce low core loss but at higher \( H \).

**Annealing.** Generally, a cobalt steel that offers 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 lower temperature, but it increases core loss. On the other hand, stator cores may need lowest-loss steels, so annealing at a higher temperature is recommended.

**Anisotropy.** MagWeb data shows that magnetic properties of cobalt steels are not independent of direction. It depends on flux angle, which can vary from Rolling Direction (0°) to Transverse direction (90°). Fig. 15 illustrates typical anisotropy of these steels. It shows that core loss of Hiperco 50 at 400 Hz can vary by as much as 20% as one moves from RD to TD.

**Aging.** Core loss of cobalt steels generally increases with aging. Geist\(^{46}\) demonstrated that Hiperco 27 is more thermally stable than other cobalt steels.

**Yield Strength.** Yield strength depends on annealing schedule. Hiperco 50 HS offers highest yield strength ranging 70 to 99 ksi while Hiperco 50 offers 60 to 70 ksi (1 ksi = 7MPa). Hiperco 50A offers lowest at 53 ksi. **Stress.** The MagWeb data shows that a compressive stress always increases core loss. On the other hand, a small tensile stress (~ 50 MPa) seems to minimize the core loss. **Temperature.** Only in Hiperco 27 the core loss beneficially decreases with increasing temperature (Fig. 16). Other cobalt steels are not that thermally sensitive.

**Figure 15.** Core Loss of Cobalt Steels varies with direction of flux.

**Figure 16.** Hiperco 27’s Core Loss beneficially decreases with temperature
8. E. NICKEL STEELS

*MagWeb’s Nickel Steel Folder* has 193 excel files listing B(H) Core Loss curves of these materials, produced by 7 manufacturers. Of these, 126 files contain B(H) magnetization /permeability curves while 72 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

**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 (25 μm) thick ribbons, but thinner ones at 0.125 mil (3 μm) 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. But its saturation induction (~0.8 to 1.1T) is lower than that of 50% Ni steel. It is sold under various trade names such as Permalloy, Mumetal, Ultraperm, Magnifer 7904 etc. But their properties of all differ because of difference 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. But its saturation induction of 1.6T - higher than that of 80% Ni steel. 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 this Steel powders are called MPP cores.

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

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

**Applications.** They are employed in high frequencies upto 100000 Hz in inductors, transformers in communication, EMI Shielding plus anti-shop lifting devices. To achieve 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.
9. F. STAINLESS STEELS

MagWeb’s Stainless Steel Folder has 49 excel files for B(H) and Permeability Curves of magnetic stainless steels produced by diverse manufacturers. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

Stainless Steel here refer steels alloyed with chromium (Cr). They offer far better corrosion resistance than the 1000 series low carbon steels (which rust). Their yield strength is higher than these mild steels - but elongation is lower. Generally, as the percentage of Cr increases, their magnetic properties degrade, but their corrosion resistance increases. They may have “ferritic”, “martensitic” or “austinitic” phases. Its permeability depends on the relative distribution of these phases.

“Ferritic” stainless steels (409, 430, 446) are most easily magnetizable. They have good magnetic properties because of their BCC structure. But their magnetic properties depend on annealing and percentage of carbon. Unfortunately, most producers do not control carbon percentage 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 least expensive. They are best suited for 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 have 14 to 18% Cr. Ti, Nb are 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 have 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 have 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.

MagWeb database also has B(H) and permeability curves for following magnetic stainless steels:

**8-FM** has 8% Cr. It is FM (Free Machinable) and offers high saturation induction (Js ~ 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 core less 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 Js = 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 ($J_s = 1.42$T) among stainless steels. So it is useful in applications that need high corrosion resistance, but do not need high flux densities.

**430FR** is similar to 430F. But it has higher wear resistance and hardness. Its higher resistivity 760 $\mu$Ω 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 ($J_s \sim 1.5$T). Its permeability at 1T is 1700. Table 5 below compares their magnetic properties.

**Table 5 Magnetic Properties of various stainless steels.**

<table>
<thead>
<tr>
<th>Name</th>
<th>% Chr</th>
<th>% C</th>
<th>% Si</th>
<th>Sat. Ind. ($J_s$ Tesla)</th>
<th>Resistivity ($\mu$ohm cm)</th>
<th>Properties at 1.5T</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-FM</td>
<td>8</td>
<td>0.03</td>
<td>0.50</td>
<td>1.86</td>
<td>50</td>
<td>2354</td>
</tr>
<tr>
<td>12-FM</td>
<td>12</td>
<td>0.03</td>
<td>0.50</td>
<td>1.77</td>
<td>57</td>
<td>2641</td>
</tr>
<tr>
<td>13-FM</td>
<td>13</td>
<td>0.03</td>
<td>1.25</td>
<td>1.70</td>
<td>78</td>
<td>6401</td>
</tr>
<tr>
<td>13-XP</td>
<td>13</td>
<td>0.03</td>
<td>1.50</td>
<td>1.70</td>
<td>82</td>
<td>23800</td>
</tr>
<tr>
<td>405</td>
<td>13</td>
<td>0.08</td>
<td>1.00</td>
<td>1.60</td>
<td>60</td>
<td>5670</td>
</tr>
<tr>
<td>410</td>
<td>11</td>
<td>0.15</td>
<td>1.00</td>
<td>1.60</td>
<td>57</td>
<td>6395</td>
</tr>
<tr>
<td>416</td>
<td>13</td>
<td>0.15</td>
<td>1.00</td>
<td>1.56</td>
<td>57</td>
<td>11000</td>
</tr>
<tr>
<td>430</td>
<td>17</td>
<td>0.12</td>
<td>1.00</td>
<td>1.56</td>
<td>60</td>
<td>13560</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>% Chr</th>
<th>% C</th>
<th>% Si</th>
<th>Sat. Ind. ($J_s$ Tesla)</th>
<th>Resistivity ($\mu$ohm cm)</th>
<th>Properties at 1.2T</th>
</tr>
</thead>
<tbody>
<tr>
<td>430F</td>
<td>18</td>
<td>0.07</td>
<td>0.50</td>
<td>1.56</td>
<td>61</td>
<td>1153</td>
</tr>
<tr>
<td>430F-RB75</td>
<td>18</td>
<td>0.07</td>
<td>0.50</td>
<td>1.56</td>
<td>60</td>
<td>1522</td>
</tr>
<tr>
<td>430F-RB82</td>
<td>18</td>
<td>0.07</td>
<td>0.50</td>
<td>1.42</td>
<td>60</td>
<td>2190</td>
</tr>
<tr>
<td>430F-RB87</td>
<td>18</td>
<td>0.07</td>
<td>0.50</td>
<td>1.42</td>
<td>60</td>
<td>1993</td>
</tr>
<tr>
<td>430FR</td>
<td>18</td>
<td>0.07</td>
<td>1.25</td>
<td>1.52</td>
<td>76.4</td>
<td>1478</td>
</tr>
<tr>
<td>440</td>
<td>18</td>
<td>0.68</td>
<td>1.00</td>
<td>1.52</td>
<td>60</td>
<td>15500</td>
</tr>
</tbody>
</table>

**440** is a Martensitic stainless steel. It 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 as razor blade steel, it is valued for high corrosion resistance/ hardness, in surgical instruments, valve seats.

444 is a 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 steels with 18% chromium, and poor.

**Permeability and Annealing.**
Fig. 17 shows that, to pass 1.5T flux, a 8% Cr steel may require low magnetizing current (H ~2400 A/m). But a 18% Cr steel may demand two orders of magnitude higher magnetizing current (H= 240,000 A/m).
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 ultrasonic testing of pipe lines 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) 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.

"Austenitic" Stainless Steels (300 series – 302, 304, 316 etc.) have FCC structure. They are nonmagnetic. They contain Nickel in addition to Chromium. But cold working can transform an austenitic phase to martensitic phase increasing permeability, causing it to become magnetic in small local areas. This can occur at sharp corners, sheared edges or machined surfaces. Welding also can transform an austenitic phase to ferritic phase, thereby increasing permeability locally. The welded zones can become "hard magnets" (they attract magnets or iron filings). Such zones can be demagnetized by heating to 1050C followed by rapid cooling. 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, higher permeabilities can be expected in those with low nickel such as 301(1.4310), 321 (1.4541) & 347 (1.4550).

Applications. Magnetic stainless steels are valued for their corrosive resistance. They are used in solenoids in corrosive fluids pumps (e.g., antlock 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.

Selection of a particular stainless steel depends on application requirements vs. material's capabilities. A high corrosive resistance requirement often conflicts with 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). In addition, trading mechanical strength with loss, thermal conductivity, hardness, machinability, weldability etc and cost plays a critical role.

Saturation Induction $J_s$. 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 method of annealing and 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 a tests by Apostolopolous\textsuperscript{47}. Also expect 8 to 15% reduction in $J_s$ as temperature increases to 200 C.

Materials with high permeability require less H so require lighter currents. This leads to smaller and cheaper parts with less power input. Note: To attain datasheet values of permeability, the finished stainless part must be annealed. Typical annealing schedule is to heat to 1500F in dry hydrogen, cool at 20F per hour to 110F and air cooling further. Table 5 presents saturation induction and resistivity of various stainless steels.

**Coercive Force.** Low coercive force $H_c$ permits rapid demagnetization, reducing the force required to open and close without “sticking”, allowing a higher speed solenoid.

**Core loss** of stainless steel is rarely published. Higher electrical resistivity reduces wasteful eddy currents. At best core loss has to be inferred from its coercive force and 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. But high Cr steels have lower permeability so demand much more magnetizing current. So switching to high % Cr steel increases can copper loss increases.

**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 hybrid electric vehicle that uses 430 steel rotor with 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 lot of costly material. If flux is kept constant, this increases the effective flux density, which increases core loss!

**Induction cook tops** are made of aluminum housing brazed to a stainless steel disc bottom. It is placed over an induction coil which is essentially spiral shaped air cored Litz coil. The coil carries current at 24 kHz, so radiates HF flux pattern into 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 cook top.

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 $\mu$). An (1T, 24kHz) flux impinging it concentrates eddy currents in a 0.18 mm skin. Alternatively consider 8-FM steel with (50 $\mu \Omega$ cm, 2338$\mu$). A (1.2T, 24kHz) flux impinging it reduces skin to 0.074 mm. This significantly increases flux density, hence eddy heat.

\textsuperscript{47} Apostolopolous, Magnetization, resistivity, structure of AISI 430 ferritic steel after heat treatment, 2013.
10. G. CARBON STEELS

*MagWeb’s Carbon Steel Folder* has 182 magnetic property files of a large variety of carbon steels. 87 of them contain B(H) curves of *Low Carbon Steels* (0.02% to 0.2 % C), which have better magnetic properties but have lower tensile strength. 93 of them contain B(H) curves of *Industrial Steels* (0.2% to 2%C), which have poorer magnetic properties, but are stronger. (Steels with more than 2%C are called cast iron, wrought iron, malleable iron etc. Their properties are listed in the “Cast Iron” folder.)

For a list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY. 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 database has B(H) curves for 87 low carbon steels. They are available in several forms, such as rounds, flats, tubes, pipes etc. in several thicknesses. They are usually thicker than electrical steels. They are also more ductile and machinable.

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

Fig. 18 shows the 1.5 T permeability for a variety of low carbon steels. It shows that, as carbon increases from 0.005% C (in ULC steels) to 0.2%C (in 1020 steel) the 1.5 T permeability reduces by an order of magnitude. This magnetic degradation is due to precipitated carbon which obstructs flow of flux. It can be countered somewhat by annealing. But annealing can increase the permeability only by a factor 2 at most, not 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, higher the permeability. But because they contain precipitatable carbon, their magnetic properties degrade with age. Resistivity of most low carbon steels is ~ 12μΩ 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/mm² (60 ksi)
Pure Iron (9)
Pure iron is one that has less than .003% C (and no Si). It has high permeability and saturation induction of 2.158 T\(^4\) (all other steels saturate earlier). This high permeability feature makes it attractive for DC electromagnets. It’s extremely low carbon content prevents increase of core loss with time (aging). 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 4 grades. Several other manufacturers produce similar material, but with different carbon and trace impurities. The total impurities can range from 0.02% to 0.5%. Out of this, the carbon impurity can range 0.003 to 0.02%. Unfortunately, all label their product as “pure Iron”. But minute differences in %C impurity causes permeability of all these “pure irons” differ with manufacturer. Low grade pure iron offers far lower permeability of 500. But high grades (those with lowest % C) offer a 1.5T permeability of 5000.

Pure iron is available in sheets, bars, plates and wire. But to attain data sheet values, it must be annealed after machining. It is also available as hydrogen annealed sheet which has much higher permeability. ARMCO’s pure iron can be annealed per Schedule A or B. That with schedule B offers peak permeability of 7000 at 1.32T.

1002 Ultra Low Carbon Steels (7)
Steels with 0.005 to 0.03% C (and without Si) are called 1002 Ultra low carbon steels 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.

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https://nvipubs.nist.gov/nistpubs/jres/26/jresv26n1p1_a1b.pdf
1006 to 1020 Steels (aka Mild Steels, Soft Steels) (57)

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

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

**INDUSTRIAL STEELS (93)**

MagWeb database has B(H) curves for 93 Industrial steels (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. The can also vary with form and size. Other factors include: rolling (cold, hot), annealing (annealed, unannealed), stress (stressed or unstressed), temperatures (high, low). MagWeb database describes several of these effects and assist in selection of appropriate carbon steels.

**Medium Carbon Steels (aka industrial steels)**

They have 0.2 to 0.6%C. They are stronger than mild steels. The 1.5 T permeability of steels with 0.2% C is ~ 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 Steels, with about 0.35%C. Of these, 4130, 4140, 4340 steels (with yield strength of 65 ksi) offer 1.5T permeability of 565, 363 and 326 respectively. A high strength steel called D6ac steel (with high yield strength of ~220 ksi) has lower 1.5T permeability of 257.

**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 axis than around periphery. MagWeb lists magnetic properties in both directions; it also documents the impact of stress on their magnetic properties.

MFL (Magnetic Field Leakage) device 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\(^{49}\). For example, MagWeb database shows that the peak permeability point of X52 is ~700 at 0.7T. Magweb’s permeability curves can locate 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 Steels. Those with 0.6 to 1% C are known as spring steels. The 1.5 T permeability of such steels with ~0.6%C can be ~ 300.

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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 50 to 110 ksi (350 to 770 MPa).

The MagWeb database contains digital B(H) curves of 8 grades of Rotor Forgings. Note however, their 2T permeability is poor, ranging only 40 to 70. So they require large (~ 30000 A/m) magnetizing current. This large magnetizing current can produce 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 less than 10 mm when carrying ac flux. (In loud speakers, they are used to carry low level flux at high frequencies).

Fig. 19 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 12μΩ 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 lot of material and increases eddy core loss.

![Figure 19. The central core of a thick steel may not carry AC flux](image)

**Annealing**
The term “Annealing” refers herein to a process to improve its magnetic properties (e.g., higher permeability, lower core loss etc.). A decarburizing anneal is one that reduces the carbon content. A stress relief anneal is one that reduces mechanical stress. In contrast, the term
“heat treatment” refers to a process to improve mechanical property (e.g., fatigue strength, yield strength, hardness etc.). Examples: tempering, hardening, quenching. Hardening produces steels with more austenitic phase (with FCC unit cell) that has high mechanical strength.

Fig. 20 shows how during annealing, thermal vibrations cause carbon atom to get “squeezed” inside an iron crystal. As a result, crystal structure can change from BCC to FCC, or BCT. This alters the texture and orientation of crystals, its grain size and hence magnetic or mechanical properties.

**Figure 20. Annealing squeezes carbon atom inside an iron crystal**

For annealing low carbon steels, one can refer to classic papers by Burrows\textsuperscript{50}, Cheney\textsuperscript{51} or recent investigations by Stokes\textsuperscript{52}, Ghodsi\textsuperscript{53} Zhetvin\textsuperscript{54} list annealing schedules and their impact on magnetic properties. Unfortunately, annealing schedule differ with carbon content. Typical annealing schedules for some low carbon steels are given below.

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

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

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


\textsuperscript{52} Stokes, J. L (1983) Magnetic properties of iron-carbon steels for soft magnet application, Naval Weapons Center, TP 6455.


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

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

MagWeb’s Castings Folder has 52 excel files listing 51 B(H) curves and 1 core loss curve of these materials. These include cast steel, gray cast iron, wrought iron, malleable iron, ductile iron etc. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

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

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

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

Cast Iron is used to make high volume (occasionally large) magnetic parts of intricate design at low cost. The ease of casting facilitates mass production. Fig. 21 overviews the magnetic properties of typical cast irons and cast steels.

<table>
<thead>
<tr>
<th>Trade Name</th>
<th>Class</th>
<th>Structure</th>
<th>Sat. Induction</th>
<th>Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>GJL-250</td>
<td>cast iron</td>
<td>flake graphite</td>
<td>1.76</td>
<td>67</td>
</tr>
<tr>
<td>GJS-500-7</td>
<td>cast iron</td>
<td>spherical /ferritic</td>
<td>1.75</td>
<td>45.9</td>
</tr>
<tr>
<td>GJS-700-2</td>
<td>cast iron</td>
<td>spherical /ferritic-feralitic</td>
<td>1.69</td>
<td>50.7</td>
</tr>
<tr>
<td>GJS-400-15</td>
<td>cast iron</td>
<td>spherical/feralitic</td>
<td>1.77</td>
<td>47.6</td>
</tr>
<tr>
<td>GS-52</td>
<td>cast steel</td>
<td></td>
<td>2.03</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Figure 21. Magnetic Properties of typical Cast Iron and Cast Steel

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

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

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

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

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

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

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

**Wrought Iron**
It is close to pure iron. Unlike cast iron, wrought iron has only minute carbon (0.08%) and Silicon (0.12%). It also contains trace S (0.018%) and P (0.02%). It is tough, malleable, ductile, forgeable and weldable.

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

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

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

**Ductile Iron Castings**
MagWeb database contains 3 B(H) files of ductile iron castings. They show that when unannealed they offer a poor permeability of 130 at 12T. Annealing can improve their permeability to about 580.
12. I. IRON POWDER CORES + SMC

MagWeb’s Iron Powder Cores + SMC Folder has 174 excel files on B(H) and Core Loss curves of these materials, produced by 7 manufacturers. It includes both Iron Powder Cores (which use uninsulated iron particles) and Soft Magnetic Composites (which use insulated iron particles). Of these, 89 contain B(H) and Permeability curves while 851 contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

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. Their intent is to store energy in the distributed gaps formed by 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, fly back transformers. Occasionally they are also used as EMI Filters. Their usable flux density is below 0.2 T, and rarely exceeds 2000 A/m. This keeps copper loss and iron loss in check.

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

Core loss
All producers express core loss as mW/cc. MagWeb converts them to w/Kg for a better “feel”. For example, a 2 w/kg will be acceptable loss, but not 20 w/kg. But if one says it as 1000 mW/cc, one has no idea if it is too low or high. 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 50 to 2000 Hz for use in electric motors. Their intent is 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 reduce 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 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 top grade that offers best efficiency and performance.
Fig. 22 shows such SMC material map for a machine operating at 1.5T, 50 Hz. It uses MagWeb data to compare B(H) and Core Loss of SMC materials from firms A and B. It shows SMC materials from firm A offer lower core loss and higher permeability than those from firm B.

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

Figure 22. Property Map of SMC at 1.5T, 50 Hz. Firm A offers superior SMC.

High frequency SMC. They are used in heat treatment of steels by induction heating. They intent to achieve 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 less than 2 cm (1 in). They can be very intricate. They are useful in several applications. They are made by INDO-MIM, India, Sintex, Denmark etc. Hot Isostatic Pressing (HIP) is another process which is similar to MIM, and is also used to make intricate small size soft material parts. Unfortunately, methods to measure magnetic properties for small intricate parts are not yet developed, so their properties are not available.
13. J. ALLOY POWDER CORES

*MagWeb’s Alloy Powder Core Folder* has 92 magnetic property files of these materials, produced by 3 manufacturers. Of these, 28 files contain B(H) magnetization curves/permeability curves while 64 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY. They are used in 10 to 500 kHz.

**Alloy Powder Cores** are made by pulverizing uninsulated iron-alloy powders, mixing with epoxy resins and compressing it at high pressure to form toroids, pot cores etc. Most can operate up to 200 C, except Amoflux which is limited to 155 C. Several firms produce powder cores 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 losses up to few hundred kHz, but expensive. Fig. 23 lists trade names, their alloy powders and saturation flux density.

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

*Figure 23. Core loss of various alloy powders*

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

**Applications.** They are used as inductor and transformer components in power electronics circuits. They are called Power Factor Correction Inductors, Flyback transformers, Noise Filters etc. Core loss at design point is a dominant factor in selection of a specific material. 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 0.2T, 100 kHz wave on it. The H required to produce ripple flux density rarely exceeds 2000 A/m.

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

**Core loss** of powder core varies with material in addition to flux density and frequency. So far MPP cores were thought to offer the lowest core loss. Fig. 24 compares core loss of various powder cores at 0.1T, 10 kHz. It shows that *Koolmu-Max* has far lower core loss than other powder cores.

*Figure 24. Trade Names and alloy powders*
14. K. FERRITE CORES

*MagWeb’s Ferrite Cores Folder* has 288 excel files of B(H) and core loss curves of these materials, produced by 7 manufacturers. Of these, 88 files contain B(H) magnetization curves/permability curves while 288 files contain core loss curves. For a full list of commercial names of all these materials, please go to MagWeb.US, click on MATERIAL DIRECTORY.

It is made of iron oxides alloyed with either MnZn \((\text{Mn}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4)\) or NiZn \((\text{Ni}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4)\). The oxides interact with nonmetallics to produce magnetic properties. The mixture is pressed, fired in a kiln at very high temperatures and machined to specific shape. Ferrites are brittle and have poor mechanical strength. Ferroxcube uses “3” to denote MnZn Ferrites and “4” to denote NiZn Ferrites.

**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.

**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 vs. 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. \(\text{MnZn}\) ferrites have lower resistivity (0.1 to 10 \(\Omega\)m), so are used below 1MHz. \(\text{NiZn}\) ferrites have higher resistivity (\(10^4\) to \(10^6\) \(\Omega\)m), so can be used between 1 to 500MHz.

**Core Loss vs. Temperature.** The resistivity varies with temperature, hence core loss of ferrites varies with temperature\(^{56}\). In fact, there exists an optimal “sweet spot” in the temperature/frequency plane at which the core loss attains a minimum – and it is tricky to find it. Unfortunately, only few vendors furnish \(P(B, f, T)\) core loss curves that show its variation with flux density, frequency and temperature. So most users miss the sweet spot.

**Core Loss Vs Amplitude.** Its core loss increases with the square of flux density. Hence they are used below 0.2 T. Conflicting requirements for a specific need makes their sizing fairly complex\(^{57}\).

**Saturation Induction.** They saturate far earlier than alloy powder core, which limits their ability to carry DC bias. \(J_s\) for MnZn ferrites ranges 0.3 to 0.5 T. That for NiZn ferrites is < 0.35T. It reduces significantly with temperature. For example saturation induction \(J_s\) 3C8 reduces from 0.42T at 25C to 0.34T at 100C. As a result, one expert\(^{56}\) suggests that maximum operational flux density \(B_{\text{max}}\) be 0.5\(J_s\) below 50kHz, 0.1 \(J_s\) above 1 MHz.

**Permeability.** MnZn Ferrites offer relatively higher permeability, ranging from 500 to 20,000. NiZn Ferrites suffer from lower range of 10 to 2000. But it changes with temperature, see below.

**Stresses.** Excessive stresses degrade their permeability. Ferrites are also brittle. So one must ensure that they are not subjected to severe thermal or mechanical stresses.

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\(^{58}\) See [http://www.engr.colostate.edu/ECE562/88lectures/l27.pdf](http://www.engr.colostate.edu/ECE562/88lectures/l27.pdf)
**Complex Permeability.** Some vendors express core loss in terms of complex permeability $\mu^*$

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

Here real part $\mu'$ relates to stored energy and imaginary part $\mu''$ 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 $\delta$.

They express core loss as the loss factor or loss tangent $\tan \delta$ 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. Inverse of $\tan \delta$ is called quality factor $Q$. MagWeb shows such permeability data shaded yellow. The index file shows $\tan \delta$ shaded yellow.

They furnish complex permeability $\mu'(f)$, $\mu''(f)$ 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

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

where $\gamma = \text{weight density (kg/m}^3\text{)}$ and $H_o$, $J_o$ denote the operating point at which they are measured. But $\mu'(f)$, $\mu''(f)$ 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.

Ferrite used above 1 GHz are known as microwave ferrites. Their Saturation induction is less than 0.04T. Their resistivity is higher than that of conventional ferrites.

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.

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 controlled via isolators, phase shifters, circulators. They are used in communication devices, e.g., GPS, Bluetooth, Wi-Fi, cell phone, satellite radio, keyless entry, security systems, tire pressure monitoring in home, auto, and military applications.

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15. ELECTRICAL MACHINE DESIGN SOFTWARE

Table below lists all Finite Element Magnetic field software used to design electric machines. Table (A) lists Free Software (which use mostly 2D FEM) and Table (B) lists Commercial FEM Software (which use mostly 3D FEM). Also listed is custom 1D software for Motors and Inductors. Many have only few B(H) or core loss curves. If you need assistance in choosing software, please contact: rao@magweb.us

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<td>FEMM, USA</td>
<td>femm.info/wiki/Download</td>
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<td>laacg.lanl.gov/laacg/services/download_sf.phtml</td>
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<td>CST</td>
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<td>FEMTET</td>
<td>Murata, Japan</td>
<td><a href="https://www.muratasoftware.com/en/">https://www.muratasoftware.com/en/</a></td>
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<td>fieldp.com</td>
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<td>Cobham Tech., UK</td>
<td>operafea.com</td>
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<td>16</td>
<td>SAMARIUM</td>
<td>Vitatech, India</td>
<td>vitatechindia.com/welcome.php</td>
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## (C) MOTOR DESIGN SOFTWARE

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## (D) INDUCTOR DESIGN SOFTWARE

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