Energy Savings with Thin Gage Silicon-Iron

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Summary

With rising energy costs, increased regulatory pressure, and ongoing environmental concerns, there is renewed interest in higher performance materials that offer energy savings for electrical equipment. The potential for improving energy efficiency in production, transmission and use makes thin gage Silicon-iron (Si-Fe) increasingly attractive as an alternative for components and machinery that use electrical steel.

This paper outlines some of the inherent advantages thin-gage Si-Fe offers in many applications and explores some of the key energy saving considerations that may make thin-gage Si-Fe the best option for many types of equipment.

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Introduction

Demands for improved electrical device efficiency, which started decades ago due to economic factors, have accelerated, propelled by the unprecedented rise in energy costs and given further impetus by the alleged impact of energy consumption on global weather instability. This drive for efficiency has forced those who design and specify electrical equipment to take a serious look at performance factors that relate to the materials used.

The single most-utilized material in electrical devices is the soft magnetic flux-carrier. And the most commonly used soft magnetic material is silicon-iron, Si-Fe, often referred to as "electrical steel". The two largest uses for electrical steel are 1) transformers or inductors and 2) motors or generators. For each of these broad categories of equipment, different characteristics of the flux carrier are of greater interest for improving performance and reducing energy cost.

Transformers and inductors are used by utilities for electrical power distribution and in virtually every power supply in every electrically powered electronic device in industry, offices and homes. Even incremental increases in efficiency for transformers, for example, can result in significant energy savings.

Motors, once almost exclusively industrial, are finding more and more uses in home, office, automotive, and recreational devices. A striking example where higher efficiency with thin gage Si-Fe has high value is in the automotive arena, with the traction drive motor in hybrid and fully electric vehicles to reduce weight and increase driving range.

Whether the interest is in improving the efficiency of transformers or of rotating machinery, Si-Fe can be a solution that yields higher output and gains in efficiency and performance.

Electrical motor-driven systems consume over half of the transmitted electricity in the U.S.

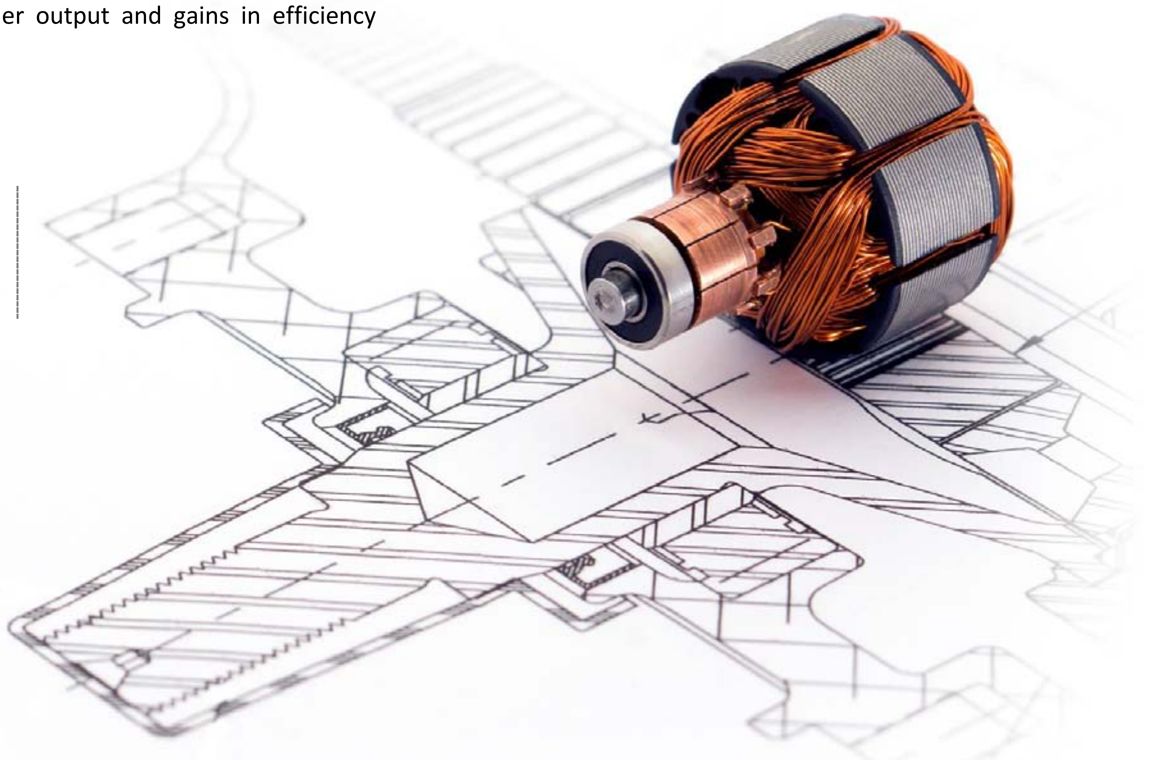
Increasing Motor Efficiency

When the total cost of ownership-over-time is considered, the operational cost of a motor far outweighs the original purchase price. Thus, the argument for higher efficiency is significant for those paying attention to total cost, rather than just initial purchase price.

Total cost of ownership (TCO) is strongly correlated to energy cost over the product lifetime. More than 95% of an electric motor's life-cycle cost is the energy cost[7]. Higher efficiency not only reduces energy costs, but also means less degradation of motor components due to heat which, in turn, extends lifetime.

Question: *"Can thin gage Si-Fe be used to improve the efficiency of transformers and rotating machinery and if so what material and design characteristics must be optimized?"*

To address this question, it is helpful to understand the different types of thin gage Si-Fe and their particular advantages in these applications.



Internal Structure Matters: Grain Oriented vs. Non-Grain Oriented Si-Fe

The internal structure of Si-Fe dramatically affects its magnetic properties and end-uses. Silicon-iron is available in both Grain Oriented (GOES) and Non-Oriented (NGOES) forms. Both forms have particular advantages over alternative materials and, when optimally applied, offer opportunities for more efficient use of the electrical steel, resulting in energy and cost savings.

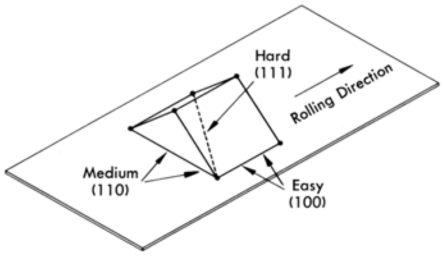
Silicon-iron consists of BCC (body-centered-cubic) crystals which, during rolling into strip, are stretched and flattened. If they are left in this state, the magnetic properties are maximized in the rolling direction, i.e. along the length of the strip. In this contrast-enhanced photo (Fig.1) we can see the elongated and flattened structure of Grain Oriented Electrical Steel (GOES). When a final heat treatment is performed, nearly isotropic magnetic properties are achieved within the plane of the strip. This is due to the almost total elimination of the grain structure.

Fig. 1: Grain structure of GOES

By the 1940's it was well known that the iron single crystal has a preferred direction along which magnetization is easier – the Goss structure[1]. This translates to higher permeability and lower core loss in the rolling direction, the "cube-on-edge" direction. It was recognized that if the bulk of the grains in a lamination can be aligned this way, the lamination can be cut to take advantage of the performance enhancement. This structure and process were developed to create the preferred orientation in the rolled silicon steel strip. The process involves a combination of cold working and heat treating to produce a strip where most of the metal grains are oriented along the rolling direction. While the material is not uniform in all directions, many components such as wound cores and stamped/ stacked E cores can be made to maximize the positive aspects of orientation.

As shown in the accompanying Figs. 2 and 3, the easy axis (of magnetization) lies along the <100> crystal axis, that is, along the edge of the cube. The "hard" axis extends from one corner to the diagonally opposite corner: the <111> crystal axis.

Fig. 2: Crystallographic structure of silicon-iron [1]



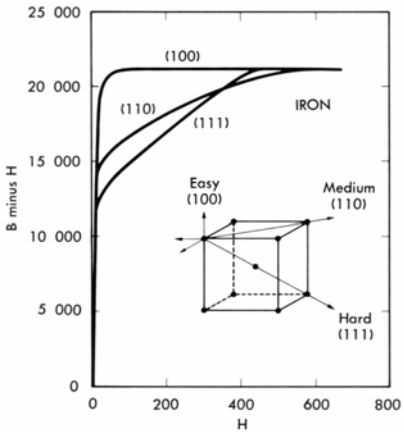


Fig.3: Magnetic properties of a single crystal of iron as measured along different crystallographic directions [1]

The directional crystal orientation of GOES provides for anisotropic properties of permeability, flux density and core loss with optimal properties along the rolling direction. The accompanying Fig. 4 from Bozorth[2] shows how pronounced the differences are and why oriented silicon-iron is so useful for transformers or inductors where the relative angles of the magnetic field and the rolling direction of the alloy strip can be closely aligned.

On the other hand, rotating machinery provides continuously changing angle of incidence of the applied field relative to the lamination steel rolling direction. Although some segmented designs are being investigated, the great majority of rotating machines use Non-Grain Oriented Electrical Steel (NGOES).

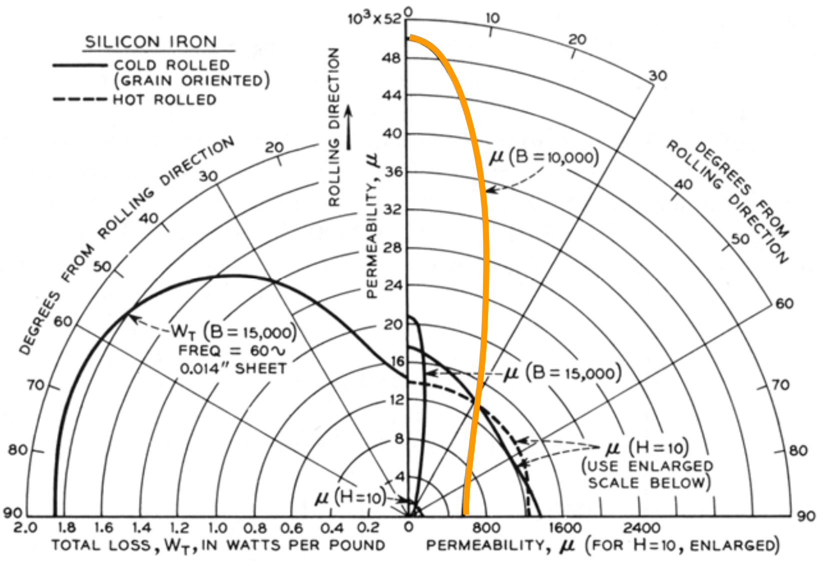


Fig. 4: Dependence of permeability and losses of hot rolled and grain-oriented (GOES) sheet on direction of measurement. Note how permeability peaks in the rolling direction. [4]

Contributors to Energy Loss

Both GOES and NGOES show energy loss of three types, graphically illustrated in Fig. 5[3] and Fig. 6.

- **Hysteresis loss**: residual energy dissipated as a function of the hysteresis properties.
- **Classical loss**: a function of several variables as shown in this formula.

$$W_{cl} = \frac{\pi^2}{6}\frac{\sigma d^2 J_p^2 f}{\delta}$$

  Where:

  W_{cl} = Classical loss per unit mass

  σ = conductivity

  δ = density

  d = lamination thickness

  J_p = Peak Polarization

  f = frequency

- **Anomalous (or "Excess") loss**: This is the difference between measured and calculated losses of the other two kinds. Efforts have been expended to calculate anomalous losses, but with limited success to-date.

While reviewing potential advantages of thin gage silicon-iron, a great many variables were identified and relationships among these variables established. This is presented in Fig. 6 in four columns. The first two columns contain input variables contributing to energy loss. The third column is a listing of Loss Contributors. As the fourth column shows, energy loss in motors (and in generators) is exhibited primarily in heat, and a small amount of loss due to vibration and stray electromagnetic fields.

Not surprisingly, many of the variables listed affect other variables. For example, as frequency increases, the skin depth is reduced, decreasing the "effective" thickness of the steel. The skin effect also causes a phase shift in the magnetic field within the steel. If the steel is adequately thick, the field can be 180° out of phase. Another example: as frequency increases, the hysteresis curve shape changes.

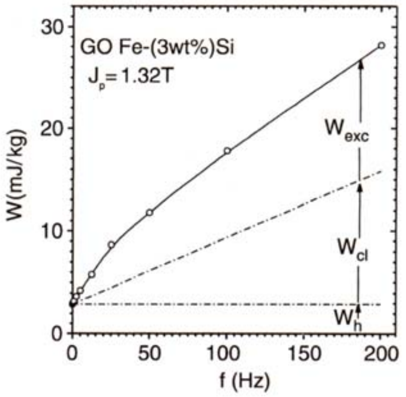


Fig. 5: Specific energy loss per cycle versus frequency [3]

Frequency is often viewed in its simplest form: that of a sinusoidal wave. While many consumer and industrial motors use power from the energy grid with little or no modification, many motor controllers make substantial changes to the applied voltage waveform. Brushless DC motors (BLDC), also called ECM's (electrically commutated motors), often use more complex waveforms[5] for energy supply. Frequency, as applied to magnetic fields, must be interpreted not in the macro sense as in 50 Hz sinusoidal current, but in the actual rate of change of voltage/current (and resulting field) in the modified waveform. The high frequency content increases with sharp transitions in the waveform, even though the applied frequency of the underlying waveform is lower.

Furthermore, one of the common motor control mechanisms is the application of voltage for variable time periods. Known as pulse width modulation (PWM), the voltage is turned on and off at very high rates of change, but may remain on or off for variable durations. The issue becomes more complex since the actual current flow which generates the magnetic field is affected by the induction of the windings.

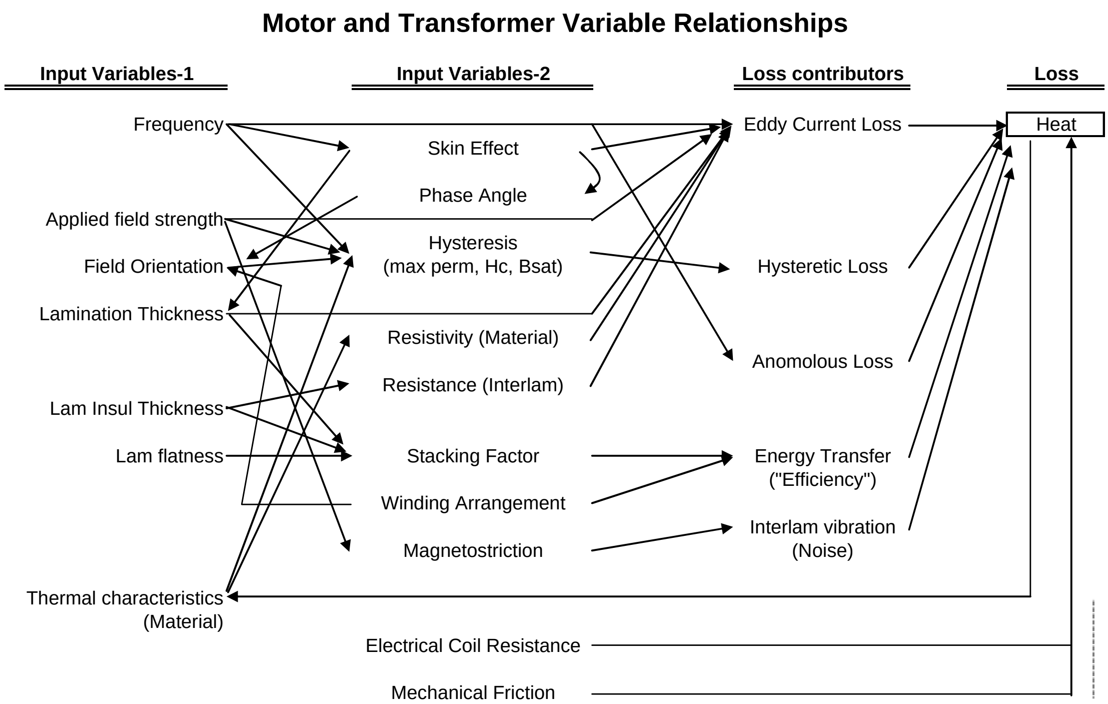


Fig. 6: Factors contributing to energy loss, most of which is heat

There are many types of pulse width modulated power systems including Clocked Turn-on (shown in Fig. 7)[4], Hysteresis, Clock Turn-off, Dual Current Mode, and Triangle (or sinusoidal) PWM.

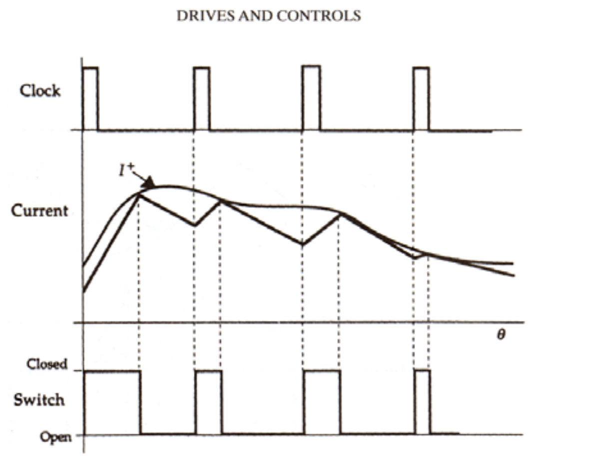


Fig. 7: Clocked Turn-on PWM waveforms [4]

As frequency increases two changes occur in the hysteresis loop of ferromagnetic steels. The first is that the value of H_{cB} increases. If all else is equal, the increase in H_{cB} results in an increase in hysteresis energy loss proportional to the increased area within the hysteresis loop.

The second change is that the hysteresis loop becomes distorted. This distortion has several contributors including eddy current and back EMF effects and domain reversal delay. The magnitude of eddy currents is proportional to the rate of change of the applied magnetic field (which is proportional to the rate of change of current in the windings). Eddy currents create a magnetic field that is in opposition to the applied field, delaying propagation of the applied field through the lamination structure. This delay results in the field within the lamination structure being out of phase with the applied field, resulting in efficiency losses.

Bozorth[2] shows us an example plot for an iron sheet of 0.2 cm thickness with an applied frequency of 1,000 Hz (Fig. 8). The solid line is the relative magnitude of the field within the sheet. By definition, the skin depth is at a distance from

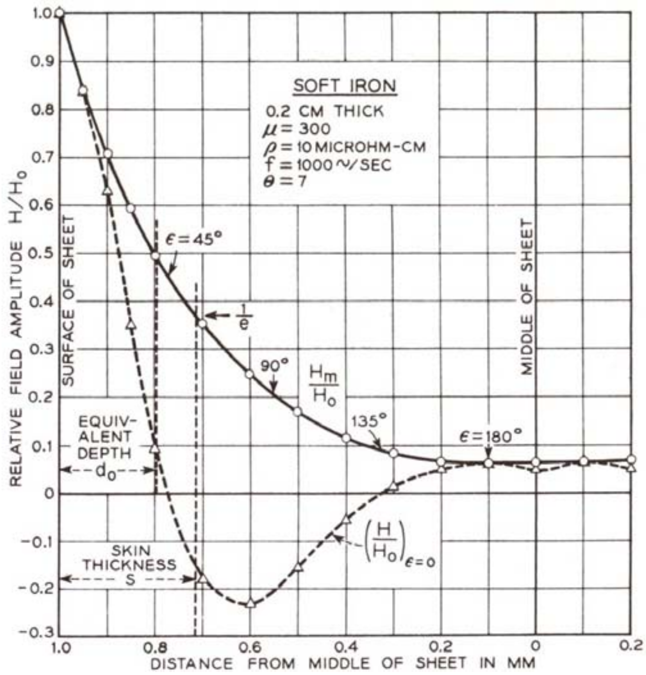


Fig. 8: Change in magnetic field strength (or induction) with position inside a sheet [2]

the surface where the field has dropped to 1/e (where e is the natural logarithm, 2.718…) or approximately 37% of the value at the surface of the sheet. In this example, the skin depth is 0.29 mm and the phase angle at this depth is one radian. This suggests that some portion of the lamination structure will be operating at well below surface field levels and, therefore, at well below steel saturation.

Silicon-iron used for laminations is nominally 3% silicon by weight. Lower silicon content has lower resistivity; higher silicon becomes difficult to roll to thin strip (too brittle). A practical upper limit is 6% silicon which is used in some thicker transformer laminations. Using published information for three alloys (Fig. 9), a plot of skin depth was created and is in close agreement with the Bozorth example for plain iron (0.29 mm at 1000 Hz).

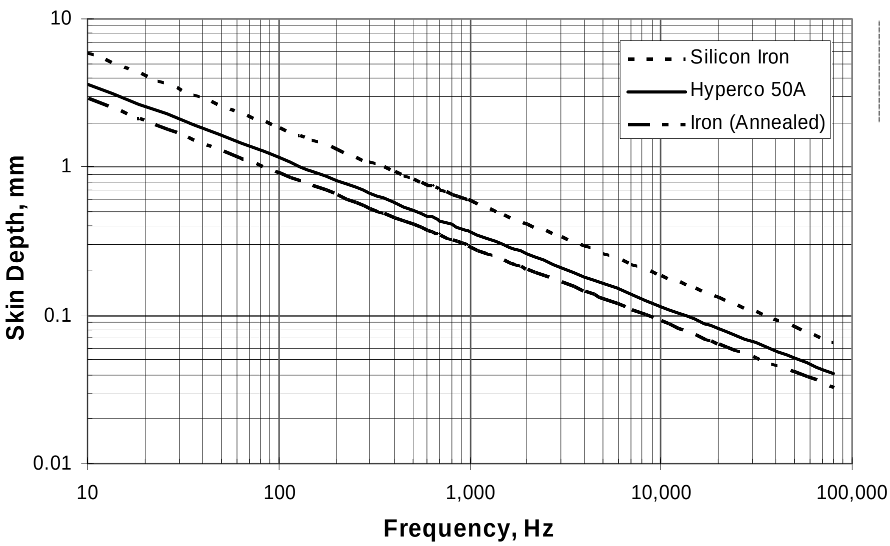
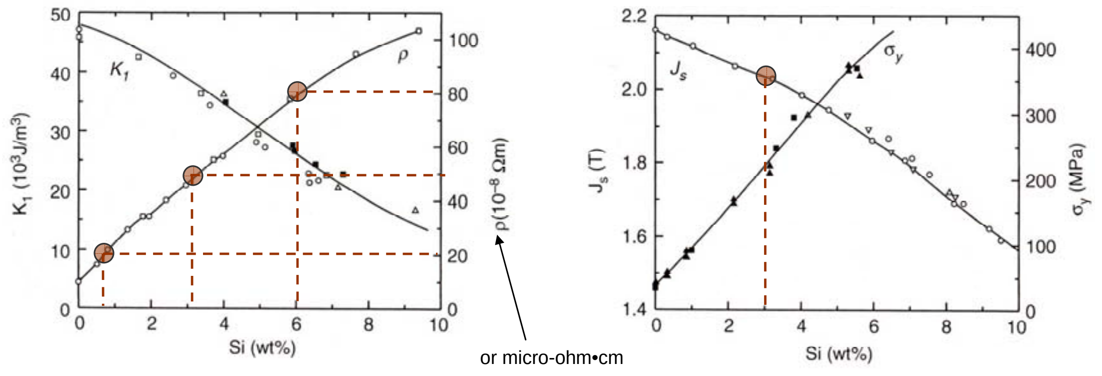


Fig. 9: Skin Depth vs. Frequency of common lamination materials

Fig. 10: Si-Fe properties vs. silicon [3]



Methods of Reducing Core Loss: Increasing Resistivity

Both eddy currents and skin depth are affected by material resistivity. Resistivity of annealed, low carbon iron is 10 micro-ohm-cm; cobalt-iron alloy 2V-permendur (*Hiperco 50®*) is 42 and 3.2% Si-Fe is 48. In addition to the ability to easily roll Si-Fe to strip form at 3.2% silicon, this is the point at which saturation magnetization is minimally affected. The accompanying charts in Fig. 10 (modified) from Fiorillo[3] show resistivity, saturation magnetization and yield stress as a function of silicon content.

In Fig. 10, points highlighted on the chart at the left show resistivity increasing from 20 to 80 micro-ohm-centimeter at low, nominal and 6% silicon weight percent values. In the chart at the right, we see that above 3% silicon the saturation magnetization falls off more rapidly. The practical maximum Js value for 3.2% silicon-iron is actually about 1.9 Tesla. The stress curve shows a rapid, linear increase with silicon content with the alloy becoming untenably brittle above 6% silicon.

Methods of Reducing Core Loss: Hysteresis Curve

Core loss is proportional to the area within the hysteresis loop. This area represents the work required to magnetize and then reverse the magnetic orientation of the material. Traditionally, it has been thought that two criteria were necessary for optimal performance: a low value for H_{cB} and a very square loop shape. Advantageously, the H_{cB} value for Arnon is lower than for other commercial Si-Fe materials, providing lower core loss, and the saturation magnetization is high. All the lamination structure is not driven to saturation, a problem that worsens as frequency increases, nor is the entire structure simultaneously driven to the same point on the hysteresis curve.

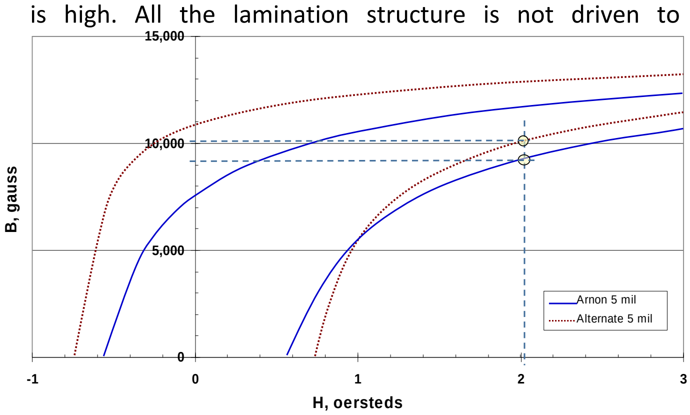


Fig. 11: Comparison of Arnon 5 and alternate Si-Fe product

Let's examine core loss measurements for two samples of 0.005" Si-Fe lamination steel (as measured by a third party). For clarity, only measurements taken at 50 and 400 hertz are shown. (Fig. 12)

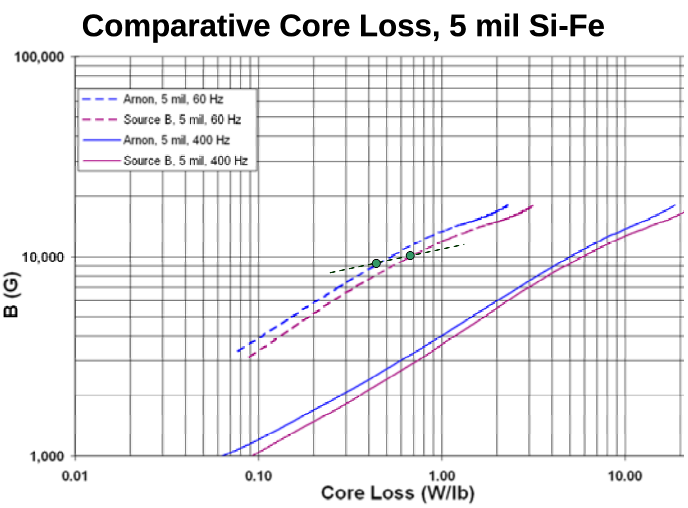


Fig. 12: Comparative core loss accounting for variation in B for a drive field (H) of 2 oersteds

Both materials are 0.005" thick silicon-iron. At a drive field of 2 oersteds (in the first quadrant), the Arnon 5 exhibits an induction of 9200 gauss; the alternate material exhibits 10,000 (Fig. 11). If we now refer to the core loss chart for these materials (Fig. 12) we can compare the losses of these materials at the same drive field. Core loss for the Arnon 5 is 34% lower than for the alternate material. The H_{cB} values for the two materials are:

- Arnon 5: 0.59 Oe
- Alternate Material: 0.67 Oe

This is only a 12% difference in H_{cB} but would result in approximately a 25% difference in area within the hysteresis loops for similar shape loops and corresponding energy savings.

Advantageously, the H_{cB} value for Arnon is lower than for other commercial Si-Fe materials, providing lower core loss.

Stacking Factor Considerations

As lamination thickness decreases, the insulating coating represents a greater percentage of strip thickness (Fig. 13). Coating on Si-Fe is generally the C-5 type and applied to a finished thickness of 0.000075" (0.002 mm). 0.014" (0.35 mm) Si-Fe strip coating represents 1% of the total thickness. At 0.005" (0.13 mm) metal strip thickness, the coating represents 3% of total thickness. This factor should be taken into account for device design, since only the Si-Fe metal provides a flux path.

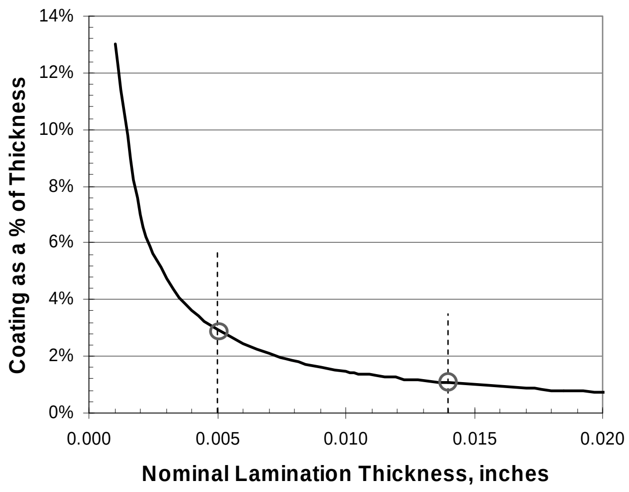


Fig. 13: Coating as a % of lamination thickness [14]

Rolled alloy strip is not perfectly flat. This aberration from flatness shows up in two major ways: 1) wedge from edge to center and edge to edge and in 2) waffle texture. Another name for waffle texture is waviness, an undulating deviation from a perfectly flat strip.

Wedge effect can be minimized by rotating each subsequent lamination by a fraction of a full turn, for example, 45°. The stack will be less than fully dense, but will build up to the same height at all points around the perimeter. Waffle or waviness cannot be eliminated except in the strip manufacturing process and even a well-controlled process will produce some amount.

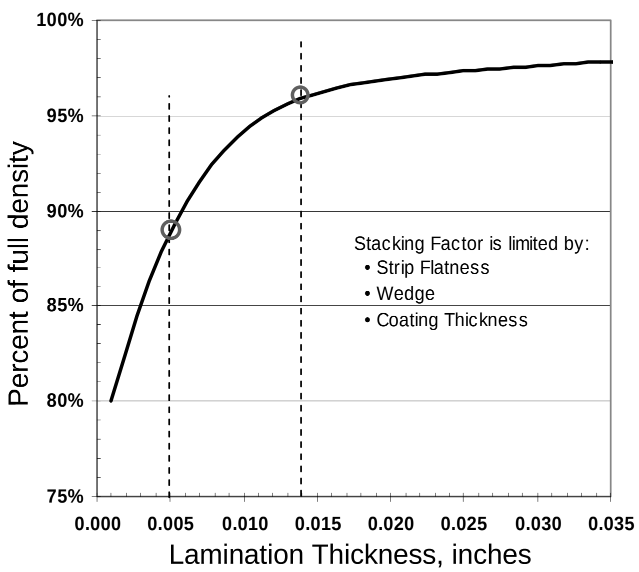


Fig. 14: Stacking Factor

The combination of coating, wedge and waffle result in a stack that is less than 100% metal alloy. Actual production values reach as high as 98%. Thinner strip results in lower values of metal "loading" as shown in Fig. 14 and more laminations are required to stack to the same overall thickness. For example, a 50 mm stack height would require 136 laminations of 0.014" (0.35 mm) thickness (97% stacking factor) or 350 laminations of 0.005" (0.13 mm) thickness (89% stacking factor). There is a commercial trade-off between additional cost of the thinner lamination structure versus the improvement in performance.

Methods of Reducing Core Loss: Reducing Lamination Thickness

Reducing lamination thickness is a common method for reducing core loss. (Fig. 15) Lamination thickness has historically been ~0.030" (0.75 mm) in devices for use with commercially supplied electricity at 50 and 60 Hz. Increased efficiencies have been achieved through use of laminations of 0.014" (0.35 mm). Large steel mills now produce laminations down to 0.009" (0.23 mm). Specialty and very high frequency applications demand still thinner gages. GOES steel has been routinely supplied at 0.001 to 0.006" (0.025 mm to 0.15 mm) for demanding transformer applications and at 0.005 and 0.007" (0.13 and 0.18 mm) in NGOES grades for high speed or high power density rotating machinery.

Arnold's Arnon® 5 and Arnon® 7 have recently been re-measured for core loss over a range of frequencies from 60 to 20,000 Hz. Below about 400 Hz there is little difference in core loss between the two materials, though Arnon 5 can still be of benefit to demanding applications. Above 400 Hz, the difference becomes exponentially larger and the benefits of thin gage become pronounced.

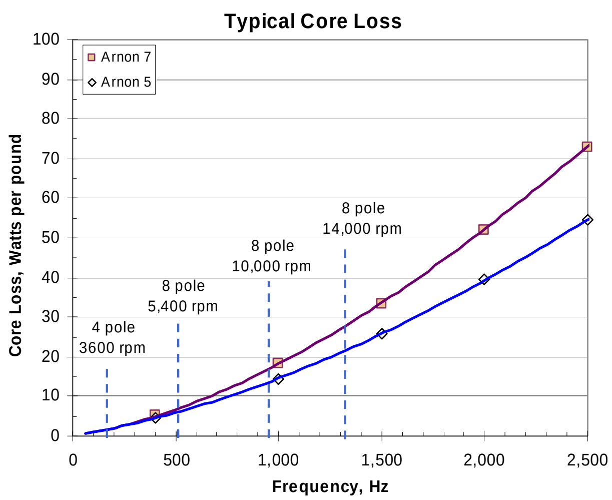


Fig. 15: Core loss vs. frequency for 0.005 & 0.007" Si-Fe

Thin-gage grain-oriented Si-Fe is particularly advantageous for high-frequency transformer applications. The benefits of thin gage Si-Fe become more pronounced for frequencies above 400 Hz.

Comparison of Silicon-Iron with Other Materials

Selecting the optimal material is not just an issue of gage, but can include factors such as saturation magnetization, permeability and the other variables shown earlier in Fig. 6.

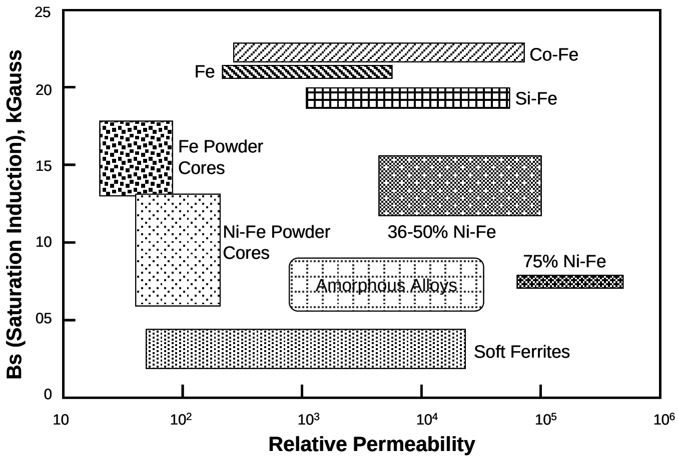


Fig. 16: Relative permeability versus saturation magnetization for selected soft magnetic alloys

Both higher relative permeability and higher saturation magnetization generally provide better electrical device performance (Fig. 16). By comparison, Cobalt- iron provides the highest saturation while nickel-iron has the highest relative permeability. Silicon-iron is almost as high in saturation as cobalt-iron. (Low carbon) Iron has potentially high relative permeability but must be “dead” annealed. Any mechanical stress or contamination in the composition greatly reduces its performance.

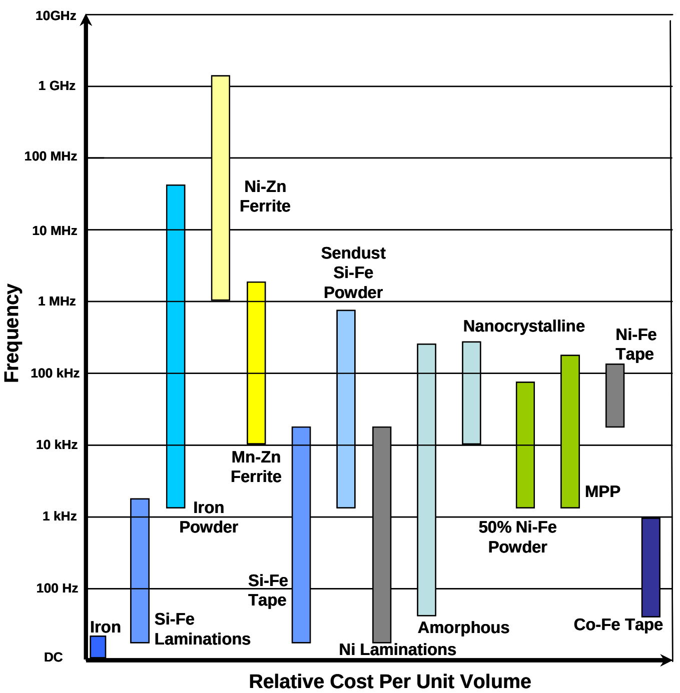


Fig. 17: Relative material cost versus usable frequency range for selected soft magnetic materials

Material cost (Fig. 17) has dominated material selection for consumer and general industrial equipment for decades. Legislated higher efficiency standards will push designers to use higher performing materials. However, cost will always be a significant factor. Systems engineers will feel increasing pressure to alter designs to favor lower cost, abundantly available materials.

There are a growing number of equipment applications where Si-Fe is a clear favorite, its efficiency advantages far outpacing cost considerations. These include many types of high density power equipment, totally enclosed motors, and motors, transformers, and inductors in medical environments as well as heat-sensitive equipment in general. Thin gage Si-Fe is particularly advantageous for high-frequency transformer applications. For rotating equipment, because heat generation is a key factor in wire insulation breakdown and bearing failure, the use of thin gage Si-Fe often translates into longer equipment life and improved reliability.

For rotating equipment, the use of thin gage Si-Fe and other high efficiency materials often means longer equipment life and improved reliability.

Manufacturing NGOES

Arnold Magnetic Technologies has been manufacturing Arnon® thin gage electrical steel for over 50 years. To obtain optimal performance requires at least these ten manufacturing steps.

- Melting and continuous casting of slabs
- Hot Rolling to thickness of ~2 mm
- Pickling and cold rolling to intermediate gage
- Annealing (750 to 900°C)
- Cold rolling to final gage (0.13 – 0.35 mm)
- Decarburization & re-crystallization anneal (830 – 900°C)
- Final anneal (850 – 1100°C)
- Coating (cleaning, coating, drying)
- Slitting to width
- Laser cutting or punching to shape

Also, to optimize properties after final shaping (punching, bending) an annealing process is performed on the finished product. This extensive process is responsible for the superior magnetic properties, but results in a higher priced product which is often justified for applications requiring minimal heat build-up or performance at very high switching frequencies.

Summary

Measurements of energy efficiency of prototype and production devices repeatedly show thin gage Si-Fe to outperform other materials at higher frequencies with the performance differential increasing rapidly above 400 Hz. Marketplace feedback indicates a 35 to 50% improvement over conventional silicon-iron laminations and this is empirically confirmed in core loss and magnetic measurements.

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