Selecting Optimal Lamination Materials

Steve Constantinides; Orlando, Florida; January 23, 2019

Slide 1: Title Page

Slide 2: Why is the selection of soft magnetic material important?

- Perhaps the material limits the performance of the device you are designing.
- Or the optimal performance material costs too much.
- Iron-Cobalt is a high-performance material, but the cost and availability of cobalt is in question.
- Or is your need to improve efficiency to meet increasingly tough mandated standards and competition.

Slide 3: Key Figures of Merit (Main ones)

- How does one select an optimal material?
- What metrics are used to evaluate or predict material performance?
- Electrical resistance affects eddy current and coercivity affects hysteresis loss of the material, both of which cause the material to absorb energy and heat up.
- It is the nature of the materials that most (but not all) magnetically soft materials are also physically “soft”. That is they are malleable – can be rolled to thinner strips or bent to shapes.
- If the material is deformed or mechanically worked, it may be desirable to thermally anneal it to re-establish low H_{cB}.

Slide 4: Key Figures of Merit (Other)

- And there are other important characteristics that determine how well a material will perform.

Slide 5: Key Figures of Merit (Cost)

- Perhaps the overriding characteristic for consumer applications is material cost.
- However, demanding applications requiring performance in small volume, low weight, and super high output will be less concerned with material cost and more with ultimate performance.

Slide 6: Cost of Operation - Calculations

Two points:

- First, efficiency improvements in small motors (first column, 0.5 HP) will have a small effect on overall operating costs and national electricity consumption.
- Still good to go after for new motor purchases, but less bang for the buck than large motor efficiency improvements.
- Second, increases in cost of electricity have a profound effect on operating costs and on the benefit of improved efficiency.
- Compare the last two columns.

Slide 7: Permeability and Saturation

- The magnetic properties of interest for soft magnetic materials lie in the 1st quadrant of the hysteresis loop and in the complete loop.

- The two most interesting values in the 1st quadrant are the maximum permeability which is the slope of a line from the origin to the "knee" of the curve such as the dashed line in this chart intersecting the Supermendur curve at the marked location.
- The higher the slope, the easier the material is to magnetize.
- The second figure of interest is the saturation magnetization – on these curves, the value of intrinsic flux density, J_s.
- The value for Deltamax is noted on the chart.

Slide 8: Hysteresis Energy

- A magnetically "soft" material has very small H_{cB} and the area within the loop is small, such as for the green curve shown here.
- On the other hand, a permanent magnet exhibits a much greater H_{cB} and a larger area within the loop as shown in the tan portion of the figure.
- Both curves shown here are Normal curves.
- The green "soft" material is typical of silicon iron (Si-Fe) and the tan curve is typical of alnico 8.
- The energy to force a magnet around the loop is proportional to the area within the loop.
- Therefore, transformers and laminations in motors subjected to AC fields benefit from being made of soft materials with very low H_{cB} and correspondingly small areas within the loop.
- Notes about terminology:
- The values of B_S represent the magnetic saturation and H_S is the applied field strength at which saturation occurs.
- For reference, B_S has been used to represent the point of saturation on both the normal and the intrinsic hysteresis curves. Alternate symbols are B_{is} and B_{sat} for saturation on the intrinsic curve. The preferred symbol (and terminology) on the intrinsic curve is J_S, saturation polarization.

Slide 9: Hysteresis Loss – Frequency Effect

- When the frequency of the applied magnetic field is increased, hysteresis loss also increases.
- This is manifested as an increase in the area within the hysteresis curve(s). (See the left chart).
- Also as frequency increases, another aspect of core loss begins to appear, distortion of the hysteresis loop due, in large part, to eddy currents.

Slide 10: Core Loss

- When soft materials are used in stators (and rotors) of motors and generators, we can measure the delta between energy input and energy output.
- That difference is known as core loss and is divided into three types as noted here.
- The Steinmetz equation, in original form or the improved general Steinmetz equation are used to mathematically describe the loss.
- The most dependable way to determine core loss is to measure samples.
- For example, one source of core loss, eddy currents, can be dramatically affected by lamination shorting at edges, from irregularities during punching and stacking, or from imperfections in the insulating coating which provides lam-to-lam contact.

Slide 11: Loss Variable by Category

- This slide demonstrates the complexity for the set of variables involved with selecting the proper lamination material grade and thickness.
- Lower efficiency is mostly the result of energy being converted to heat.
- Note that many of the variables are interactive. For example, switching frequency affects how deep the field will penetrate a lamination which affects required lamination thickness which affects stacking factor, etc.
- The use of thin gauge alloy can minimize the losses associated with many of these variables but introduces its own set of problems.

- These variables can be grouped into similar categories for further discussion as desired and the 5 groups have been created here as shown in the upper right of the chart.
- Simplifying this graphic is likely a Sisyphean task.

Slide 12: Core Loss Measurements

- Core loss is presented by manufacturers in charts such as this one for 11 mil (0.28 mm) silicon-iron.
- The test can be performed on strips mounted in an Epstein Frame or on strip rolled into toroidal shape.
- Stressing the material during handling requires annealing prior to performance of the test.
- Core loss is measured as a function of frequency and induction resulting from varying magnitude of applied field strength.

Slide 13: Soft Magnetic Material Forms

- Soft magnetic materials are used in three forms: bulk solid, thin sheet or strip, and powder.
- Each form has its benefits and shortcomings. Each is processed in different ways to get optimized magnetic and mechanical properties.
- Bulk materials are large formed shapes, usually annealed after manufacture to minimize H_{cB}.
- Sheet or strip products are characteristically much thinner than they are wide or long. These are most commonly produced by rolling block material but may also be formed by melt-spinning thin strip.
- Powders are materials that are directly formed as a powder, for example by atomizing, or are made into powders by milling bulk forms. Powders are usually used to make larger shapes after the powder is processed through compacting or molding.

Slide 14: IEC Classifications

- Soft magnetic materials: H_{cB} <1 kA/m

Slide 15: Slater-Pauling Curve

- The Slater-Pauling curve shows the calculated magnetization for several transition elements (Period 4 of the Periodic table) and for binary combinations.
- The highest magnetization is exhibited by a mix of iron and cobalt at approximately 2.4 Bohr magnetons.
- The calculated value is very close to that achieved in products such as Supermendur and vanadium Permendur.

Slide 16: Soft Magnetic Materials: Composition and Properties

- This is a listing of most of the commercial soft magnetic materials showing generic chemistry and typical properties.
- Most of these alloys contain iron with either (or both) cobalt and nickel.
- The highest saturation materials contain cobalt.
- All but a few are crystalline. The two non-crystalline materials shown are Metglas® which is processed to remain essentially amorphous – that is without long range crystalline structure.
- While the saturation magnetization of Metglas® is lower, the maximum permeability can be exceptionally high - meaning there is little resistance in the material to exhibiting an induced field.

Slide 17: Comparing Magnetic Properties

- There is a trade-off between magnetization and coercivity.
- Plotting the coercivity, H_{cB}, against the saturation polarization for a number of commercially important materials results in this chart.
- A large H_{cB} indicates that the material will most likely have high (hysteresis) core loss.
- From this loss standpoint, the 80% Nickel alloys, with low H_{cB}, are desirable.
- Where high saturation (flux carrying capability) is required, silicon iron and iron cobalt are desirable.
- Iron cobalt is used less often than silicon iron as it is far more expensive.

Slide 18: Saturation versus Permeability Comparisons

- This slide plots the saturation induction versus permeability for common soft magnetic materials.
- Both properties are desirable.
- From this data, one can see that while the Co-Fe alloys are expensive, they are among of the best performers.

Slide 19: Resistivity of Silicon-Iron (Si-Fe)

- While it's possible to make a motor without a permanent magnet, it is extremely difficult to do so without a flux path provided by soft magnetic components.
- The most common soft magnetic material has been silicon-iron (Si-Fe).
- Silicon added to iron increases the resistivity thus reducing eddy current loss.
- An optimal silicon content is between 3 and 6.5 weight percent. At 3 weight percent, the alloy is adequately malleable to allow rolling to thin gauge.
- At 6.5 weight percent, the alloy is far more brittle but 70% greater resistivity.

Slide 20: Magnetostriction of Si-Fe

- Magnetostriction of 3% grain-oriented Si-Fe varies from about 23 in the easy axis to a negative 6 in the hard axis of orientation - - both numbers x10E-6.
- At ~6.5% Silicon, magnetostriction reaches a minimum. However, at this level of silicon, the alloy is too hard to roll successfully, especially to thin gauge.

Slide 21: 6%+ Si-Fe and other Material Research

- A Japanese company, JFE, supplies 6.5% Si-Fe made by diffusing silicon into the thin lamination strips after rolling to desired thickness and prior to stamping/forming.
- The process adds significantly to the cost and a less expensive way of achieving 6.5% silicon content is being sought by researchers in several countries.
- Soft magnetic alloys are heavy – density around 7.5 +/-. There would be cost savings to having lighter devices – such as in transportation (airplanes and cars). AK Steel has been funded to lead research on this.

Slide 22: Metglas

- Soft magnetic alloys can also be melt-spun resulting in remarkable properties.
- The company that spearheaded this development was Allied Signal.
- Allied Signal purchased Honeywell and then took the Honeywell name. Shortly thereafter, the Metglas® business unit was sold to Hitachi who remains the owner.
- The name Metglas® is apropos as the materials are amorphous, i.e. non-crystalline – just as glass is a non-crystalline solid.
- Some grades of Metglas® have extraordinarily high maximum permeability (ease of magnetization) such as grade 2714 with μ_{max} of 1,000,000.
- However, there is frequently a trade-off between maximum permeability and saturation magnetization.

Slide 23: Amorphous Metal for Motors

- Can amorphous materials be used in motors?
- The materials are sensitive to handling – mechanical deformation increases H_{cB} and reduces maximum permeability.
- Through proper processing and device design, Hitachi has shown a potential for use of Metglas® in motors.

Slide 24: 3D-Printing

- Exmet of Sweden has IP regarding 3D-Printing of amorphous metals.

- Researchers at CAMAL have produced bulk amorphous structures using the Exmet process.

Slide 25: 3D-Printing (cont.)

- Yiyu Shen at Missouri University of Science & Technology published his thesis in the spring of 2018 on "Research on additive manufacturing of metallic glass alloy". During the course of study and publication, bulk amorphous alloys were produced.
- Ref: http://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=3693&context=doctoral_dissertations

Slide 26: Nano-crystalline

- Another family of materials are nano-crystalline soft magnetic alloys.
- These go by the trade names such as:
  - Finemet® - Hitachi
  - Nanoperm® – Magnetec GmbH
  - Vitroperm® – Vacuumschmelze
- Each material offers benefits with trade-offs in properties, handling, manufacturability, cost, etc.

Slide 27: Summary Data

- Giselher Herzer has published numerous papers on soft magnetic alloys. Two of note are from:
  - 1996 from which Table 1 is extracted and shown here
  - 2013 with much up-to-date information (see reference list on last slide).

Slide 28: References

- Four particularly substantive references regarding soft magnetic materials.

End