Characterization of Power Losses in Soft Magnetic Materials

Aleta T. Wilder

Abstract- The power density of electric machines may be increased by designing for operation at higher rotation speeds and temperatures. Such operation increases the mechanical stresses, frequency, and temperature attained in the soft magnetic materials. Increased power losses in the magnetic material can be quantified empirically by controlled hysteresis experiments allowing improved simulation of machine operation. Standard hysteresis experiments operate at ac excitation, room temperature, and no applied mechanical stress. This is the extent of variables considered by some electromagnetic simulation programs. The involved research community is currently developing semi-empirical models that account for additional power losses due to rotation, pulse waveform modulation, compressive stress, and residual forming stresses and/or machining damage. Concurrently, models also account for reduced power losses due to tensile stress and increased temperature. This paper will discuss a model for each environmental variable using the performance of Hiperco®50HS (a cobalt-iron-vanadium steel) as an example.

Index Terms- magnetic loss, magnetic hysteresis, magnetic variables measurement, soft magnetic materials

I. INTRODUCTION

In rotating electric machines, soft magnetic laminate materials convert electrical power into torque. Materials processing during manufacturing and machine operation can influence the core power loss associated with this conversion. Some simulations of electric machine operation use dc permeability data and 50/60 Hz loss data, extrapolating to other sinusoidal frequency regimes using an eddy current relationship (described later in this paper). Unfortunately, this type of input data can seriously underestimate total power losses.

Commercial software is now available to accommodate induction and power loss performance maps that more accurately represent the behavior of the soft magnetic laminate material [1]. Similarly, the involved research community has made progress in developing semi-empirical models that can be used to extrapolate sinusoidally excited hysteresis behavior at zero applied stress and room temperature to applicable environments projected for the magnetic cores in prototype electrical machines. Sinusoidally excited hysteresis behavior is relatively easy to obtain. Measurement guidelines and commercial hardware for this purpose are available from several sources.

The total power loss may be discussed in terms of three additive components: the hysteresis (or dc "frequency independent") loss, the eddy current ("classical") loss, and the anomalous ("excess") loss. A general review of the subject is given in [2].

Use of accurate magnetic performance maps is extremely important when designing innovative, power dense, electric machines where higher rotation speeds and temperatures are sought. Not only can thermal loads be more accurately calculated, the designer may also more effectively modify the design and power controls to optimize performance.

This paper seeks to draw attention to the major environmental variables that effect power loss. Simplistic values of total specific power loss differences are used for comparison purposes, only; and more in-depth references are sited. For reasonable comparison, Hiperco®50HS [3] (a high-strength 49Fe-49Co-2V commercial laminate sheet) is used exclusively at a thickness of 0.0152 cm (0.006 in.). The effects of environmental variables on other hysteresis properties are also described. The effects described here should not be extended to soft magnetic laminates (particularly amorphous materials) close to phase transformations such as the Curie point. A description of magnetic behaviors close to phase changes is also reviewed in [2].

II. EXPERIMENTAL

Pieces of Hiperco®50HS sheets were stacked, fixtured, and turned on a lathe to an outer diameter of 3.810 cm (1.500 in.) and an inner diameter of 3.2385 cm (1.275 in.), meeting the requirements in [4]. The rings were carefully cleaned and electrically isolated using thin layers of paper. A ring stack was then wound with primary (excitation) and secondary (induction) coils. Sinusoidally excited hysteresis behavior was then measured following the guidelines in [4]. All hysteresis measurements reported here were made using a Walker Scientific LDJ AMH-25 hysteresisgraph. Measurements at temperatures other than room temperature were carried out by immersing the toroid in a temperature controlled bath of polyethylene glycol.

The total specific power losses of the annealed toroid reported in Fig. 1 are higher than those reported in [3] for Hiperco®50HS and lower than reported in [5]. The differences are likely due to variations in the annealing processes and in the dimensions of the toroids.

III. DISCUSSION OF ENVIRONMENTAL VARIABLES

The following discussion includes the effect of temperature, machining damage, mechanical stress, rotational losses, and various waveform excitation schemes.

This work was supported by the U.S. Office of Naval Research through the Electric Ship Research and Development Consortium. Aleta T. Wilder is with the Center for Electromechanics- The University of Texas R7000, Austin, TX 78712 (e-mail: *a.wilder@mail.utexas.edu*).

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A. Temperature Effect

Power losses decrease in nonoriented crystalline, soft magnetic materials as temperature increases. A well-known equation used to approximate specific eddy current power loss at full flux penetration and at frequencies below 500 Hz is

$$P_e = \frac{\left(\Pi^2 B^2 t^2 f^2\right)}{\left(6\times10^7\, d\, \rho\right)} \text{Watts / kg},$$

where flux density (B) is in Gauss, frequency (f) in Hz, laminate thickness (t) in cm, density (d) in g/cm^3, and electrical resistivity (ρ) in μΩ-cm. This suggests a decrease in eddy current power loss proportional to the reciprocal of resistivity. Hysteresis of the annealed Hiperco®50HS toroid at 10,000 G was measured between 3°C and 100°C. In this temperature range, the increase in electrical resistivity can be approximated as a linear function of temperature [3]. For Hiperco®50HS, the change in resistivity from 21°C to 100°C is only 1.00 μΩ-cm. The corresponding change in specific total power loss as a function of frequency is shown in Fig. 2 for both measured and calculated values. Given a constant flux density and frequency, other characteristics such as coercivity, remanence, and squareness ratio did not vary significantly within this temperature range. Alloys having a greater increase in resistivity with temperature can exhibit a larger power loss dependence on temperature [4].

B. Forming Stresses and/or Machining Damage

Residual stresses or irreversible (plastic) strain are detrimental to magnetic properties for rotating machines. This includes anisotropy in the laminate sheet. Machined or stamped laminates may be partially or fully annealed as an assembly step to minimize losses due to forming stresses and machining damage. If however, laminate stacks are given a final lathe cut, machining damage may be present. The associated increased losses with plastic (irreversible) strain are well known, and an example is shown in Fig. 3. The sample was prepared by stacking several rings with laminate edges cut on a lathe to form a toroid. After measurement, the rings were annealed for comparison measurements. The difference is observed in both the dc loss ("hysteresis loss") and in frequency-dependent losses.

The increased power loss due to the machining damage is proportional to the total power loss of the annealed material at a specified frequency and induction as demonstrated in Fig. 4.

It is important to recognize that the induction response of the material to the applied field is greatly affected by the forming and/or machining stresses as shown in Fig. 5.

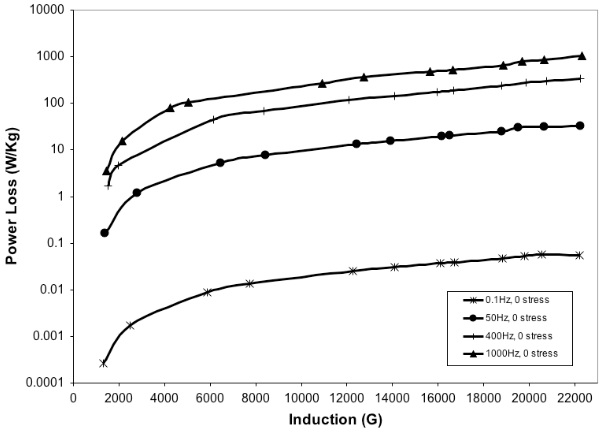

Fig. 1. Total specific power loss vs. induction of annealed Hiperco®50HS at room temperature.

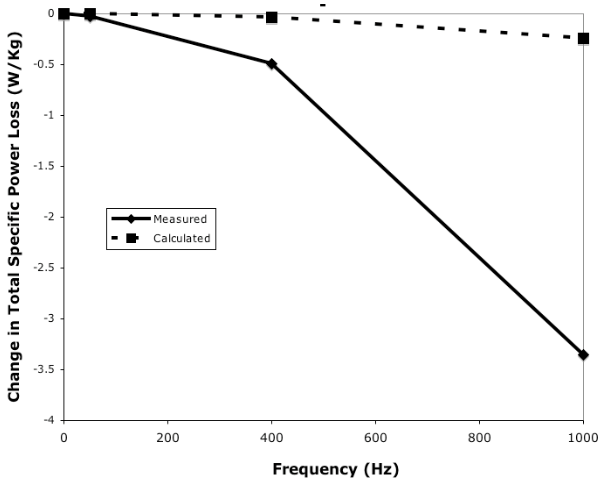

Fig. 2. Change in total specific power loss of Hiperco®50HS at 10,000 G from 21°C to 100°C vs. frequency.

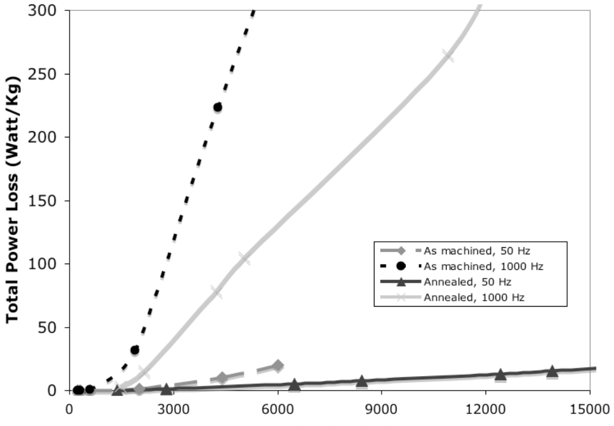

Fig. 3. Total power loss of as-machined Hiperco®50HS vs. induction.

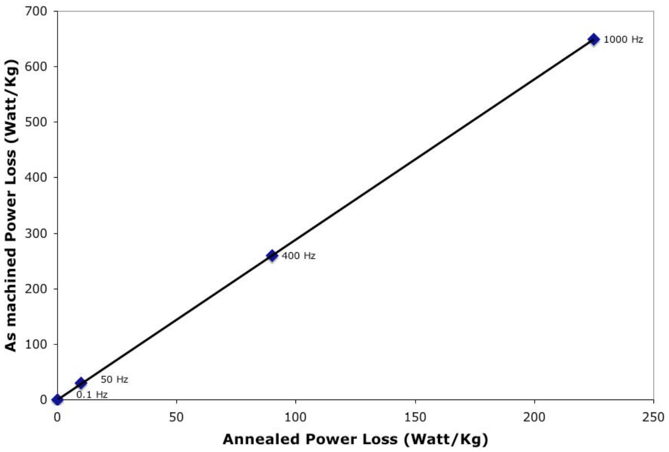

Fig. 4. Total power loss comparison of as-machined and annealed Hiperco®50HS with frequency at 10,000.

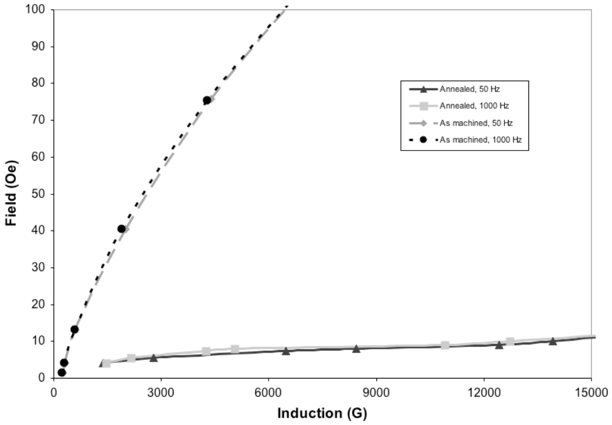

Fig. 5. Permeability curves of as-machined and annealed Hiperco®50HS.

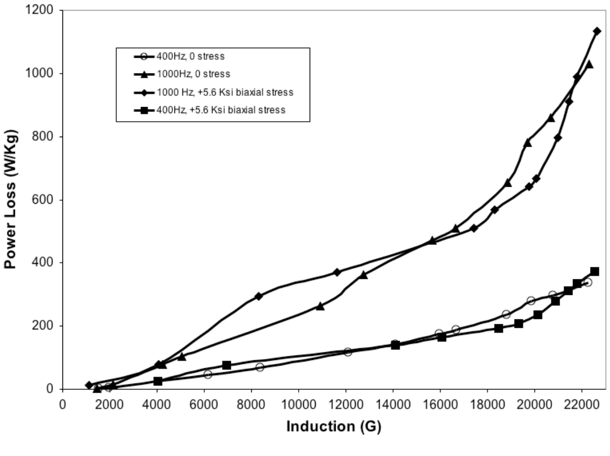

Fig. 6. Total specific power loss of Hiperco®50HS vs. induction under no load and +5.6 ksi biaxial stress.

C. Mechanical Stress

The effect of elastic (reversible) stresses on total specific power loss is indicated by the sign of the magnetostriction under operation conditions. Hiperco®50HS exhibits a relatively high, positive magnetostriction. Examples of these sorts of stresses in rotating machines are end-ring compression, results of methods of securing the rotor core to the shaft, as well as centrifugal (biaxial, in-plane) stresses developed during operation. Although useful models have been published on this topic [8,9,10], currently the effects of elastic mechanical stress must be measured.

1) Uniaxial compressive stress

A recent study reported the effects of uniaxial compressive stress on a wound toroid sample of Hiperco®50HS perpendicular to the laminate ("ring") plane. The total specific power losses of Hiperco®50HS increase exponentially with applied uniaxial compressive stress [11]. Using sine excitation, the peak flux density was kept constant at 18,000 G and the frequency was varied between 400 and 1500 Hz. At a stress of -4 ksi and 1,000 Hz, the total specific power loss increased by +150 Watt/kg.

Coercivity, remanence, and permeability also change in a complex manner with compressive load. The values of parameters are lower than at the zero stress state. The eddy current loss component is not expected to change as resistivity remains constant. An increase in the anomalous loss component of the total loss is suggested to be responsible for the increase in power losses due to this compressive stress [11].

2) Uniaxial tensile stress

It is anticipated that an uniaxial tensile stress in the laminate plane will cause a decrease in total specific power loss. The data presented in [12] for Hiperco®50HS suggests a generally linear decreasing trend. These measurements were made at a peak flux density of 18,000 G and at 1,000 Hz. At an applied uniaxial stress of +4 ksi, the total power decreased by -6.6 Watt/kg. The absolute value of this change in power loss is not as dramatic as with uniaxial compressive loading.

3) Biaxial tensile stress

Application of biaxial, in-plane tensile stress has an interesting effect on total power losses for Hiperco®50HS [13]. A comparison is shown in Fig. 6 for a toroid sample at +5.6 ksi and no applied stress as a function of induction. The slightly higher loss measured between ~4,000 to 14,000 G and slightly lower loss measured between ~14,000 to 21,000 G with biaxial stress was observed at 50, 400, and 1,000 Hz. The decreased loss at higher inductions may be advantageous in rotor cores.

The permeability curve shown in Fig. 7 for this same experiment emphasizes that other magnetic parameters of importance in machine design can be greatly affected by biaxial tensile stress. These parameter differences should be noted in effectively choosing laminate materials.

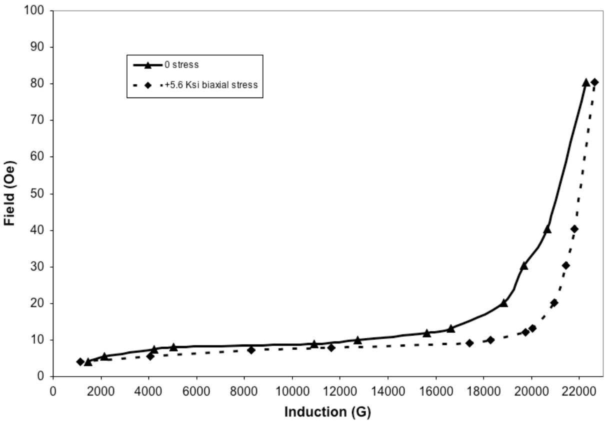

Fig. 7. Permeabiliy curves for Hiperco®50HS at 1,000 Hz with no applied stress and +5.6 ksi biaxial stress.

D. *Rotational Losses*

Rotational losses occur when the applied field is at an angle to the magnetization. Localized areas with total losses of approximately 1 to 2 times those losses associated with sinusoidal excitation are produced in isotropic laminations. Unlike ac losses, however, rotational losses fall to zero as the induction level approaches saturation. The areas of highest loss tend to be near machine teeth roots. If flux distributions are mapped using FEA methods in a rotating machine core, these localized losses can be calculated [14].

No data has been found for rotational losses in Hiperco®50HS. Although significant theoretical work has been accomplished in this area [15,16], it involves relatively low rotation speeds. Rotational losses increase with the rotation speed ("frequency") [17]. It is generally accepted that the maximum loss in non-oriented laminates occurs at an induction to saturation induction ratio of ~0.75. This 0.75 ratio value is expected to decrease at much higher rotation speeds. It is planned to pursue analysis of rotational power loss at high rotation speeds due to the potentially large impact in power dense machines.

A crude estimate of rotational loss in Hiperco®50HS suggests that at 18,000 G (~0.8 induction/saturation induction ratio), the rotational loss will be a factor of 2 times the total ac power loss (e.g., +48 Watt/kg at 50 Hz). Similarly at 10,000 G (~0.4 induction /saturation induction ratio), the rotational loss will be a factor of 1.5 times the total ac power loss (e.g., +15 Watt/kg at 50 Hz).

E. *Square Waveform*

When comparing a square voltage excitation waveform to a sine wave having the same peak flux density (B), the square waveform will have a lower mean value of dB/dt in the resulting triangular flux density waveform [18]. For a duty ratio of 1, this results in lower power losses. The measured ratio of total power loss with square wave excitation to total power loss with sine wave excitation was measured to be 0.85 at 400 Hz and 10,000 G for a nonoriented electrical steel [18]. Given the Hiperco®50HS total specific power loss of 89 Watt/kg at 400 Hz sine wave excitation and a peak flux density of 10,000 G, a rough approximation for the total specific power loss with the same peak flux density gives 75 Watt/kg. The difference between total specific power losses is then approximately -14 Watt/kg. Note that the relative permeability measured with square wave excitation changes [19].

Duty ratios of less than 1, however, can present much higher total losses [20]. The power loss ratio of 0.85 above is divided by the duty ratio (D = time on / switching period) [20]. A duty ratio of 0.6 would give a power loss ratio of ~1.4, resulting in a difference in total specific power losses of approximately +37 Watt/kg.

F. *Pulse Waveform Modulated (pwm) Losses*

The modulation waveform, carrier frequency, and modulation index provide variability in pwm power control. The modulating waveform can be varied without affecting power losses if the peak fundamental flux density is held constant [21]. Carrier frequency also has little effect under this same condition [22]. As the modulation index decreases from unity, however, power losses can increase dramatically. This increase depends to a large extent on the flux waveform distortion and the material characteristics [22]. The flux distortion (and the ensuing power losses) can vary locally within the machine core [23]. Methods for extrapolating pwm losses from sinusoidal loss data are available both with [24,25], and without dc bias ripple (or minor hysteresis loops) [26].

Due to the complexity of choosing any pwm system, the difficulty relating hysteresisgraph results to a rotating machine core, the lack of pwm data for Hiperco® 50HS, and the use of Epstein frame methods in most literature comparisons, extrapolation of the sine wave excited loss measurements to a pwm situation is not meaningful at this time. The power loss difference may vary from zero to well over 100% depending on the situation. Little has been reported as to the effects of pwm on other hysteresis parameters. This discussion is intended to emphasize the importance of the continuing work of the involved community in recognizing pwm features that can minimize core loss in rotating machines.

IV. SUMMARY

Examples of the effects of environmental variables on the power losses of Hiperco®50HS are listed in Table I. These examples emphasize the need for using realistic loss data in machine simulation. This is relevant as codes are available to accept complex data and models for extrapolation to these environmental regimes are available. The examples here are meant as a guide, and rigorous extrapolation of test data should be used on a case-by-case need. In some examples, variations of other important hysteresis parameters were also observed. As the involved community continues to extend our knowledge of soft magnetic materials behavior, optimization of design through machine simulation for power dense rotating machines is becoming increasingly viable.

TABLE I. ESTIMATION OF ENVIRONMENTAL EFFECTS ON TOTAL SPECIFIC POWER LOSS OF HIPERCO®50HS

Environmental Variable	Change in Specific Power Loss	Loss Component
Temperature (21°C to 100°C)	-3.35 Watt/kg @10,000 G, 1,000 Hz	eddy current
Machining damage (lathe turning)	+415 Watt/kg @10,000 G, 1,000 Hz	anomalous loss hysteresis Loss
Mechanical stress -4 ksi uniaxial load	+150 Watt/kg @18,000 G, 1,000 Hz	anomalous loss
Mechanical stress +4 ksi uniaxial load	-6.6 Watt/kg @18,000 G, 1,000 Hz	anomalous loss
Mechanical stress +5.6 ksi biaxial load	-67 Watt/kg @18,000 G, 1,000 Hz	anomalous loss
Rotational loss (compared w/ sine wave excitation)	+15 Watt/kg @10,000 G, 50 Hz +48 Watt/kg @18,000 G, 50 Hz	anomalous loss hysteresis loss eddy current loss
AC frequency (0.1 to 1000Hz, at room temperature)	+250 Watt/kg @10,000 G +580 Watt/Kg @18,000 G	anomalous loss hysteresis loss eddy current loss
Square wave (compared with 400 Hz sine wave)	-14 Watt/kg @10,000 G, D=1 +37 Watt/kg @10,000 G, D=0.6	anomalous loss eddy current loss

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