# MAGNETIC MATERIALS FOR HIGH ROTATIONAL VELOCITY MACHINES: A FRESH LOOK AT AN OLD PROBLEM.

Aleta T. Wilder

*Abstract*—**The diameter and speed of rotors in electromagnetic machines are limited by materials. Machines having high tip-speed rotors demand materials performance in both magnetic and mechanical behaviors. As a result, soft magnetic materials are used both for energy conversion and for structural support. Unfortunately, desirable magnetic characteristics are linked to materials with inferior mechanical properties. Furthermore, a material's magnetic characteristics change with temperature, mechanical stress, frequency, laminate thickness, etc., complicating direct comparison between materials candidates. Two new metrics for materials comparison under such multifactoral conditions are presented. A "next generation" category of magnetic materials is identified and some issues facing machine designers for the effective use of these materials are suggested.**

*Index Terms*—**soft magnetic materials, magnetic hysteresis, rotating machine mechanical factors, steel.**

## 1. INTRODUCTION

Electric machines are increasing in flexibility, efficiency, and reliability. Machine performance requirements are met by effectively combining mechanical design, power control, and materials engineering. Due to demands for higher power density, there is a trend towards higher frequency, higher temperature, and higher rotation speeds.

That magnetic materials are the gap technology for power density in machines having high rotational velocities is well-known. The mechanical stresses generated in these materials during operation determine to a large extent the maximum size of a rotor at a given rotational speed. To push the performance envelope, soft magnetic alloy variations were studied up to the 1980's. During the following two decades, permanent magnet material compositions received significant attention. Amorphous/nanocrystalline materials have also been recently studied.

Yet it is electrical steels that are still of primary importance for high velocity rotors. The economic manufacture of steel strip and fabrication of laminated cores is clearly shown in both the tonnage and expenditure comparisons of non-grain-oriented electrical steels with grain-oriented electrical steels and all other soft magnetic products (including ferrites, powdered materials, and amorphous alloys). In 1998, 79.9% by weight of this market category was non-grain-oriented electric steel. Only 3.9% was the "other" category.[1] This market analysis did not include "carbon" (i.e., structural) steels.

Of current design interest is deviating from rotors with permanent magnets fixed on the outer rotor circumference to a steel laminated rotor core with slots set back from the air gap into which such magnets are inserted (e.g., the hybrid internal permanent magnet motor). This further illustrates the continuing importance of electrical steels. The permanent magnets boost the flux density whereas the soft magnetic material provides flux density, a magnetic path, and structural support.

Optimum magnetic behavior was developed in electrical steels for use at low frequencies (typically DC or 50/60 Hz) and low speeds. These traditional non-grain-oriented steels are not usually hardenable through heat-treatment and exhibit yield stresses below 690 MPa (100 ksi) in the fully annealed state. Substitution of structural steels (e.g., 4130 or 4340) has permitted higher tip speeds by utilizing appropriate heat-treatments. The controlled quench-and-temper processing of these structural steels forms precipitates due to carbon and trace metal content. This processing can double yield stresses. Concurrently, toughness decreases, magnetic behavior suffers, and aging may be an issue at sustained high temperatures.[2]

This paper will first address appropriate characterization of magnetic behavior and then suggest development of a "next generation" of steels for high rotational velocity machines.

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A. T. Wilder is with the Center for Electromechanics- The University of Texas, Austin, TX 78758 USA (phone: 512-232-1617; fax: 512-471-0781; e-mail: a.wilder@mail.utexas.edu).

## 2. ROTOR TIP SPEED

Rotor tip speed is directly proportional to the outer diameter times the rotation speed (e.g., rpm). Traditional power output approximations for radial machine topologies are given by (1):

$$P \sim BALD^2 \cdot S \qquad (1)$$

where B is the air gap flux density, A is the electrical load, L is the rotor length, D is the air gap diameter (or rotor diameter), and S is the rotation speed.[3] For axial machines, power is proportional to D cubed. A proportionality often exists between rotation speed and frequency. Clearly, one approach to power density is to increase rotor tip speed and/or frequency. Tip speeds of 100 m/sec are achieved on large, industrial, traction motors [4] and approach 130 m/sec on smaller, prototype motors [5].

Difficulties arise in that significant stresses can develop in the rotor. The Young’s modulus controls the rotor expansion into the gap at stresses below yield. Young’s modulus, as traditionally measured, does not vary much between steel alloys. The exception is the nickel-iron alloys that tend to exhibit a lower Young’s modulus. In the presence of a magnetic field, the Young’s modulus can decrease. This decrease depends on the metal alloy, the heat-treatment, and temperature. In some cases, the modulus decreases up to 20% near saturation.[6]

Yield stresses can be quickly achieved with high tip speeds. A simple example shows that in a 60 cm (24 inch) diameter rotor with a 20 cm (8 inch) center hole rotating at 10,000 rpm, stresses can reach 690 MPa (100 ksi). For variable speed and rapidly accelerating machines, toughness of the rotor materials becomes important in resisting fatigue and fracture.

Higher temperature operation compounds the importance of the mechanical properties of the rotor materials. Mechanical properties tend to degrade with increasing temperature and creep can become an issue.[7]

## 3. CHARACTERIZATION OF MAGNETIC BEHAVIOR

With the emergence of advanced materials processing, flexible power control options, and a variety of robust virtual prototyping techniques, careful characterization of magnetic material behavior is more important than ever before. It allows Designers to maximize performance in novel machine designs for these speeds when magnetic behavior is less than ideal**.** The magnetic behavior of a material changes with parameters such as frequency, current waveform, DC bias, mechanical stress, and temperature. This complicates characterization, and clarity of machine performance criteria helps to establish effective characterization datasets.

Loss measurements of electrical steels are typically reported as a function of ac frequency to compare magnetic behavior of materials. Losses increase nonlinearly with frequency. For precipitation-strengthened steels, the anomalous loss component can be large and a simple eddy current approximation should be avoided. Various modified Steinmetz equations are fit to loss data for use in modeling programs.[8] Although this empirical approach is well-used, it is insufficient for materials comparison under complex control algorithms and high mechanical stress.

A comparison of the normal B-H curve for annealed iron and a tempered 4130 steel is shown in Fig. 1. The low initial permeability of the 4130 steel is typical of precipitation-strengthened steels. Because the B-H relationship is sensitive to heat treatment, it should be measured for quality assurance. The shape of the hysteresis loop, the normal B-H curve, and the core loss may change with applied mechanical stress.[9] The sensitivity to mechanical stress varies with alloy and heat treatment.

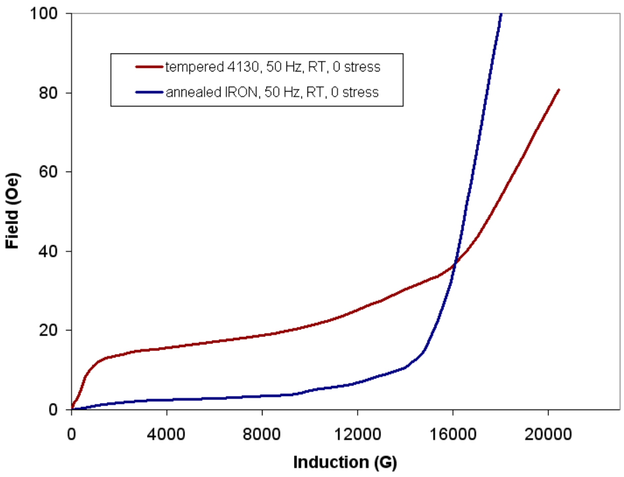

Fig. 1 The normal B-H relationship for annealed iron and a tempered 4130 steel at room temperature and no applied stress.

## 4. TWO NEW METRICS

To improve direct comparison between materials, two new metrics have been developed to describe magnetic behavior under multiple variables. These are available induction power and induction efficiency.

### 4.1. Available Induction Power

The available induction power is calculated by subtracting the specific core loss from the specific exciting power.

Exciting power describes the amount of power induced into the material by the exciting current. The values of specific exciting power in the trends presented were calculated from measured induction and field values using the relationships given in ASTM Standard Test Method A927. This metric can be plotted as a function of induction as shown for a tempered 4130 steel in Fig. 2. Even with the very high core losses at 1000 Hz, the importance of frequency in increasing power is obvious.

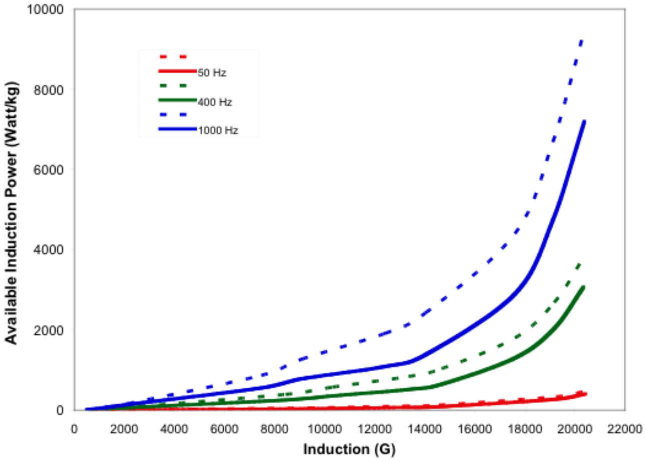

Fig. 2 Available induction power as a function of induction for a tempered 4130 steel at three frequencies. (Exciting power is plotted as dashed curves for reference.)

### 4.2. Induction Efficiency

Using the simple concept that power input minus losses (i.e., power output) divided by power input is an efficiency, induction efficiency is calculated for a material by dividing the available induction power by the exciting power. This metric is depicted for Hiperco® 50HS [10] in Fig. 3A as a function of frequency and induction at zero stress. Similarly, induction efficiency is depicted in Fig. 3B as a function of biaxial tensile stress and induction at 400 Hz. The utility of this metric is in performance maps to permit best utilization of soft magnetic steels under multiple variables.

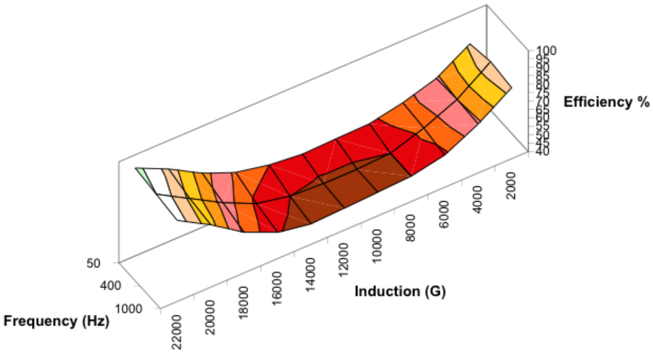

Fig. 3A Induction efficiency map for Hiperco® 50HS at zero applied stress.

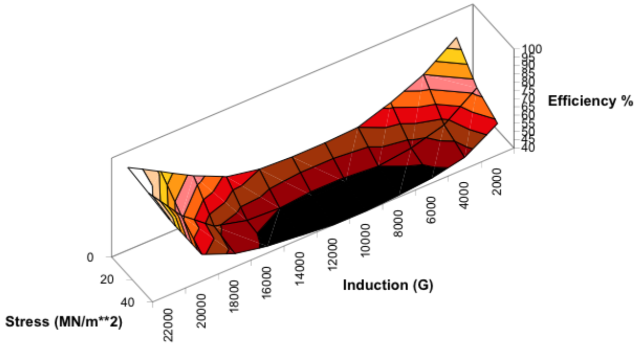

Fig. 3B Induction efficiency map for Hiperco® 50HS at 400 Hz.

### 5. "NEXT GENERATION" ROTOR MATERIALS

Although development of electrical steels for rotating machines has been limited since the 1980's, development of high performance, "aerospace" steels has continued. These steels are all precipitation-hardenable. Some of these steels are ferritic and exhibit good stress-corrosion resistance. By further identifying such steel alloys that can be precipitation-hardened for a combination of high yield stress and high toughness, a new category of soft magnetic materials is defined. This category is depicted as a "Next Generation" of magnetic steels in Fig. 4. Development efforts are required to effectively characterize these steels and adjust machine design and power control for best performance in high rotational velocity machines.

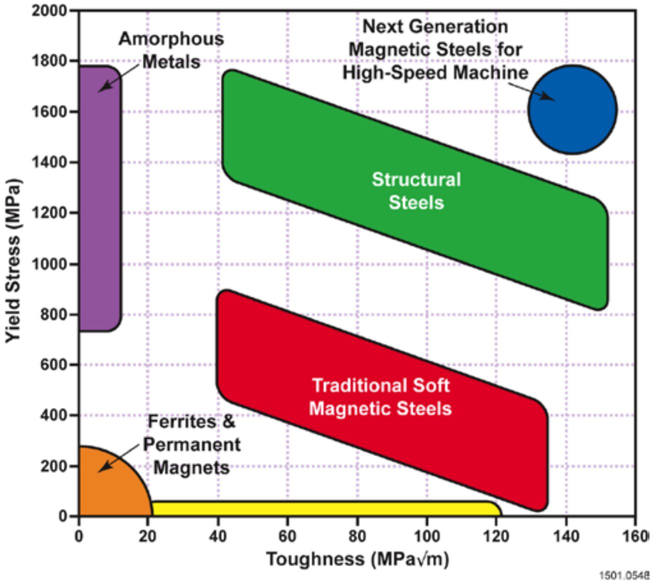

Fig. 4 Comparison of mechanical properties of classes of magnetic materials.

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[10] Hiperco® 50HS is a Co-Fe electrical steel product of Carpenter Technology Corporation, www.cartech.com

## 7. BIOGRAPHY

**Aleta T. Wilder's** research interests involve performance enhancement /trade-offs via materials processing: especially for dielectric, optical, electrochemical, electromagnetic, fatigue, stress-corrosion, tribology, and biocompatibility issues. Aleta is currently with the Center for Electromechanics, characterizing electromagnetic materials for machinery through ONR's Electric Ship R&D Consortium. She enjoys working with small companies on materials processing of high performance polymer systems, capacitors, and electrodes for power systems applications. Aleta managed two research programs in the medical device industry; first as Advanced Technology Division Group Leader at Sulzer Orthopedics, and then as Vascular Research Manager at Guidant Corporation. She was previously with Lawrence Livermore National Laboratory. She has earned the following degrees: Ph.D., Ceramics Science, SUNY-Alfred University, 1986; M.S., Ceramics, Pennsylvania State University, 1983; B.S., Materials Science & Engineering, University of Florida, 1981.