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Citation: *Journal of Applied Physics* **115**, 17A319 (2014); doi: 10.1063/1.4864247

View online: <http://dx.doi.org/10.1063/1.4864247>

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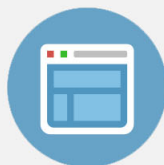
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High speed electric motors based on high performance novel soft magnets

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(Presented 7 November 2013; received 23 September 2013; accepted 4 November 2013; published online 10 February 2014)

Novel Co-based soft magnetic materials are presented as a potential substitute for electrical steels in high speed motors for current industry applications. The low losses, high permeabilities, and good mechanical strength of these materials enable application in high rotational speed induction machines. Here, we present a finite element analysis of Parallel Path Magnetic Technology rotating motors constructed with both silicon steel and Co-based nanocomposite. The later achieved a 70% size reduction and an 83% reduction on NdFeB magnet volume with respect to a similar Si-steel design. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4864247>]

I. INTRODUCTION

Integration of electric motors in military, industry, and transportation sectors and household appliances, drives efforts to reduce the size of the motors while increasing their output power. The ratio of the output power to motor volume, output power density (W/L), characterizes compactness of an electric motor design.

High speed electric motors offer good output power density. A limitation to reducing their size, weight, and cost is performance of permanent and soft magnets at high speeds. High energy density permanent magnets are based on rare earth intermetallic compounds. The availability of rare earth elements (REEs) may be at risk as ~80% of the strategic materials are produced in China.¹ Mining of individual REEs can be expensive and a source of environmental concern.² Thus, transformational technology to limit REEs use is needed for high output power and torque density motors.^{3,4}

Performance aimed at limiting reliance on REEs can be addressed by using state-of-the-art soft magnets to develop electric motors containing less REEs. New soft magnet nanocomposites reach high flux densities with low core losses at high frequencies due in part to the higher resistivity of the amorphous matrix. High frequencies are required for high speed electric actuators and motors, including switched reluctance and hybrid motors (with both soft and hard magnets). Fe-rich amorphous soft magnetic materials have been incorporated into stators for high-speed motors,⁵ but nanocomposites offer higher thermal stability.

A new class of Fe-Co-based amorphous and nanocomposite materials, HiTperms,⁶⁻¹² show promise for high frequency applications. Low losses, tunable anisotropies, and robust mechanical properties suggest their use in high efficiency, high speed motors both at room temperature and operating temperatures >300 °C. For motors where material strength is critical, Co-rich compositions offer good soft

magnetic properties without the brittleness found in Fe-rich alloys. While these compositions have lower saturation inductions compared to other HiTperms,¹³ they have superior mechanical properties. Here, we discuss more efficient machines enabled by state-of-the-art magnetic materials.

II. SOFT MAGNETIC MATERIALS FOR HIGH SPEED ELECTRIC MACHINES

The output power of an electric motor is $P = \omega \cdot T$, where ω is the angular speed and T is its torque. High power densities (torque per unit volume) are achieved by running at the highest speed. Rotor speed depends on the number of poles and switching frequency. The speed is often limited by mechanical strength and practical gearing requirements, but even before that, increasing power loss imposes severe constraints. The cooling capability of the machine limits the power loss density. For air-cooled machines, the power loss density of the magnetic material is usually limited to approximately 300 W/L.

Losses in soft magnetic materials arise from hysteric phenomena that can be separated into three different contributions with different power law dependences on frequency: static hysteresis loss (proportional to the switching frequency), classical eddy current loss, and anomalous or excess loss.¹⁴ The last two contributions are due to the electric currents induced in the magnetic material. The classical eddy current loss of a material under unidirectional sinusoidal magnetization is $P_{class} \approx \pi^2 \sigma t^2 B_p^2 f^2 / 6$,¹⁴ where t is the material thickness and σ its conductivity. Excess loss is related to the domain wall motion in the material. Static hysteresis loss dominates at low frequencies while eddy currents dominate at high switching frequencies. As a composite system, a fit to a single Steinmetz equation represents the data well. A more detailed analysis might reveal some variation of the Steinmetz power laws with frequency, but as a practical predictive tool, these fits are adequate.

M-19 non-oriented silicon steel is commonly used for soft magnetic components of electric motors. This material has a hysteresis loss density of ~10 W/L at 60 Hz and at a

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peak flux density of 0.9 T. The hysteresis loss of HTX-005C (a HiTperm alloy) under the same conditions is <0.5 . This explained by Alben's random anisotropy model¹⁵ extended by Herzer;¹⁶ when grain dimensions are kept below the ferromagnetic exchange length, the anisotropy of homogeneously distributed nanocrystals averages to zero.

Approaches to limit eddy current loss focus on stacking isolated thin magnetic laminations. M-19 thicknesses are typically 0.36 mm (0.014"). Although materials as thin as 0.12–0.20 mm are being produced, the cold rolling manufacturing process currently in vogue precludes significant reduction of the thickness for silicon steel. HiTperms can be produced with a thickness in the range of 0.005–0.050 mm.

With its high electrical resistivity and low coercivity, the iron loss of HTX-005C is much lower than electrical steels. Co-based materials are more mechanically ductile than Fe-based nanocomposites and had proven to be extremely resilient over long operating times.¹⁷ HTX-005C opens up a possibility to develop high output power density motors running at speeds in well excess of 1000 Hz.

Properties of M-19 electrical steel and Co-based nanocomposite HTX-005C are compared in Table I. Electrical steel properties are from manufacturers' data sheets, whereas the properties of the novel HTX-005C were measured through conventional techniques.

Fig. 1 shows loss density vs. frequency for M-19 and HTX-005C. The inset shows the 1 kHz B-H curve. Iron loss density for M-19 is shown for a 1.5 T peak flux density and for 0.9 T to allow direct comparison with HTX-005C. A linear log-log plot for HTX-005C is seen for 10–10,000 Hz because eddy current loss contributions are small in this frequency range. The curve increases sharply for M-19 above 200 Hz due to the dominating effect of eddy current loss.

Limiting the iron loss density to 300 W/L for air-cooled machines, the switching frequency has to be lower than 600 Hz for M-19 G29/0.9 T (3600 rpm if the machine employs just two poles), but it can be as high as 2830 Hz for HTX-005C/0.9 T (170 000 rpm again for a conventional 2-pole motor). Furthermore, the maximum switching frequency and speed limits can be increased if the peak flux density is reduced; e.g., 13 kHz for HTX-005C/0.2 T.

These frequencies are attractive for high speed machines currently required in several industry applications, e.g., a 7000 kW/14 700 rpm motor driven compressor for the oil industry,¹⁸ a 220 kW/730 000 rpm motor for turbo-machinery applications,¹⁹ a 21 kW/50 000 rpm motor to drive a small

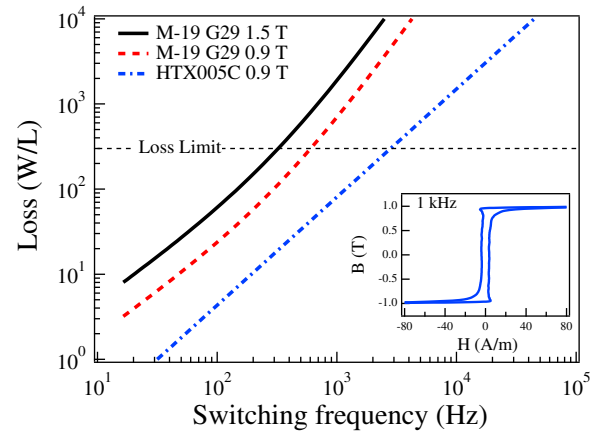


FIG. 1. Comparison of iron loss for M-19 G29 ($B_p=1.5$ and 0.9 T) and HTX-005C ($B_p=0.9$ T) vs. f . Horizontal dashed line shows a 300 W/L iron loss limit of air-cooled machines. Inset: hysteresis loop of HTX-005C at 1 kHz.

compressor in industrial cooling applications,²⁰ a 15 kW/120 000 rpm motor for air blower cooling fuel cells,¹⁹ and a 2 kW/150 000 rpm switched reluctance motor drive system.²¹ A state-of-the-art survey of high speed electrical machines is presented in Ref. 22.

III. HITPERMS AND PPMT MACHINES

Another strategy to design higher efficiency motors is to exploit novel HiTperm soft magnets and to improve the electromechanical design of the device. A novel motor architecture that can achieve significant peak power density with low or no rare earth content²³ is based on the Parallel Path Magnetic Technology (PPMT). In this magnetic circuit, field coils are used for two purposes: to provide driving flux and to switch the magnetic flux generated by hard magnets. A PPMT generator produces greater output power density with cooler operation due to their better efficiency than conventional technologies. PPMT can be applied to virtually any electromagnetic application that produces a holding force or any motion; rotary motors, linear actuators, and generators. PPMT device actuators and motor speeds are limited only by the magnetic materials performance and inertial constraints.^{24–26} We show the advantages of using HTX-005C soft magnet in comparison to M-19 G29 in a PPMT rotary motor reported in Ref. 25 (Fig. 2).

All motors are designed to give the same output power and with iron loss limited to 300 W/L. The maximum

TABLE I. Comparison of electrical steel and HTX properties for motors. Peak flux density (B_p), dc coercivity (H_c), loss, and conductivity (σ) are given at room temperature.

Material	M-19 G29 Silicon steel	HTX-005C Co-based nanocomposite
Manufacturing process	Rolling	Planar flow casting
Thickness (mm)	0.36	0.010
Typical B_p (T)	1.5	0.9
H_c (A/m)	42.5	20
σ (S/m)	2×10^6	1.1×10^6
Loss at 60 Hz and typical B_p (W/L)	26	2.3

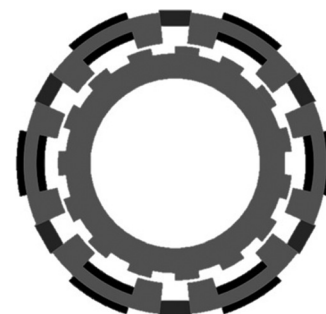


FIG. 2. Rotary PPMT motor. The rotor is built with a soft magnet (light grey) and is mounted on a non-magnetic shaft. The stator is built with hard (dark grey) and soft magnets (light grey). The coils are located in the black areas.

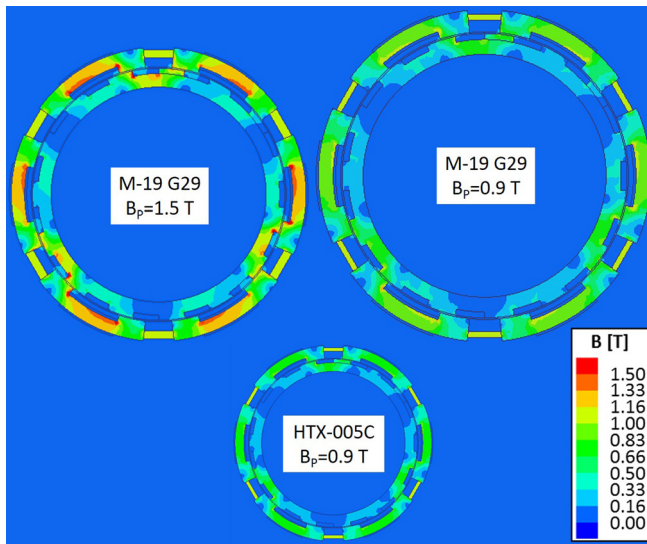


FIG. 3. ANSYS FEM analyses of PPMT rotary motors with different soft magnets and peak flux densities. All motors use NdFeB permanent magnets, give the same output power, incur the same iron loss and are in the same length scale.

switching frequencies (for the 300 W/L iron loss limit) for M-19 G29 at 1.5 and 0.9 T and HTX-005 C at 0.9 T are used to calculate the maximum angular speeds of PPMT motors as the one of Fig. 2 (1200, 2320, and 11320 rpm, respectively). We set the output power to 10 kW. This value and the angular speeds (in rad/s) are used to calculate the required torques of the motors (80, 41, and 8.4 Nm, respectively). The motor built with HTX-005 C runs at lower torque but at higher speed than the motors built with M-19. Since we set the output power arbitrarily, we prefer to show the scalability of the results at lower and higher output power as a separate stand-alone result that considers both the thermal and inertial constraints as well as strength of materials issues. This extended work is in progress. The single power used here serves the purpose of demonstrating the size scaling which is the main point of this paper.

The constitutive relations and Maxwell's laws are used to describe the magnetic circuit of the motor in 2D and to calculate device dimensions. All machines use the same permanent magnets (NdFeB, $H_C = 890\,000$ A/m) and have the same dimension ratios (e.g., length to motor radius ratio is 1:1). A first approach of a static model with linear and isotropic materials is followed in this work. Soft magnets are simulated with the permeabilities corresponding to the operating switching frequencies and peak flux densities.

ANSYS finite element (FEM) analyses were used to verify the output torques of PPMT motors. Relative sizes and flux densities are shown in Fig. 3.

The machine built with HTX-005 C operating at $B_p = 0.9$ T is 70% smaller than the machine with M-19 G29 $B_p = 1.5$ T, i.e., the power density is more than 2 times higher. Moreover, the HTX-005C/0.9T motor needs 83% less rare earth permanent magnet than the M-19 G29/1.5T motor to give the same output power at the same power loss limit.

IV. CONCLUSIONS

New Co-based soft magnetic nanocomposites have very low power loss at high switching frequencies, tunable anisotropies, and robust mechanical properties both at room temperature and at operating temperatures as high as 300 °C. We demonstrated a large size reduction (70%) of a PPMT rotary motor when using HTX-005C alloy instead of the conventional M-19 G29 electrical steel. Furthermore, we could reduce the scarce and high cost NdFeB magnets by up to 83%. HTX-005C opens up a possibility to develop high output power density motors running at high speeds with switching frequencies higher than 2.5 kHz.

ACKNOWLEDGMENTS

This work was supported by CONICET, UBACyT Grant No. 2013-2016 20020120300073BA and FONCyT through Grant No. PICT-2012-1097.

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