Materials for Advanced Electric Machines: An Overview

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***Abstract*-Materials behavior, along with the machine design, controls the performance of the electric machine.**

Advanced electric machines are placing increased demands on materials behavior especially to achieve power density, efficiency, and endurance. For the Electric Ship, such advanced electric machines include actuators, motors, generators, certain energy storage systems, electric clutches and brakes, and specialized machines for weaponry. Small engineering refinements from practice are often inadequate for the advanced electric machine systems and the associated materials utilized in these machines to meet performance goals. A method for directing appropriate attention to materials requirements based on the machine performance goals is needed. This paper will present a method for prioritizing materials issues based on ten machine performance categories. As each advanced electric machine will present a unique set of requirements, the prioritization guides valuing of associated materials issues.

Index Terms -- **materials technology, electric machines, materials integration**

I. INTRODUCTION

The integration of advances in power electronics, digital signal processors, and control science with machine design science continues to revolutionize electric machine technology.[1] Advances in materials technologies contribute to performance successes. The integration of materials in this process often appears to be a matter of choosing one commercially available material versus another. The value of materials science and technology (S&T) remains to be fully exploited. Materials S&T not only supports materials behavior trade-off decisions, it provides new and improving materials and appropriately identifies areas of materials development of greatest performance significance. Full integration includes both machine-specific materials characterization (quantifying the impact of machine operation on materials and vice versa), and machine-specific materials processing (for manufacturing and assembly operations).

A simple method for directing appropriate attention to materials issues based on the machine performance goals is needed. It is ineffective to build and test machine prototypes to determine the most problematic materials issues and then reengineer to accommodate those particular issues. To bridge between machine science and materials S&T, we use ranking of machine design categories based on performance and our assessment of the ability of materials to impact those categories. The result is a prioritization of the categories for material. The prioritization allows identification of associated materials issues to support behavior trade-offs and investment decisions. This paper describes the method more fully. The method is intended as a template, to be updated to a particular need and modernized as technologies evolve.

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II. PRIORITIZATION METHOD

The method described here uses a ranking of the performance required of the advanced electric machine weighted by a value representing the ability of materials to influence that performance.

A. Ranking of Performance Required of Machine

Successful deployment of each advanced electric machine system presents a unique set of performance requirements to the designers. We choose to use the same ten performance categories as described in another paper in this symposium [2]. These ten categories are: efficiency, noise, condition based maintenance (CBM), fault tolerance, power density, torque density, acceleration, temperature, lost motion, and cost.

As described in [2], these ten performance categories can be ranked based on Navy system operation priorities on a scale of 1 to 10, where 10 is highest priority. For example, the electromagnetic actuator performance criteria rankings for the submarine bow plane were given as efficiency 3, noise 10, condition-based maintenance 8, fault tolerance 8, power density 4, torque density 10, acceleration 4, temperature 4, stiffness 10, and cost 7.[2]

B. Relationship of Performance Categories to Materials S&T

The intersection between advanced electric machine design and modern materials can be based on performance requirements as interpreted through design. To bridge between machine design technology and materials S&T, a brief interpretation of each performance category is necessary using concepts familiar to materials scientists and engineers.

1) Efficiency

Efficiency is dominated by reducing losses in conductive, dielectric, magnetic, and moving components/materials, especially reducing energy dissipation. There is also a component of energy or power transfer magnitude to efficiency that should not be ignored.

2) Noise

Noise (or smoothness of performance) is often associated with microstructural features such as anisotropy, residual stress, inhomogeneity, porosity, precipitates, etc. Such features accompanying contacting surfaces can accentuate or damp noise. Surface treatments and wear are known to affect the acoustic response of contacting surfaces. The mechanical response of a material to changing electric, magnetic, and acoustic fields leads to other specific noise sources (e.g., electrostriction), which depend uniquely on the material and its environment. All such materials issues, as well as elastic moduli, can be modified to some degree.

3) Condition Based Maintenance

Condition based maintenance is the performance category most influenced by materials. Aging, fatigue, and stress-corrosion are multifactor processes that dominate reliability and endurance. Lifetime prediction is predicated on reproducible materials behaviors and baseline property characterization.

4) Fault Tolerance

Fault tolerance (and reconfigurability) is nominally influenced by materials. There are currently few materials issues that have impact on reconfigurability and/or system availability. Unique materials properties do impact the operation of brakes, springs, and other release mechanisms essential for fault tolerance.

5) Power Density

Power density represents high-duty-cycle EM systems that require materials to operate at high frequency and velocity. Specific issues dominate in each component such as eddy current phenomena, dielectric response to field pulse shapes, and centrifugal expansion of rotating masses (in very high speed motors or generators). This is a materials research area that has recently increased in priority due to advances in power electronics.

6) Torque Density

Torque density can be considered through low-duty-cycle EM systems that are often required to hold high forces for extended periods. Combined improvements in multiple materials properties such as toughness, hardness, strength, and magnetic flux saturation are sought.

7) Acceleration

Acceleration is best considered from a materials viewpoint as the quality or rapidity of response. Viscosity, hysteresis, slip, and windage are familiar materials concepts. Also considered part of this performance category is significant materials S&T available for responsiveness of solid-state sensors and materials for shielding.

8) Temperature

Temperature includes cooling systems, ambient temperature, the acknowledgement of temperature extremes during operation, and their effects on component materials. It is important to recognize how the active materials each contribute to the heat generated by the operating system. This performance category is usually handled by designing appropriate cooling systems. There are opportunities for insertion of high performance dielectrics and composites into EM systems to allow the system to run at a higher temperature, reducing the requirement for cooling systems. (Materials development to support superconductive design concepts continues to be essential.)

9) Stiffness / Lost Motion

Stiffness / lost motion is given a high value for materials as much development remains for design with materials S&T (going beyond high modulus materials choices). Tolerances, fastening processes, and thermal expansion mismatches are probably the most ignored design issues, and they have a strong materials processing component.

10) Cost

Cost depends on effective selection of material processing and raw materials. Materials S&T dominates manufacturing process development and component quality control. New and improved manufacturing processes can reduce cost, especially for exotic materials.

C. Value of Materials S&T

Over 70 materials issues related to advanced electric machine performance are categorized in Table I. This generalization is intended to illustrate the wealth and complexity of materials S&T utilized. The categorization of issues in Table II should be reassessed for specific advanced electric machines. For example, "magnetostriction" no longer fits into the "noise" category for a magnetostrictive actuator, and characteristics of giant magnetostriction behavior would be listed in several categories.

TABLE I
MATERIALS ISSUES

EFFICIENCY (9)	energy conversion, energy dissipation, core energy (B*H), core losses, quality factor, lubricity/friction, electrical conductivity/impedance, permeability, permittivity, excitation power
NOISE (7)	elastic moduli/acoustic response, magnetostriction, electrostriction, anisotropy, vibration, residual stress/inhomogeneity/porosity/precipitates, stress concentrators, surface treatments/wear (impact history)
MAINTENANCE CBM (10)	durability, aging, fatigue, energy isolation, voltage-stress grading, reaction with environment: corrosion/contamination/ exposure to harmonics/voltage spikes, high-current-density-coil-to-insulation interface phenomena, partial discharge, radiation hardening

TABLE I
MATERIALS ISSUES
(continued)

FAULT TOLERANCE (2)	geometry/size constraints, stored strain energy and sliding contact energy, piezoelectrics, shape memory alloys
POWER DENSITY (8)	friction, yield stress/strength, composite design, pmw loss, eddy current phenomena, field penetration, core loss, centrifugal expansion, frequency/pulse shape (e.g., dV/dt) response
TORQUE DENSITY (7)	magnetic flux density, magnetic field concentration, toughness, hardness, mechanical stress matrix, "air gap," rotational loss of magnetic energy, DC dielectric breakdown
ACCELERATION / RESPONSE (3)	viscosity, hysteresis, viscoelasticity, slip, windage, capacitance, density, responsiveness of solid-state sensors, shielding via materials (from various fields)
TEMPERATURE / COOLING (7)	changes in material properties with ΔT (e.g., impedance), thermodynamic stability, phase changes (e.g., Curie T, glass transition), core loss, contact friction loss, dissipation factor, heat capacity, thermal conductivity, cooling processes
STIFFNESS / LOST MOTION (7)	high modulus materials choices, composites, roughness, surface finish, fastening processes (adhesion, brazing, soldering, potting, etc.), tolerances, thermal expansion mismatches, internal friction, dynamic mechanical response
COST (9)	effective selection of material processing and raw materials/"trade-offs," complex forming operations, manufacturing process control/quality assurance, surface finishing/modification processes

Our assessment of the ability to influence each machine performance category through appropriate use of materials S&T is valued as listed in Table 1 in parentheses, and also in Table II (column 2).

In multiplying the ranking of each machine performance category by the corresponding materials value and then normalizing to a maximum of 10, the prioritization of each performance category for materials requirements is reached. Continuing with the example of a submarine bow plane actuator, the relative prioritization is calculated and listed in Table II. The method indicates that for this actuator application, materials S&T for conditioned based maintenance is of highest priority and acceleration is of lowest priority. Noise, torque density, stiffness, and cost categories are also of high materials priority.

III. SUMMARY

A simple and flexible method for prioritizing categorized materials issues has been demonstrated. The method is intended to aid integration of materials S&T into electric machine technology.

TABLE II
MATERIALS PRIORITY FOR SUBMARINE BOW PLANE EMA

Performance Category	Value of Materials	Machine Performance Ranking	Materials Priority
Efficiency	9	3	3
Noise	7	10	7
CBM	10	8	8
Fault Tolerance	2	8	2
Power Density	8	4	3
Torque Density	7	10	7
Acceleration	3	4	1
Temperature	7	4	3
Stiffness	7	10	7
Cost	9	7	6

IV. REFERENCES

[1] R. Krishnan, *Electric Motor Drives: Modeling, Analysis, and Control.* New York: Prentice Hall, 2001. (ISBN: 0-13-091014-7)

[2] D. Tesar, "Electro-mechanical actuators for the Navy's ships." Presented at the IEEE Electric Ship Technologies Symposium, Philadelphia, PA, 2005.