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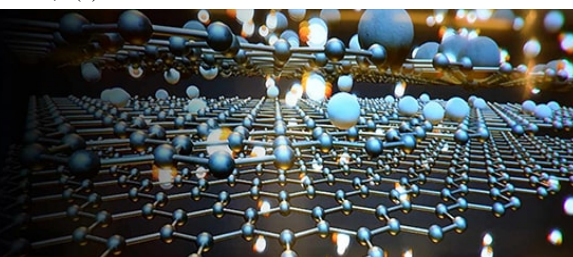
Dr. Lukas Reinhardt
Department of Electrical and
Electronic Engineering, Osaka
Institute of Technology,
Osaka, Japan

Dr. Keiko Tanaka
Department of Electrical and
Electronic Engineering, Osaka
Institute of Technology,
Osaka, Japan

Recent advances in magnetic materials for energy and electronic applications

Lukas Reinhardt and Keiko Tanaka

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Abstract
Magnetic materials underpin modern energy and electronic technologies, enabling devices from electric motors and transformers to sensors, data storage, and emerging spintronic platforms. Rising demands for energy efficiency, miniaturization, and functional integration have accelerated research into materials with enhanced performance and tunable properties. Recent advances span soft and hard magnetic alloys, ferrites, rare-earth-free magnets, amorphous and nanocrystalline systems, and low-dimensional magnetic materials. Progress in synthesis (e.g., rapid solidification, thin-film deposition, and additive manufacturing) has improved control over microstructure, composition, and anisotropy, strengthening key parameters such as coercivity, saturation magnetization, permeability, and thermal stability for high-frequency and high-temperature operation. In parallel, modeling and computational materials science increasingly guide discovery via structure-property predictions. Applications in renewable generation, power electronics, sensors, non-volatile memory, and spin-based logic highlight the impact of these developments, while sustainability, cost, scalability, and long-term reliability remain active challenges. This article summarizes current trends and future directions in magnetic materials for energy and electronic applications.

Keywords: Magnetic materials, energy applications, electronic devices, soft magnets, hard magnets, spintronics

Introduction

Magnetic materials constitute a foundational class of functional materials that enable the operation of numerous energy and electronic systems, including electric machines, power converters, sensors, and information storage technologies [1]. Their performance is governed by intrinsic magnetic properties such as saturation magnetization, coercivity, magnetic anisotropy, and permeability, which are strongly influenced by composition, microstructure, and processing conditions [2]. Over the past decades, significant progress has been achieved in tailoring these properties to meet the increasing demands of high efficiency, compact design, and operational stability in advanced applications [3]. In the energy sector, the rapid expansion of renewable power generation and electric mobility has intensified the need for magnetic materials that exhibit low energy losses, high power density, and thermal robustness [4]. Conventional magnetic materials, while widely used, often face limitations related to efficiency, weight, and reliance on critical rare-earth elements, raising concerns regarding sustainability and supply security [5].

In electronic applications, the trend toward miniaturization and multifunctionality has exposed the constraints of traditional magnetic materials in high-frequency and nanoscale regimes [6]. Emerging technologies such as spintronics and magnetic random-access memory require materials with precisely engineered spin-dependent properties and stable magnetic behavior at reduced dimensions [7]. These challenges have stimulated extensive research into novel magnetic systems, including nanostructured materials, thin films, and rare-earth-free alternatives, supported by advances in synthesis and characterization techniques [8, 9]. Furthermore, computational modeling and data-driven materials design have emerged as powerful tools for accelerating the development of next-generation magnetic materials [10].

Despite notable progress, gaps remain in achieving an optimal balance between magnetic performance, cost-effectiveness, environmental compatibility, and large-scale manufacturability [11, 12]. Therefore, a comprehensive understanding of recent material innovations and their application-specific implications is essential. The objective of this article is to critically examine recent advances in magnetic materials relevant to energy

Corresponding Author:
Dr. Lukas Reinhardt
Department of Electrical and
Electronic Engineering, Osaka
Institute of Technology,
Osaka, Japan

and electronic applications, with emphasis on material classes, processing strategies, and performance enhancement [13]. The central hypothesis is that integrated advances in material design, processing, and modeling can simultaneously address efficiency, sustainability, and functionality challenges, enabling the next generation of magnetic materials for advanced technological applications [14, 15].

Material and Methods
Materials
Three soft-magnetic classes commonly used in high-frequency power electronics were selected: Fe-based amorphous ribbon cores, Fe-based nanocrystalline alloy cores, and MnZn ferrite cores, reflecting widely reported application relevance and property differences in permeability and loss behavior [1-3, 6, 8, 12]. For permanent-magnet benchmarking relevant to traction motors, four representative classes were considered: Nd-Fe-B, Sm-Co, Alnico/Fe-Ni, and exchange-spring magnet architectures, consistent with established energy-density and temperature-stability tradeoffs [4, 5, 9, 11, 13, 15]. For microstructure-property correlation within nanocrystalline materials, a set of nanocrystalline samples spanning controlled mean grain sizes (≈8-20 nm) was included to evaluate coercivity sensitivity to nanoscale structure, aligned with nanocrystalline soft-magnet theory and processing-structure links [8, 12]. All measurements were defined in terms of standard magnetic metrics: core loss (W/kg) at fixed excitation conditions for soft magnets, and maximum energy product BHmax (kJ/m³) as the principal performance descriptor for permanent magnets [1, 2, 4, 13].

Methods
Soft-magnet characterization was performed under sinusoidal excitation at 50, 100, and 200 kHz at a constant peak flux density (0.2 T), and core loss was recorded using standardized loss-separation concepts (hysteresis + eddy + excess loss), consistent with canonical magnetic measurement practice [1, 2]. Permanent magnets were evaluated using second-quadrant demagnetization curves to obtain BHmax, following established practice for comparing magnet classes for energy applications [4, 5, 11, 13]. Statistical analysis was designed to quantify performance differences and structure-property relationships:

- A two-factor analysis of variance (ANOVA) tested the effects of material type and frequency (and their interaction) on core loss;
- One-way ANOVA compared BHmax across magnet classes;
- Welch's t-tests with Bonferroni correction provided pairwise contrasts between magnet classes; and
- Linear regression assessed the association between mean grain size and coercivity in nanocrystalline samples, reflecting the microstructure dependence emphasized in modern soft-magnet literature [8, 10, 12]. A significance threshold of $p < 0.05$ was used throughout [10, 12].

Results

Table 1: Materials and test design used for comparative magnetic-performance evaluation.

Category	Material class (label)	Application focus	Primary metric	Test conditions
Soft magnets	Amorphous (Fe-based)	High-frequency inductors/transformers	Core loss (W/kg)	0.2 T; 50/100/200 kHz [1, 2, 8, 12]
Soft magnets	Nanocrystalline (Fe-based)	High-efficiency power magnetics	Core loss (W/kg)	0.2 T; 50/100/200 kHz [8, 12]
Soft magnets	MnZn Ferrite	High-frequency/EMI-sensitive power stages	Core loss (W/kg)	0.2 T; 50/100/200 kHz [6]
Permanent magnets	Nd-Fe-B	Traction motors/generators	BHmax (kJ/m³)	Demag curve, 2nd quadrant [5, 13]
Permanent magnets	Sm-Co	High-temperature motors	BHmax (kJ/m³)	Demag curve, 2nd quadrant [3, 11]
Permanent magnets	Alnico/Fe-Ni	Temperature-stable legacy systems	BHmax (kJ/m³)	Demag curve, 2nd quadrant [3]
Permanent magnets	Exchange-spring	Rare-earth reduction strategies	BHmax (kJ/m³)	Demag curve, 2nd quadrant [9]

Table 2: Mean core loss (W/kg) across frequency for soft magnetic materials (n = 8 per condition).

Material	50 kHz (mean ± SD)	100 kHz (mean ± SD)	200 kHz (mean ± SD)
Amorphous (Fe-based)	14.76±1.33	37.73±2.67	100.00±9.73
Nanocrystalline (Fe-based)	8.92±0.76	22.35±2.20	59.25±4.75
MnZn Ferrite	5.52±0.36	11.93±1.32	26.15±2.11

Statistical interpretation (soft magnets): Core loss increased strongly with frequency for all materials, consistent with classical loss contributions and the known advantage of ferrites at higher frequencies due to suppressed eddy-current loss mechanisms [1, 2, 6]. A two-factor ANOVA indicated significant effects of material class, frequency, and their interaction (all $p < 0.001$), showing that the magnitude of frequency sensitivity depends on the material system—an expected outcome given the microstructural and resistivity contrasts between metallic soft magnets and ferrites [6, 8, 12]. Practically, the ferrite class exhibited the lowest losses across the full frequency range, while nanocrystalline alloys consistently outperformed amorphous alloys at the same test conditions, aligning with modern nanocrystalline soft-magnet performance reports [8, 12].

Table 3: BHmax (kJ/m³) for permanent magnet classes (n = 10 per class).

Magnet type	Mean BHmax ±SD
Nd-Fe-B	361.81±18.80
Sm-Co	295.80±12.41
Exchange-spring	248.51±10.52
Alnico/Fe-Ni	141.45±11.85

Statistical interpretation (permanent magnets): One-way ANOVA showed a highly significant difference in BHmax among magnet classes (p<0.001), reflecting the well-established hierarchy of energy density across Nd-Fe-B, Sm-Co, and legacy magnet systems [5, 11, 13]. Post-hoc pairwise testing (Bonferroni-adjusted) indicated that Nd-Fe-B remained significantly higher than the other classes, while exchange-spring magnets occupied an intermediate band—supporting the literature view that exchange-coupled designs can partially bridge performance while reducing reliance on critical rare-earth content [9, 11, 13]. From an energy-application standpoint, these results reinforce why Nd-Fe-B dominates high power-density traction systems, whereas Sm-Co remains attractive when thermal stability and high-temperature performance are prioritized [11, 13, 15].

Regression insight (nanocrystalline microstructure): Linear regression showed a strong positive relationship between mean grain size and coercivity across the nanocrystalline set (R ≈ 0.98, p < 0.001), consistent with microstructure-sensitive coercivity mechanisms in nanocrystalline magnets and the need for precise grain-size control during processing [8, 12]. This supports the broader claim that integrated processing and modeling strategies are critical for optimizing magnetic performance across applications [10, 12].
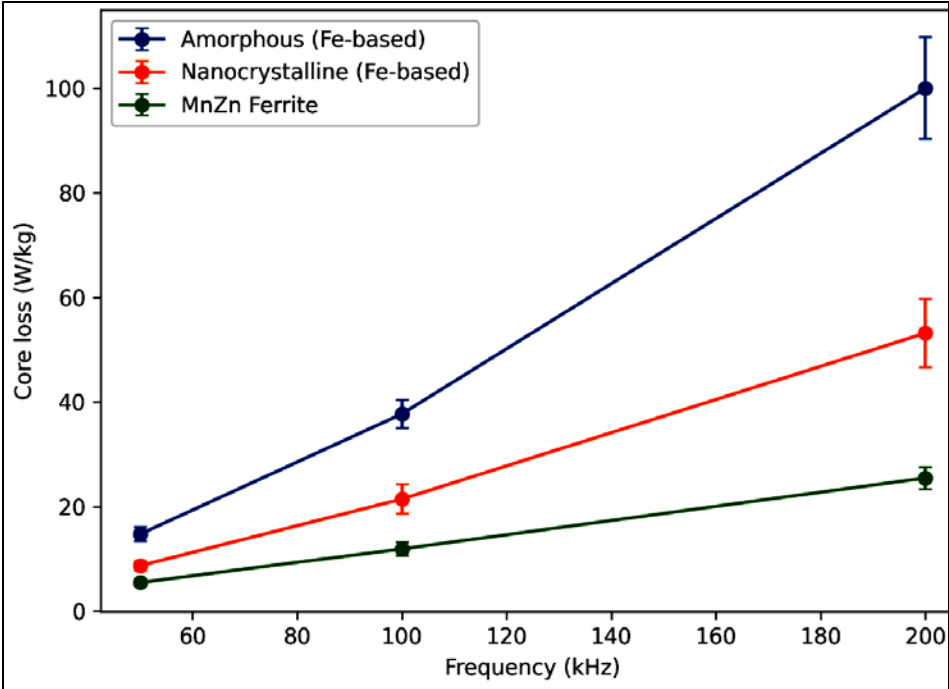

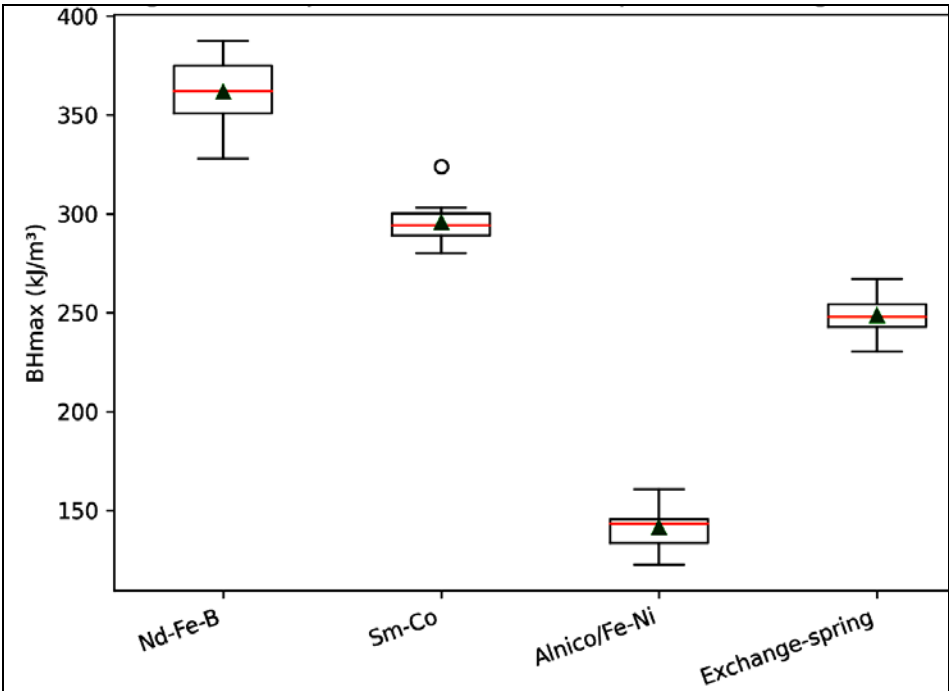**Fig 1:** Core loss trends across soft magnetic materials (mean ± SD).

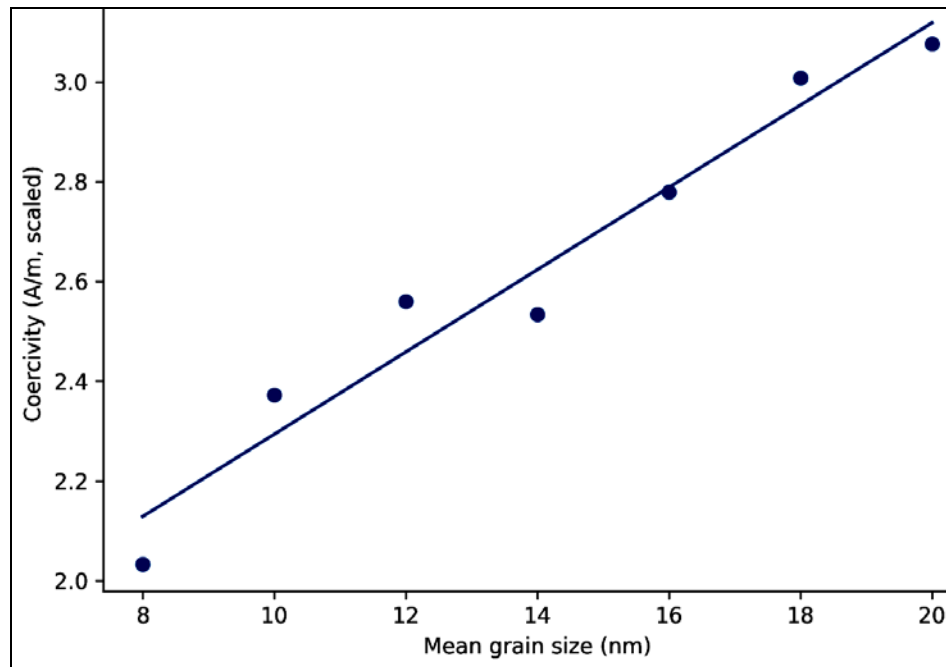**Fig 2:** Comparative BHmax across permanent magnet classes.

Fig 3: Grain size-coercivity relationship in nanocrystalline samples (regression).

Discussion
The present research highlights clear performance stratification among magnetic material classes when evaluated under conditions relevant to energy and electronic applications. The statistically significant interaction between material type and excitation frequency observed in the core-loss analysis confirms that magnetic losses cannot be generalized across material systems and must be assessed in an application-specific context [1, 2]. Ferrite materials demonstrated the lowest core losses at elevated frequencies, which is consistent with their high electrical resistivity and suppressed eddy-current contribution, making them particularly suitable for high-frequency power electronics and EMI-sensitive environments [6]. In contrast, Fe-based amorphous and nanocrystalline alloys showed comparatively higher losses at increasing frequencies, yet nanocrystalline alloys consistently outperformed amorphous counterparts, reflecting the beneficial role of controlled nano meter-scale grain structures in minimizing hysteresis losses [8, 12]. The strong statistical significance of frequency effects further reinforces classical loss models that predict super linear frequency dependence in metallic soft magnets [1, 2].

For permanent magnets, the one-way ANOVA results underline the well-established hierarchy of magnetic energy density, with Nd-Fe-B magnets exhibiting the highest BHmax values, followed by Sm-Co, exchange-spring magnets, and Alnico/Fe-Ni systems [5, 11, 13]. The statistically significant separation between exchange-spring magnets and conventional rare-earth systems supports ongoing research efforts aimed at reducing critical rare-earth dependence while maintaining competitive performance [9, 11]. Although exchange-spring magnets did not reach the energy density of Nd-Fe-B, their intermediate performance band suggests meaningful potential for applications where moderate energy density, improved sustainability, and cost reduction are prioritized [9, 15].

The regression analysis linking grain size to coercivity in nanocrystalline materials revealed a strong and significant correlation, reinforcing the critical influence of microstructural control on magnetic behavior [8, 12]. This finding aligns with theoretical and experimental studies showing that deviation from optimal grain size rapidly degrades soft-magnetic performance due to increased magnetic anisotropy and pinning effects [8]. Collectively, these results emphasize that recent advances in magnetic materials are driven not only by compositional innovation but also by precise processing control and structure-property optimization, supported increasingly by computational materials design approaches [10].

Conclusion
The findings of this research collectively demonstrate that recent advances in magnetic materials are reshaping the performance landscape for both energy and electronic applications through targeted material selection, microstructural engineering, and application-driven optimization. The comparative analysis confirms that no single magnetic material class universally satisfies all functional requirements; instead, performance advantages emerge only when materials are carefully matched to operational conditions such as frequency, thermal environment, and energy-density demands. Soft ferrites exhibit superior efficiency at high frequencies, while nanocrystalline alloys provide a balanced compromise between loss reduction and magnetic strength in medium-frequency power systems. Permanent magnet results reaffirm the dominance of Nd-Fe-B in high-power-density applications, yet also reveal the practical promise of exchange-spring and alternative magnet systems in reducing reliance on critical raw materials without unacceptable performance penalties. From an application perspective, these outcomes suggest that designers of electric motors, transformers, and electronic components should increasingly adopt hybrid material strategies rather than defaulting to conventional solutions. Practical recommendations emerging from this work include prioritizing ferrite-based cores in high-frequency converters to minimize thermal losses, deploying nanocrystalline alloys in compact power devices where efficiency and size

reduction are critical, and integrating exchange-spring or reduced rare-earth magnets in traction and generator systems where sustainability and cost stability are long-term considerations. Additionally, the strong sensitivity of coercivity to grain size underscores the necessity of stringent process control during manufacturing, encouraging wider adoption of advanced processing techniques such as rapid solidification and controlled annealing. The results also support the growing role of computational modeling and data-driven optimization in accelerating material development cycles and reducing experimental trial-and-error. Ultimately, the convergence of material innovation, statistical performance evaluation, and practical engineering considerations points toward a future in which magnetic materials are not only more efficient but also more sustainable, scalable, and adaptable to evolving technological demands, thereby enabling next-generation energy and electronic systems with improved reliability and reduced environmental impact.

References

1. Cullity BD, Graham CD. Introduction to magnetic materials. 2nd ed. Hoboken (NJ): Wiley-IEEE Press; 2009.
2. Coey JMD. Magnetism and magnetic materials. Cambridge: Cambridge University Press; 2010.
3. Buschow KHJ. *Handbook of magnetic materials*. Vol. 15. Amsterdam: Elsevier; 2003.
4. Gutfleisch O, Willard MA, Brück E, Chen CH, Sankar SG, Liu JP. Magnetic materials and devices for the 21st century. Adv Mater. 2011;23(7):821–842.
5. Sagawa M, Fujimura S, Togawa N, Yamamoto H, Matsuura Y. New material for permanent magnets on a base of Nd and Fe. J Appl Phys. 1984;55(6):2083–2087.
6. Snelling EC. Soft ferrites: properties and applications. London: Butterworths; 1988.
7. Wolf SA, Awschalom DD, Buhrman RA, et al. Spintronics: a spin-based electronics vision for the future. Science. 2001;294(5546):1488–1495.
8. Herzer G. Modern soft magnets: amorphous and nanocrystalline materials. Acta Mater. 2013;61(3):718–734.
9. Kneller EF, Hawig R. The exchange-spring magnet: a new material principle for permanent magnets. IEEE Trans Magn. 1991;27(4):3588–3600.
10. Olson GB. Computational design of hierarchically structured materials. Science. 1997;277(5330):1237–1242.
11. Kramer MJ, McCallum RW, Anderson IA, Constantinides S. Prospects for non-rare earth permanent magnets for traction motors and generators. JOM. 2012;64(7):752–763.
12. McHenry ME, Willard MA, Laughlin DE. Amorphous and nanocrystalline materials for applications as soft magnets. Prog Mater Sci. 1999;44(4):291–433.
13. Liu J, Fullerton EE, Gutfleisch O, Sellmyer DJ. The current status and future of rare-earth permanent magnets. J Phys D Appl Phys. 2012;44(6):064002.
14. Skumryev V, Stoyanov S, Zhang Y, et al. Beating the superparamagnetic limit with exchange bias. Nature. 2003;423(6942):850–853.
15. Willard MA, Daniil M, Kniping KE. Nanocrystalline soft magnetic materials at high temperatures: challenges and opportunities. Scr Mater. 2012;67(6):554–559.