Discover Materials

Review

Advanced thermal and magnetic materials for high-power and high-temperature applications: a comprehensive review

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Received: 2 April 2025 / Accepted: 11 June 2025
Published online: 30 September 2025

Abstract
This comprehensive review explores the advancements, applications, and challenges of advanced thermal and magnetic materials in high-power and high-temperature environments. These materials, including high-temperature superconductors, ferromagnetic materials, and magnetic alloys, are crucial for industries such as energy, aerospace, automotive, and electronics. They are crucial for managing heat, converting energy, and storing it, which boosts the efficiency and dependability of renewable energy systems, electric vehicles, and aerospace technologies. Nonetheless, they encounter major obstacles, such as material breakdown under harsh conditions, expensive production, and sustainability issues. The study explores essential thermal properties like heat capacity, thermal conductivity, thermal expansion, and thermal stress, highlighting the significance of ceramics, composites, metals, carbon nanotubes, and phase-change materials. It also investigates magnetic properties like permeability, coercivity, and remanence, essential for high-power applications. Emerging technologies such as nanotechnology, additive manufacturing, and machine learning offer promising solutions to overcome existing limitations. The review highlights the need for interdisciplinary research to develop sustainable and cost-effective materials capable of withstanding extreme conditions while maintaining performance. It underscores the importance of continuing research and development to address global energy and environmental challenges, paving the way for next-generation technologies. In summary, cutting-edge thermal and magnetic materials are set to transform industries, paving the way for more efficient and dependable technological advancements.

Keywords Thermal materials · Magnetic materials · Energy storage · High-power applications · Machine learning · Sustainability

1 Introduction

The future of material discovery, property prediction, and application-specific development has become a critical area of innovation, driven by machine learning (ML)-guided design, additive manufacturing techniques, and data-driven models. ML algorithms now enable rapid screening of material databases to predict thermal stability and magnetic coercivity, while additive manufacturing allows precise fabrication of complex geometries tailored for extreme environments. These interdisciplinary approaches are accelerating the transition from lab-scale discoveries to industrial applications. In particular, exploring thermal and magnetic materials has garnered significant attention due to their unique properties and wide-ranging potential applications [1–3]. Advances in magnetic materials, including rare-earth-free magnets and soft

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magnetic composites, have led to enhanced magnetic properties, such as higher Curie temperatures and lower energy losses. These advancements make these materials particularly well-suited for high-power applications [4, 5].

The developing advanced thermal and magnetic materials is critical for high-power systems operating under extreme conditions. Recent studies highlight nanostructured thermal materials such as graphene-reinforced composites for power electronics and Boron Nitride Nanotubes-embedded polymers (300% conductivity gains) for aerospace applications [6, 7]. Hybrid ceramic–metal composites maintain stability above 800 °C, aligning with frameworks for thermally robust systems [8, 9]. In magnetic materials, Magnesium Diboride (MgB) superconductors achieve 10 A/cm2 critical current densities at 20 K for fusion magnets, while Fe-Co alloys (2.4 T saturation, 900 °C Curie temperatures) enhance motor power density [10–12]. Advanced thermal and magnetic materials play a critical role in industries such as energy, aerospace, and automotive, enhancing efficiency and performance under extreme conditions [8]. Recent advancements in these materials have significantly improved their applicability in high-temperature and high-power environments, supporting sustainable engineering practices [9, 11, 12]. Nanostructured materials, including graphene-reinforced composites, improve thermal conductivity and magnetic performance, enabling efficient heat dissipation and operational reliability [6, 13]. Advances in polymer composites also highlight the importance of enhanced thermal properties for electronics and thermal management systems [7]. Combining advanced coatings and surface modifications further enhances thermal and magnetic stability in harsh environments, underscoring the potential of these materials to meet future technological demands [13]. As the need for high-power and high-temperature solutions grows, particularly in renewable energy, electric vehicles, and industrial machinery, these materials become essential for effective thermal management, energy conversion, and storage [14–18].

The integration of machine learning (ML) [19] into materials science has revolutionized the discovery, optimization, and application of advanced thermal and magnetic materials, particularly in high-power and high-temperature environments for effectively predicting thermal transport properties such as thermal conductivity, heat capacity, and thermal expansion coefficients, thereby overcoming limitations of traditional computational methods [20]. In this research area, ML enables predictive models that suggest new materials with specific thermal and magnetic properties like magnetization and coercivity, mapping complex relationships between composition and behavior [21]. In nano research, ML optimizes synthesis parameters and predicts nanostructure stability, enhancing functionality at the atomic level [22]. Overall, ML transforms materials science by accelerating discovery and optimizing properties for advanced materials. Furthermore, ML models trained on DFT and experimental data predict lattice thermal conductivity [23, 24] and Curie temperatures [25], enhancing high-throughput screening. For thermal materials, graph neural networks and convolutional models predict phonon-limited thermal conductivity [24], aiding thermoelectric material development. In magnetic materials, gradient boosting predicts magnetic ordering temperatures and facilitates the discovery of half-metallic Heusler alloys [26]. Challenges include limited data, model interpretability, and uncertainty quantification, while emerging directions involve physics-informed ML, active learning, and multi-objective optimization for balanced performance in material design.

Energy is a fundamental driver of sustainable economic and social development, playing a central role in addressing the world's most pressing economic, environmental, and developmental challenges. Its demand continues to rise steadily, yet the push for unrestricted energy supply creates conflicting ecological feedback loops, straining the environment. To meet these demands, materials used in high-power and high-temperature applications must exhibit precise thermal and magnetic properties, ensuring reliable, efficient, and effective performance under extreme conditions [27–30]. Due to these, the study of advanced thermal and magnetic materials is vital for energy innovation, improving efficiency, storage, and conversion. They improve heat management, reduce energy losses, and enable sustainable solutions, such as high-performance motors and energy storage. Research drives next-generation materials, supports global energy needs, reduces environmental impact, and advances clean technologies to address climate challenges. In an era where technological advancements push the limits of performance and efficiency, the demand for materials capable of withstanding extreme conditions has never been greater. High-power and high-temperature applications, ranging from aerospace and energy systems to electric vehicles and advanced electronics, require materials that can operate reliably under intense thermal and electromagnetic stresses. The shortage of energy and environmental pollution are major critical problems worldwide [31–33].

Therefore, a detailed study is necessary to evaluate the implications of energy consumption, conservation, generation, conversion, and storage materials. These materials offer distinct mechanical, electrical, and optical properties, which have been pivotal in driving recent advances in energy-related technologies. Advanced thermal and magnetic materials are particularly critical in high-power and high-temperature applications, as they enhance performance and efficiency in industries such as electric vehicles, aerospace, and chemical processing. Their ability to withstand extreme operating conditions makes them indispensable for meeting the demands of high-power and high-temperature environments.

This article examines the significance of advanced thermal and magnetic materials in demanding environments, starting with their properties, types, applications, challenges, and possible prospects. The review is structured as follows. The second section highlights the critical role of thermal and magnetic materials in high-temperature environments with a focus on their essential properties. The third section discusses key properties of thermal materials, including various types, such as ceramics, composites, metals, carbon nanotubes, and phase change materials, emphasizing their unique characteristics and applications. The fourth section discusses the fundamental magnetic properties of materials, such as magnetization, susceptibility, permeability, coercivity, and remanence, which are crucial for understanding their behavior in high-power applications. It also covers different types of magnetic materials, including soft and hard magnets, high-temperature superconductors, and ferromagnetic materials, underscoring their role in enhancing efficiency and performance under extreme conditions. The fifth section explores the synergistic applications of advanced thermal and magnetic materials in high-power and high-temperature environments. Finally, the sixth section summarizes the challenges associated with these materials and discusses future perspectives and potential solutions to address these challenges.

Having established the critical role of advanced materials in addressing high-power and high-temperature challenges, we now turn our focus to the fundamental properties and classifications of thermal and magnetic materials that underpin their performance in extreme environments.

2 Thermal and magnetic materials

Selecting materials for high-power and high-temperature applications requires a thorough evaluation of their thermal, chemical, magnetic, and mechanical properties, as well as cost considerations. The fast-paced advancement of electronics also calls for enhanced thermal management solutions. To address this, novel materials with enhanced properties are crucial. Cost-effective production using new chemicals and techniques is essential. Successful integration hinges on precisely designed materials and interfaces. Optimizing performance requires careful control of critical material properties through advanced metrology [34, 35]. These properties must ensure that the material can withstand various stresses, including exposure to chemicals, extreme heat, corrosion, and pressure. Cutting-edge thermal and magnetic materials are at the forefront of this transformation, significantly enhancing performance and efficiency for high-power applications. The growing demand for electric vehicles, renewable energy systems, and high-performance electronics is increasing the need for efficient energy storage and advanced materials with unique properties, such as thermal, magnetic, mechanical, and electronic capabilities. By fully understanding the properties and principles of thermal materials, it is possible to make informed decisions when selecting materials for specific applications, ensuring optimal performance and efficiency [27, 29, 36].

Advanced thermal and magnetic materials (e.g., ceramics, composites, superconductors) have played a pivotal role for high-power/high-temperature applications in energy, aerospace, and electronics for enhancing thermal management, energy efficiency, and performance under extreme conditions [37]. The global demand for more efficient and large-scale energy storage has driven significant research in next-generation batteries and innovative electrode materials. The future energy depends critically on the development of innovative energy storage materials for maximizing the potential of energy sources. Advanced energy storage systems are promising for addressing key grid challenges by improving stability and resilience across the entire network. In the field of nanostructured materials for energy storage, reducing materials to the nanoscale leads to substantial changes in their physical, chemical, and electronic properties. These modifications are crucial for the advancement of energy materials and the meeting of the increasing demands of modern applications. While thermal and magnetic materials are often interdependent in practical applications, understanding their characteristics is essential.

In the following sections, the specific thermal materials properties—such as heat capacity, thermal expansion, thermal conductivity, and thermal stress are described to excel in demanding scenarios.

3 Thermal materials properties and applications

Materials designed for high-temperature applications must withstand thermal stress, resist degradation, and maintain structural integrity. The thermal properties of a material describe its characteristics and behaviors related to heat and temperature [3, 29, 38, 39]. The characteristics of thermal and magnetic materials are essential for numerous applications, and analyzing these properties requires a detailed analysis of their thermal behavior, magnetic interactions, and relevance to real-world uses [40, 41].

3.1 Thermal materials properties

Advanced thermal and magnetic materials must have specific thermal properties to ensure optimal performance, reliability, and durability. These properties include heat capacity, thermal conductivity, thermal expansion, and thermal stress, which are critical for designing materials that perform effectively in demanding environments [3, 42, 43]. Understanding these properties [6–11] is essential for applications in thermal management, material selection, and energy efficiency, as they directly impact thermal expansion, conductivity, and thermoelectric effects in various materials [44, 45]. Identifying the properties and characteristics of materials is crucial for developing solutions that meet high-power and temperature demands in industries such as materials manufacturing, power generation, and aerospace, which rely heavily on high-temperature operations. Effective performance at elevated temperatures and power is essential and depends on creating materials capable of withstanding the specific mechanical and environmental stresses of each application [46]. These properties are defined below and are essential for applications in thermal management and energy efficiency.

3.1.1 Heat capacity

Heat capacity is a fundamental thermal property that quantifies the heat energy required to change a material's temperature. In high-temperature applications, materials with high heat capacity are advantageous as they can absorb and store significant thermal energy, crucial for maintaining stable operating temperatures and preventing overheating [3, 42]. This can be expressed in the equation below as expressed in Eq. 1:

$$C = \frac{dQ}{dT} \tag{1}$$

dQ represents a small differential change in energy to cause a differential change in temperature. When materials are subjected to heat, the atoms in the lattice gain energy, and thus the overall length or volume increases. High heat capacity materials (e.g., composites) absorb substantial thermal energy, stabilizing systems against temperature spikes and improving energy efficiency.

3.1.2 Thermal expansion

Thermal expansion describes the tendency of a material to change its dimensions (length, area, volume) in response to variations in temperature. In high-temperature environments, this dimensional change influences the material's structural integrity and operational performance. Understanding thermal expansion behavior is essential for developing materials that can withstand thermal stresses without failure [3, 42, 47]. Predicting this behavior helps engineers design materials resistant to thermal stress. The linear expansion equation quantifies this relationship, and can be expressed below in Eq. 2:

$$\Delta l = l_0 \alpha \Delta T \text{or} l_f = l_0[1 + \alpha(T_f - T_0)] \tag{2}$$

where α is the thermal expansion coefficient. Materials like iron-nickel alloys and ceramics, with low α, minimize stress in extreme conditions. In magnetic materials (e.g., *SmCo*, *NdFeB*), excessive expansion risks disrupting magnetic alignment or causing mechanical failure. Similarly, thermal management systems rely on low-expansion materials (e.g., heat exchangers, coatings) to ensure stability under thermal cycling. Graphite and certain composites are preferred for their high heat capacity, and Iron-nickel alloys, with a low thermal expansion coefficient ($\alpha \approx 1.5 \times 10^{-6}$ K^{-1}), are used in precision aerospace components such as satellite brackets, where minimal expansion ensures stability across extreme orbital temperatures (– 150 °C to + 120 °C). Understanding these principles enables tailored material design for performance and safety in demanding applications [48, 49].

3.1.3 Thermal conductivity

Thermal conductivity is a material's capacity to transfer heat, a crucial property in energy technologies. Materials with high thermal conductivity are essential for efficient heat conduction and dissipation. Examples include graphene, carbon nanotubes, and ceramics like silicon carbide and aluminum nitride, which are ideal for high-temperature applications [50]. Microscopically, heat conduction occurs via lattice vibrations (phonons), electrons (metals), gas molecules (porous media), or photons (infrared materials) [13, 51, 52]. The below Eq. 3, the mathematical expression of heat flux is expressed as:

$$q = -k\frac{dT}{dx} \tag{3}$$

where q is heat flux (W/m^2), k is thermal conductivity (W/m K), and dT/dx is the temperature gradient (K/m). The negative sign reflects heat flow from hot to cold, aligning with thermodynamics.

High thermal conductivity materials prevent overheating in electronics and optimize heat transfer in industrial systems. Key influencing factors include material type, temperature, density, and moisture. In aerospace, silicon carbide (*SiC*) ceramics (k ≈ 120–200 W/m K) dissipate heat from hypersonic vehicle surfaces, preventing structural failure during re-entry. Similarly, graphene-reinforced composites (k≈3000 W/m K) manage heat in high-power electronics, reducing thermal throttling in 5G base stations for the design of insulation, heat sinks, and thermal control systems [3, 47, 50].

3.1.4 Thermal stress

Thermal stress arises from temperature gradients and uneven expansion within a material, generating internal forces that can cause deformation or failure. In high-power applications, materials must be engineered to resist cracking or warping under rapid heating and cooling cycles [3, 47, 53]. The thermal stress equation quantifies this relationship:

$$\sigma = E\alpha\Delta T, \tag{4}$$

where E (elastic modulus) governs stiffness, α (thermal expansion coefficient) determines dimensional sensitivity to temperature, and ΔT reflects temperature gradients.

High E or α, combined with large ΔT (common in high-power devices), amplifies stress. Materials for motors, generators, or magnetic systems require low α, high thermal conductivity, and robust E to endure thermal cycling without degradation. Advanced materials must balance these properties to maintain structural integrity while minimizing stress. Insulation materials with low thermal conductivity are equally vital for safety in high-temperature human-facing applications [50].

3.2 Types of thermal materials for high-power and high-temperature applications

The thermal and magnetic properties of materials designed for high-power and high-temperature applications differ significantly across categories like ceramics, composites, metals and alloys, carbon nanotubes, and phase change materials. Each type exhibits unique characteristics, making them suitable for specific uses, especially in energy storage and thermal management systems. The following sections analyze these materials' properties and applications in detail.

3.2.1 Ceramics

Ceramics are highly valued for their remarkable thermal stability and ability to endure extreme temperatures, making them suitable for high-temperature uses. Materials like silicon carbide, aluminum nitride, and boron nitride are especially recognized for their high thermal conductivity and structural integrity under thermal stress. These advanced ceramic materials are utilized across a wide spectrum of demanding industrial sectors, including metallurgy, glass and cement production, aerospace, nuclear energy, and power generation. Their unique properties not only enhance performance in these fields but also contribute significantly to the development of a sustainable society by enabling energy-efficient and durable solutions [3, 54–58].

Ceramics like *SiC* and *AlN* exhibit low thermal expansion (α) and high thermal conductivity (k), making them ideal for aerospace and nuclear applications [54, 57]. These materials typically exhibit low coefficients of thermal expansion, rendering them highly resistant to thermal shock. Additionally, they often possess favorable magnetic properties, especially ferrites, which are widely utilized in high-frequency applications owing to their high magnetic permeability and minimal energy losses. Most ceramics are diamagnetic or paramagnetic, with the exception of ferrite ceramics (e.g., Fe_3O_4) that exhibit ferrimagnetism and are used in magnetic applications like inductors and transformers [35, 59–62].

3.2.2 Composites

Traditional materials for heat and power management are approaching their performance limits, prompting the development of advanced composites with tailored properties. Ceramic-reinforced polymers, for example, achieve thermal conductivities up to (k ≈5.75 W/m K while maintaining dimensional stability [13, 63]. These composites offer enhanced thermal performance, reduced thermal expansion and stress, improved structural strength, and lightweighting—making them ideal for aerospace, electronics, and automotive applications [55, 64]. Nanoparticle-reinforced composites (e.g., graphene-SiC) improve thermal conductivity and reduce thermal expansion, mitigating stress-induced degradation [65], and for further improve thermal conductivity and stability, significantly boosting heat transfer efficiency [5, 66]. Their tunable properties and growing adoption in manufacturing highlight their transformative potential in modern thermal and power systems. Composites can also be engineered to exhibit targeted thermal responses by combining matrices with fillers such as ceramics or carbon fibers. Al_2O_3 or SiC coatings on magnetic alloys (e.g., Fe-Si-B-Nb) prevent oxidation at high temperatures. Corrosion-resistant epoxy-CNT composites (e.g., doped with Fe_3O_4 nanoparticles) shield magnetic components from harsh environments [19]. When reinforced with carbon or ceramic fibers, they maintain stability at high temperatures. While most composites are non-magnetic, incorporating magnetic fillers (e.g., iron oxide) enables use in electromagnetic applications [54, 56, 67].

3.2.3 Metals and alloys

Metals and alloys exhibit high thermal conductivity and can withstand extreme temperatures, making them ideal for high-power applications and efficient heat dissipation. Their performance can be enhanced through alloying and heat treatment. Common high-temperature metals include tungsten, molybdenum, and tantalum, while steel, nickel, and copper alloys are widely used in aerospace. Copper, aluminum, and advanced superalloys are favored for heat exchangers and thermal management systems [3, 50, 54, 56, 68].

However, metals generally have high thermal expansion coefficients, which can limit their use in precision applications under extreme temperatures. Ferromagnetic metals like iron, cobalt, and nickel are valued for strong magnetic field applications. Alloys can be engineered to optimize both thermal and magnetic properties, as seen in soft magnetic alloys used in transformers [56, 69]. Thermal material properties dominated by lattice vibrations in insulators and electron conduction in metals are governed by principles including thermal expansion, thermal conductivity, and thermoelectric effects, and are crucial for predicting material behavior under temperature variation. High-temperature ceramics find application in construction, aerospace, nuclear systems, oxide fuel cells, and electronics due to their thermal stability and resistance [70]. In modern thermal and power applications, nanoparticle-enhanced composites offer superior thermal performance over traditional materials. Their enhanced thermal properties enable more efficient heat transfer, positioning them as leading solutions in advanced thermal and power management systems [66].

3.2.4 Carbon nanotubes (CNTs)

Carbon nanotubes (CNTs) are nanoscale hollow structures composed of carbon atoms, renowned for their exceptional structural, electrical, mechanical, and thermal properties. With axial thermal conductivity reaching approximately 3500 W/m K, CNTs enable highly efficient heat transfer, making them ideal for high-temperature thermal energy storage and management systems [71–74]. Their lightweight nature and superior strength-to-weight ratio further enhance their suitability for demanding applications in electronics, biomedicine, solar energy, and advanced composites [73]. CNTs are inherently diamagnetic but can be doped with magnetic elements like iron or nickel to tailor their magnetic behavior for specialized electronic and electromagnetic applications [55, 75].

This tunability allows CNTs to be engineered for multifunctional roles, including thermal management and magnetic responsiveness. Their ability to retain structural integrity at extreme temperatures reinforces their value in high-temperature environments. Additionally, CNTs have shown promise in reinforcing concrete beams under thermal stress, improving mechanical performance and durability [76]. In modern applications, CNT-polymer composites are used to cool high-density server chips in data centers, reducing energy consumption. In electric motors, CNT-doped epoxy resins help lower winding temperatures, thereby enhancing torque density and extending operational lifespan. Carbon nanotubes represent a groundbreaking class of materials with unmatched thermal, mechanical, and magnetic properties, offering transformative potential across diverse technological domains [77, 78].

3.2.5 Phase change materials (PCMs)

The energy crisis has accelerated the adoption of phase-change materials (PCMs) as critical components in thermal energy storage systems. These materials enable efficient energy management by absorbing and releasing latent heat during phase transitions, offering high energy density, reusability, and effective thermal regulation [3, 31, 54, 66, 79]. Molten salts (e.g., $NaNO_3 - KNO_3$) stabilize thermal cycling in solar storage systems, reducing temperature fluctuations [80, 81]. By maintaining near-constant temperatures during phase changes, such as solid–liquid or liquid–gas, PCMs enhance energy efficiency, improve heat transfer, and help balance supply–demand mismatches across various systems [35, 56]. They are widely used in solar energy, automotive, and construction industries for passive thermal regulation and load-shifting strategies that store excess energy during off-peak hours for later use [82, 83].

Despite their typically low to moderate thermal conductivity, performance can be enhanced through nanoparticle integration, which improves heat dissipation. While most PCMs—like paraffin wax and salt hydrates—are non-magnetic, magnetic variants can be engineered by embedding nanoparticles for specialized applications such as magnetic hyperthermia [55, 84, 85]. Material selection for high-power and high-temperature applications depends on thermodynamic, kinetic, environmental, and economic factors. Therefore, continued research into PCM properties and system integration remains essential for advancing sustainable energy solutions [31, 81, 83, 86, 87]. In solar thermal plants, molten salt PCMs (e.g., $NaNO_3$-KNO_3) store excess daytime heat at 565 °C, enabling continuous electricity generation overnight. In electric vehicle batteries, PCM-enhanced thermal interfaces prevent overheating during fast charging. PCMs like paraffin wax leverage latent heat (ΔH) for thermal energy storage. Their low k is mitigated via nanoparticle additives [31, 35].

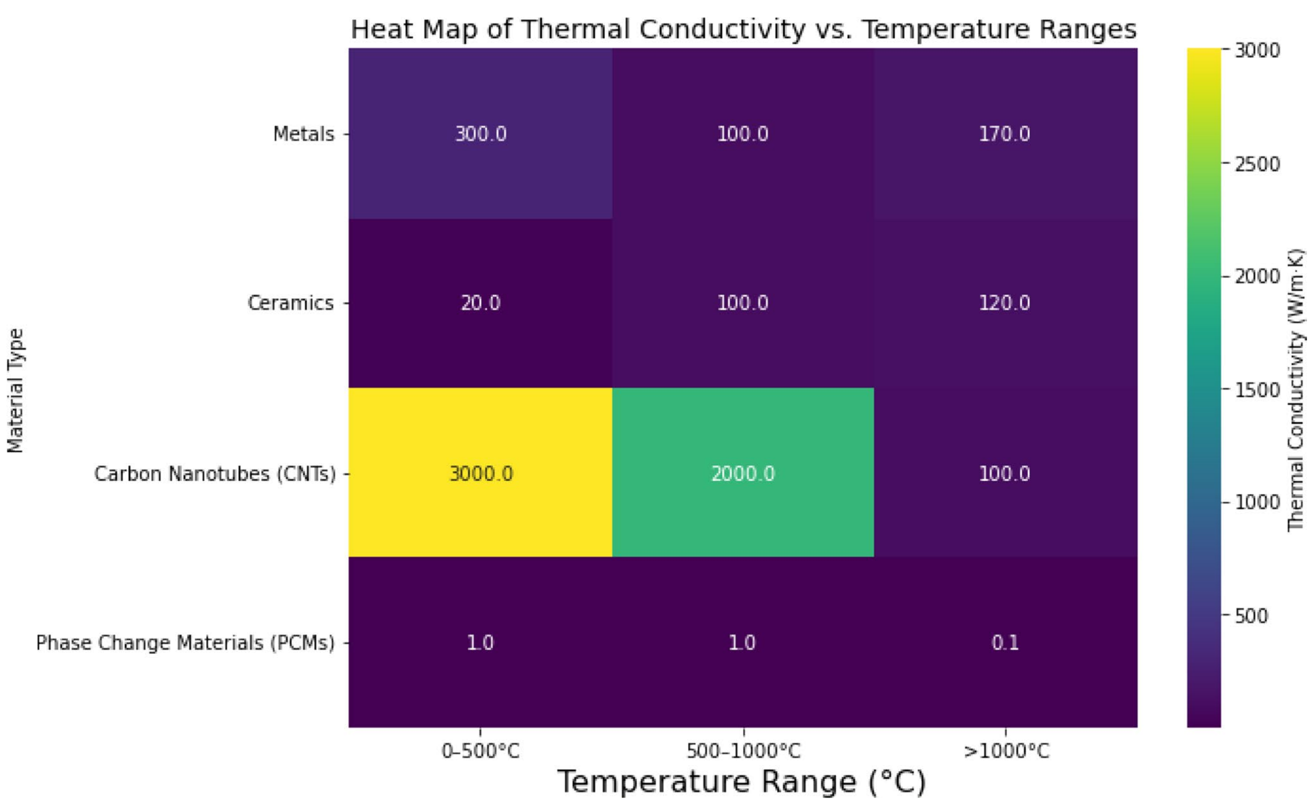

Fig. 1 The heat map, a visual representation of materials' thermal conductivity across different temperature ranges

The heat map, prepared by Python, at Fig. 1 provides a visual representation of materials' thermal conductivity (measured in W/m K) across distinct temperature ranges. Metals exhibit high thermal conductivity at low temperatures, approximately 300 W/mK. However, their conductivity decreases in the mid-range temperatures and partially recovers at temperatures exceeding 1000 °C, where it is around 170 W/mK, which is suitable for systems operating at lower temperatures, and denotes that metals are suitable for mid-range temperature systems, best for low-temperature applications. Ceramics show a steady increase in thermal conductivity from 20 W/m K to 120 W/m K as the temperature rises, making them ideal for applications involving extreme heat, which is commonly used in aerospace and high-temperature environments, highlighting their application in aerospace. Carbon Nanotubes (CNTs) lead in thermal conductivity at low and mid-range temperatures, with values ranging from 3000 W/mK to 2000 W/mK. However, their performance significantly drops above 1000 °C. This property indicates their primarily used in advanced applications, particularly in electronics cooling for advanced applications below 1000 °C.

4 Magnetic materials for high-power and high-temperature applications

Magnetic materials are essential in many electronic devices, facilitating energy conversion, data storage, motion control, and signal transmission. They are crucial for the functionality and performance of modern electronics. They ensure efficient voltage regulation in power supplies and transformers, reliable data recording in hard drives and tapes, and precise energy conversion in motors and sensors. They also improve wireless communication by optimizing antennas and RF components. Soft magnetic composites and nanocrystalline materials are pivotal in enhancing the performance of electric motors by improving power density and efficiency. They allow better modeling and understanding of magnetic properties under operational conditions, which is crucial for optimizing motor design [88].

Just as thermal stability is paramount for managing heat dissipation, magnetic materials must retain their functional integrity under similar extremes. We now shift our focus to the magnetic properties, including magnetization, magnetic susceptibility and permeability, coercivity, and remanence, that define their suitability for high-power systems.

4.1 Properties of magnetic materials for high-power and high-temperature applications

The thermal and magnetic properties of materials engineered for high-power and high-temperature applications exhibit significant variation across different categories, with each material type demonstrating unique characteristics tailored to specific uses. Magnetic materials, in particular, are defined by key properties such as permeability, coercivity, and remanence, which are critical for understanding their performance in diverse applications. Magnetic permeability quantifies a material's ability to support the formation of magnetic field lines within it; coercivity represents the material's resistance to demagnetization; and remanence refers to the residual magnetization that persists after the removal of an external magnetic field. The following subsections provide a detailed exploration of these fundamental magnetic principles [89].

4.1.1 Magnetization

Magnetization M quantifies a material's response to an external magnetic field (B). It represents the alignment of magnetic moments within the material under the influence of B. In advanced thermal and magnetic materials, M is governed by temperature, material composition, and microstructure, which collectively determine the material's magnetic behavior. In high-power, high-temperature applications, M is critical for optimizing magnetic performance, energy efficiency, and thermal stability, as it ensures functionality under extreme conditions by adapting to changes in temperature, composition, and microstructure. The magnetization of a material depends on susceptibility χ_M and the magnetic field B:

$$M = \chi_M \cdot B \tag{5}$$

Saturation magnetization, determined by aligned magnetic moments, is critical for high-power, high-temperature applications. It dictates a material's capacity to generate strong magnetic fields, enabling efficient energy conversion and stable performance. Ferromagnetic materials, with inherently aligned moments, are preferred over paramagnetic materials. High saturation magnetization minimizes energy losses and enhances thermal stability in demanding environments like electric motors and sensors. However, elevated temperatures reduce saturation, necessitating materials with high Curie temperatures and designs that retain magnetic strength under extreme conditions [50, 88, 90].

4.1.2 Magnetic susceptibility (χ_M)

Magnetic susceptibility measures a material's magnetization response to an applied magnetic field, crucial for high-power and high-temperature applications. It influences magnetic field concentration or repulsion, vital for efficiency in transformers and motors. Temperature impacts susceptibility, making stable behavior essential for extreme conditions. Materials with minimal variation are preferred. Understanding susceptibility aids in developing sensors for harsh environments and optimizing energy efficiency and thermal management in power systems [91].

$$\chi M = \frac{\Delta M}{\Delta B} = \frac{dM}{dB} \tag{6}$$

It is a dimensionless proportionality constant that indicates whether a material is;

- For diamagnetic materials, $\chi_M < 0$, weakly repel magnetic fields and are less affected by temperature changes.
- for paramagnetic materials, $\chi_M > 0$,weakly attracted to magnetic fields, with susceptibility decreasing as temperature rises.
- For ferromagnetic materials, $\chi_M >> 0$, exhibit strong magnetization and retain magnetic properties even after the field is removed, though susceptibility can vary significantly with temperature.

In high-power applications, materials with high magnetic susceptibility enhance permeability, boosting energy efficiency in devices like transformers and motors. For high-temperature environments, materials with stable susceptibility are preferred to ensure consistent performance amid thermal fluctuations. Understanding χ_M aids in selecting materials that maintain optimal magnetic and thermal properties under extreme conditions. At high temperatures, magnetic materials often undergo a phase transition known as the Curie temperature (Tc). Above this temperature, ferromagnetic or ferrimagnetic materials lose their spontaneous magnetization and transition to a paramagnetic state. This occurs because thermal energy disrupts the alignment of magnetic moments, causing the material to lose its long-range magnetic order [91, 92]. The temperature dependence of susceptibility is described by the Curie–Weiss law as:

$$\chi_M = \frac{C}{T - Tc} \tag{7}$$

where: C is the Curie constant, T is the temperature, and Tc is the Curie temperature.

Magnetization and magnetic susceptibility are essential properties for advanced thermal and magnetic materials used in high-power and high-temperature applications, including electric motors, transformers, and magnetic storage devices. These materials must maintain stable magnetic properties under extreme conditions, such as elevated temperatures and high magnetic fields, to ensure reliable performance and efficiency [92–95].

Figure 2, plotted from Python code, demonstrates how magnetization decreases as temperature approaches the Curie temperature (T_c) for a ferromagnetic material.

- Below T_c: The material retains strong magnetization;
- Above T_c: It transitions to paramagnetic behavior with weak susceptibility.
- Curie Temperature (T_c): Marked by a dashed red line, T_c is the critical temperature where the material transitions from ferromagnetic to paramagnetic.
- Ferromagnetic Region ($T < T_c$): Magnetization remains near saturation (M_{sat}) due to aligned magnetic moments.
- Paramagnetic Region ($T > T_c$): Thermal energy disrupts magnetic order, causing magnetization to drop sharply and follow the Curie–Weiss law.

Cooling systems must ensure temperatures remain below T_c to preserve magnetic efficiency. For high-power/high-temperature applications (e.g., electric vehicle motors), materials with T_c well above operational temperatures are essential to avoid demagnetization.

4.1.3 Magnetic permeability

Magnetic permeability is a fundamental property that quantifies a material's ability to be magnetized in response to an external magnetic field. Materials with higher permeability magnetize more easily, enhancing their interaction

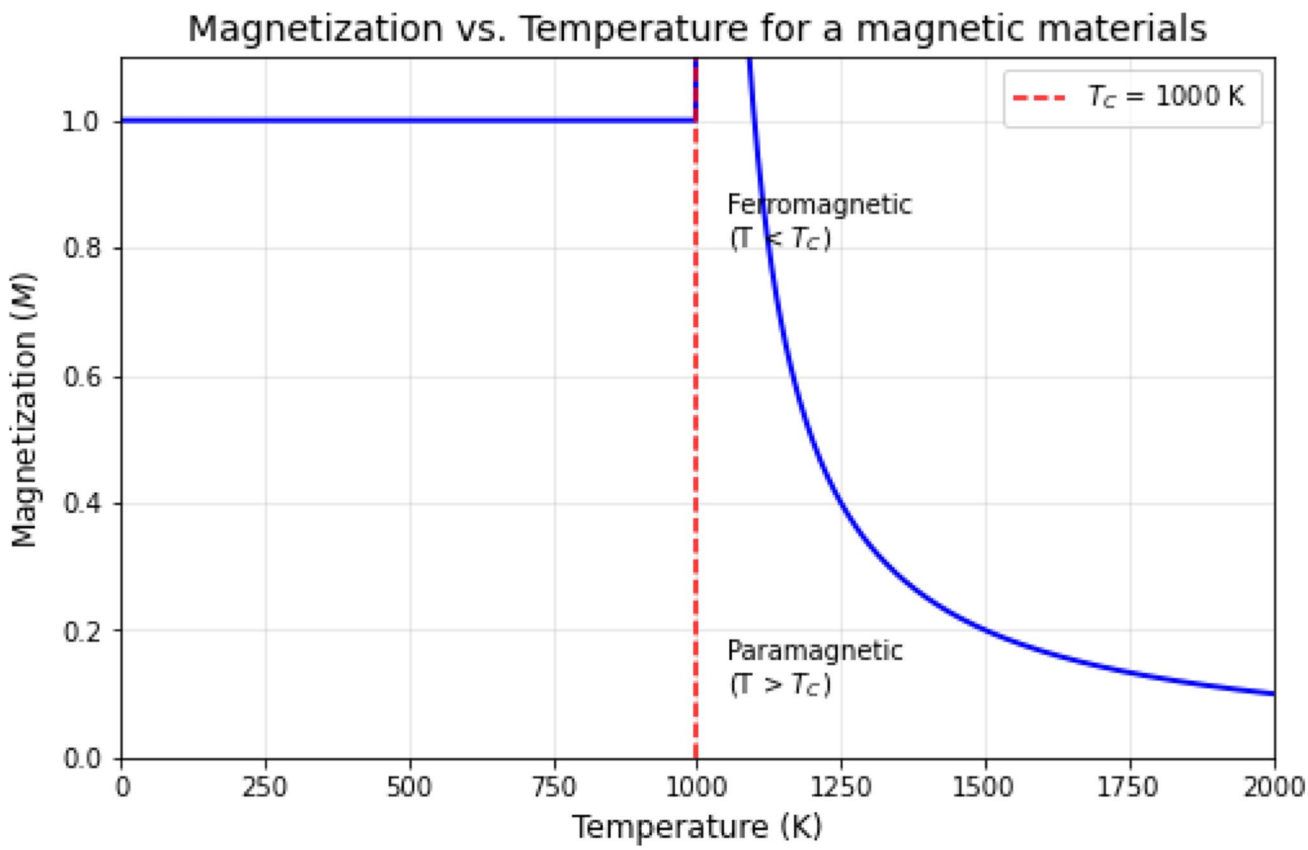

Fig. 2 The effect of temperature on magnetic behavior of magnetic materials

with magnetic fields. This property significantly influences heat and fluid flow dynamics in systems where magnetic fields are present. Understanding permeability is crucial for analyzing the interplay between magnetic fields and thermal or fluid processes, optimizing performance in applications like magnetic cooling and energy systems [49, 96]. Magnetic permeability quantifies a material's ability to support the formation of a magnetic field within itself when subjected to an external magnetic field. Materials with high permeability, such as soft iron, facilitate the efficient passage of magnetic flux with minimal opposition, enhancing their effectiveness in applications like electromagnets and transformers. Conversely, materials with low permeability, such as air or vacuum, present significant resistance to magnetic flux, making them less suitable for such applications. Permeability is a pivotal parameter in designing magnetic circuits, optimizing energy transfer in transformers, and implementing effective magnetic shielding solutions [49].

4.1.4 Coercivity

Coercivity quantifies a material's resistance to demagnetization, serving as a crucial parameter in evaluating magnetic materials for specific applications. It is defined as the intensity of the applied magnetic field needed to reduce a material's magnetization to zero after it has reached saturation. Materials are categorized as either soft (low coercivity) or hard (high coercivity). Soft magnetic materials, with their low coercivity, are optimal for applications requiring frequent magnetization and demagnetization cycles, such as transformers and inductors. Conversely, hard magnetic materials, characterized by high coercivity, are resistant to demagnetization, making them ideal for permanent magnets used in motors and data storage devices. This distinction is vital for selecting materials that meet the performance demands of various technological applications [48, 69, 97, 98]. Materials with tailored coercivity and high thermal stability are essential for maintaining performance in demanding environments. A detailed understanding of the interplay between coercivity, thermal properties, and magnetic behavior is crucial for effective material selection and design in such applications [99–101].

4.1.5 Remanence

Remanence, or residual magnetization, is the magnetization that remains in a material after an external magnetic field is removed. High remanence is desirable in permanent magnets, influencing their applications in motors and generators. High-remanence materials retain a strong magnetic field even without an external field, making them suitable for permanent magnets. Low-remanence materials retain little or no magnetization after the field is removed. Remanence determines the strength of a permanent magnet's field [67, 102–105].

The growing need for sustainable energy drives electrification, making efficient devices crucial. These devices require materials with strong magnetic properties, mechanical durability, and heat resistance. Numerous industries, from aerospace to energy production, rely on high-temperature materials in critical components. As performance demands increase, these materials must withstand increasingly extreme heat while remaining cost-effective, necessitating exceptional strength and thermal stability.

The following sections provide an overview of the key properties of soft and hard magnetic materials, high-temperature superconductors, nanocrystalline and amorphous alloys, and ferromagnetic materials [88, 89, 106, 107].

4.2 Types of magnetic materials for high-power and high-temperature applications

The magnetic properties of materials are known to depend on temperature. As the thermal vibrations in a solid increase, the magnetic moments can rotate and align in random directions. The Curie temperature T_C is where the magnetic saturation decreases rapidly to zero with increasing temperature. For certain materials like iron, Fe_3O_4, the ferromagnetic and ferrimagnetic properties disappear, and the material becomes paramagnetic [50]. There are some important examples of advanced magnetic materials used in high-temperature and high-power applications. High-power-density electric motors benefit from advanced magnetic materials, such as soft magnetic composites and nanocrystalline materials, which enhance efficiency and performance in electric vehicles [88, 108–110].

4.2.1 Soft magnetic materials

Soft magnetic materials are characterized by high magnetization with minimal external magnetic fields, due to their low coercivity and high magnetic permeability. These properties allow for easy magnetization and demagnetization, making them ideal for electrical and electronic applications. Common soft magnetic materials include iron-silicon alloys, like silicon steel sheets, and soft magnetic ferrites, which are essential for efficient energy conversion and signal processing. Hysteresis curves graph the change in magnetization due to a magnetic field, with soft magnets exhibiting thin and narrow curves compared to the wider curves of hard magnets [50, 88, 109, 111]. Iron-cobalt (Fe-Co) alloys, ferrites, and amorphous alloys are prevalent soft magnetic materials used in transformers and inductors due to their exceptional properties. Silicon steel and ferrites minimize energy losses during magnetic flux changes, crucial for enhancing the efficiency of high-power electrical devices. The demand for soft magnetic materials that perform under high temperatures and mechanical loads is increasing, particularly for high-performance electrical machines, necessitating alloys that ensure consistent magnetic and mechanical performance while maintaining thermal stability [107].

This need arises from two key factors: higher efficiency in electrical machines often requires increased speeds, generating greater thermal and mechanical stress, and the shift toward sustainable energy sources exposes electrical machines to more demanding environments. Thus, developing soft magnetic materials that maintain performance under extreme conditions is critical for the efficiency and reliability of modern electrical machines [88, 109, 110, 112].

Nanocrystalline Fe-Si-B alloys are critical in Electric Vehicles traction inverters, reducing core losses by 50% at 20 kHz switching frequencies, improving range and efficiency. Soft magnetic materials with a Curie point near the upper operational temperature range exhibit the highest magnetic permeability, ensuring optimal performance under demanding conditions, making them an essential material for advancing energy-efficient technologies in power systems [88, 92, 93, 102].

4.2.2 Hard magnetic materials

Hard magnets, or permanent magnets, are materials that retain their magnetic properties over extended periods and exhibit strong resistance to demagnetization. These magnets are integral to various technologies, including electrovoltaics, wind turbines, and hard drives [88, 113, 114]. Rare-earth magnets, such as Neodymium-Iron-Boron (NdFeB) and Samarium-Cobalt (SmCo), are particularly prominent due to their high coercivity and energy density, making them essential for efficient motors and generators in high-performance applications. NdFeB magnets in offshore wind turbines enable direct-drive generators, eliminating gearboxes and cutting maintenance costs by 40% in harsh marine environments. SmCo-based permanent magnets, in particular, exhibit a high Curie temperature and exceptional magnetocrystalline anisotropy, making them highly valuable for scientific and technological applications, especially in high-temperature environments [92, 93]. To develop smaller and lighter permanent magnets, materials with strong resistance to demagnetization and high retained magnetism are required. Achieving this necessitates the creation of powerful permanent magnets with high coercivity and remanence, which are crucial for advancing miniaturization efforts [67, 103, 106].

Hard magnetic materials are characterized by their ability to retain their original magnetism over long periods, exhibit thick hysteresis loops, possess a high maximum magnetic energy product, and maintain remnant magnetism. They also feature large coercivity, enabling them to preserve their magnetic properties even under strong external magnetic fields and resist demagnetization [107, 115, 116]. High-temperature permanent magnets, including ceramics, high-temperature superconducting (HTS) magnets, and ferrite magnets, are increasingly utilized across various industries due to their ability to maintain magnetic properties under extreme conditions. These magnets are pivotal in advancing technologies in energy, transportation, and the medical fields [6, 89, 117–119].

4.2.3 High-temperature superconductors (HTS)

Superconducting materials conduct electricity with zero resistance, revolutionizing the energy industry by enabling lossless electricity transport. High-temperature superconductors (HTS) operate above liquid nitrogen temperatures, promoting efficient power transmission and enhancing magnetic-field performance in devices like motors, thereby significantly reducing energy losses. These materials, including ceramics, polymers, superalloys, and metals, are valued for their mechanical strength and thermal resistance, making them crucial in advanced technologies [61, 89, 92, 98, 117, 120]. HTS materials uniquely exhibit superconductivity at elevated temperatures, enabling resistance-free electrical conduction [89, 121]. Their superior performance at higher temperatures and magnetic fields is vital for advancing fusion energy technology. HTS tapes, such as yttrium barium copper oxide (YBCO), are used in fusion reactors such as the International Thermonuclear Experimental Reactor (ITER) to generate strong magnetic fields necessary for plasma confinement, maintaining plasma stability at approximately 150 million °C, which is essential for sustained nuclear fusion reactions [122]. These properties make HTS materials ideal for high-field magnets in magnetic resonance machines, motors, generators, and magnetic fusion systems. They also find applications in efficient energy transmission, magnetic levitation, inductive energy storage, computing, energy-efficient power grids, sensors, aircraft, space exploration, gas turbines, and nuclear power plants. Their unique characteristics significantly impact technological advancement and energy savings [99, 123].

4.2.4 Nanocrystalline and amorphous alloys

Nanocrystalline and amorphous alloys are highly sought after for high-power and high-temperature applications due to their exceptional thermal and magnetic properties. These materials feature high magnetic permeability and low coercivity, allowing for easy magnetization and demagnetization, which makes them widely used in high-frequency inductors, transformers, and magnetic cores for power electronics [124]. Nanocrystalline alloys, such as Fe–Si–B, are particularly notable for their high initial permeability, essential for efficient magnetic performance in transformers and inductive components. Their soft magnetic properties provide advantages like reduced core losses, improved efficiency, and compact designs. High permeability facilitates efficient magnetic flux conduction, while low coercivity ensures minimal energy loss during magnetization and demagnetization cycles. These characteristics make nanocrystalline and amorphous alloys ideal for high-power and high-temperature applications, where minimizing energy losses and maintaining operational efficiency are critical [100, 125–127].

4.2.5 Ferromagnetic materials

Ferromagnetic materials are crucial in high-temperature and high-power applications, where precise temperature management and efficient energy conversion are essential [128, 129]. Ongoing research aims to enhance their utility by improving heat resistance, magnetic stability, and structural integrity. A key challenge is maintaining consistent magnetic performance under heat exposure, as these materials often lose magnetic strength near their Curie temperature, the point at which they can no longer retain magnetic properties. Thus, materials with high Curie temperatures are sought after for applications involving extreme heat and power [107, 130, 131]. As temperatures rise, ferromagnetic materials experience a decline in properties like magnetization and magnetostriction, as their magnetic order diminishes approaching the Curie temperature [132]. Despite these challenges, ferromagnetic materials are indispensable in various industries. They serve as cores in electric motors and generators, facilitating efficient energy transfer in transformers by directing magnetic flux. Additionally, they are critical for sensor applications in automotive and industrial automation, detecting magnetic fields. In data storage, these materials enable high-speed data writing and reading, even under extreme conditions. Furthermore, they provide a sustainable alternative to conventional refrigeration systems and are ideal for electrical devices, transformers, and magnetic sensors due to their exceptional conductivity and magnetic properties. Materials with high thermal stability and strong magnetic induction are highly desirable for demanding applications [133–135]. For instance, Fe-Co alloys (Tc = 980 °C) in jet engine sensors can withstand 800 °C exhausts, delivering real-time performance data without signal degradation. The interplay between thermal and magnetic properties becomes evident when these materials are integrated into real-world systems.

The next section explores how their combined use drives innovation in various sectors such as in energy, aerospace, automotive, electronics and telecommunications, data storage, and signal processing, highlighting their complementary roles.

5 Synergistic applications of advanced thermal and magnetic materials for high-power and high-temperature

The advancement of high-power and high-temperature technologies depends on the creation and use of sophisticated thermal and magnetic materials. In vital industries, these materials enhance performance, dependability, and efficiency, fostering innovation and sustainability. High-temperature materials have many industrial uses and are essential to sustainable engineering. Their importance in production and processing emphasizes the need for materials research that is centered on end-use needs. The goal of sustainable engineering is to develop solutions that promote long-term sustainability, improve resource efficiency, and reduce environmental impact [61, 136]. Thermal Energy Storage (TES) systems store thermal energy by heating or cooling a storage medium for later use and help to mitigate peak load demands and lower operational costs. Given their frequent application in high-temperature environments, TES systems commonly utilize phase-change materials and thermochemical materials to enhance energy storage efficiency and stability [137, 138].

5.1 Energy sector

High-temperature thermal storage materials, including molten salts and advanced ceramics, are pivotal in enhancing the efficiency of concentrated solar power (CSP) systems. These materials facilitate operation at elevated temperatures, boosting thermal efficiency and lowering costs. Concurrently, high-performance magnetic materials, especially rare-earth permanent magnets like neodymium-iron-boron (NdFeB), are crucial for direct-drive generators in wind turbines, significantly improving efficiency and minimizing maintenance needs [139–141]. In Concentrated Solar Power (CSP) systems, advanced thermal materials like molten salts enable efficient heat storage and transfer, operating at temperatures exceeding 565 °C to improve power generation efficiency. High-performance magnetic materials, with their high magnetic flux density, facilitate compact and efficient direct-drive designs, particularly advantageous for offshore wind farms due to lower maintenance needs and increased reliability [81, 142, 143].

5.1.1 Geothermal energy

Geothermal energy, derived from the Earth's internal heat, is a sustainable source for building heating. Advanced thermal and magnetic materials for high-temperature and high-power applications are engineered to endure extreme conditions while maintaining optimal performance. In geothermal energy systems, these materials must efficiently manage thermal energy and resist degradation under high temperatures. High thermal conductivity materials, such as copper, enhance heat transfer, while those with high thermal stability and low thermal expansion withstand cyclic thermal stresses. For components like motors and generators, materials with stable magnetic properties at elevated temperatures are essential. Ferromagnetic materials with high Curie temperatures and advanced rare-earth magnets offer high magnetic strength and thermal resistance, ensuring efficiency and reliability. These materials enable effective energy conversion and management, enhancing the sustainability and performance of geothermal power systems [144, 145].

Copper, renowned for its high thermal conductivity, is widely used in geothermal storage systems. In these systems, a long copper pipe is buried underground and connected to a heat pump. Water circulates through the pipes, absorbing heat from the ground, which the heat pump transfers to the building for heating. The system can also reverse this process to cool the building by extracting heat and transferring it to the water. Deep geothermal sources further utilize superheated steam to generate electricity, enhancing energy production. This efficient process relies on continuous water circulation and copper's thermal properties. In geothermal power plants, the choice of pipe material is critical, as the pipes must withstand high pressures and temperatures at significant depths. Underground geothermal plants often operate at temperatures ranging from 200 to 300 °C, at a certain depths [145, 146].

5.1.2 Power electronics

Power electronics are essential for managing and transforming electrical energy in various applications. In electric and hybrid vehicles, they regulate energy flow between the battery, motor, and other components. They also convert and control electricity from renewable sources like solar panels and wind turbines, and ensure efficient power delivery to energy-intensive data centers. Modern electronics rely on high-temperature and high-power materials with optimal thermal and magnetic properties. For example, the oil and gas industry uses high-temperature materials for drilling tools, while aerospace depends on high-power devices. High thermal conductivity materials are crucial to prevent overheating and ensure safe, efficient operation of electronic equipment [28, 29, 35, 147].

Operating semiconductors at high temperatures presents significant challenges, including exponential increases in junction leakage currents and substantial variations in device parameters. Traditional silicon-based devices typically operate only up to 125 °C, necessitating materials capable of reliable performance between 200 °C and 400 °C. Wide bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), show promise for high-temperature electronics, despite their existing limitations [35, 148–150]. Polymers have also been explored as potential candidates, particularly for high-energy capacitors that operate efficiently at elevated temperatures [151]. Characterization techniques are crucial for understanding how the structure of these materials behaves under high temperatures. Furthermore, as electricity and magnetism are fundamentally interconnected, the magnetic characteristics of materials play a crucial role in advancing high-temperature and high-power electronics.

5.1.3 Nuclear power

In nuclear power applications, advanced thermal materials and coolants play a critical role in reactor cooling systems, ensuring that reactors operate within safe temperature limits. These high-performance materials must withstand extreme conditions while efficiently transferring heat away from the reactor core. Furthermore, magnetic materials are essential for magnetic confinement in fusion reactors, where they help to contain high-temperature plasma, enabling sustained nuclear fusion reactions [150, 152, 153].

Advanced thermal materials, such as silicon carbide composites and liquid metals, such as sodium or lead bismuth eutectic, are widely used in nuclear reactors for efficient heat transfer and cooling [154]. These materials can withstand high radiation doses and extreme temperatures, ensuring the safety and longevity of reactor systems. Similarly, superconducting magnetic materials, such as niobium-tin and rare-earth barium-copper oxide, are employed for magnetic confinement of plasma. These materials generate the strong magnetic fields necessary to contain high-temperature plasma, a key requirement for the advancement of fusion energy research [122, 155].

5.2 Aerospace and defense

In aerospace and defense, advanced magnetic materials such as ferrites and garnets are essential for radar systems, enabling effective signal processing and transmission. These materials provide high permeability and low losses at high frequencies, ensuring efficient radar performance in critical defense applications [156, 157]. Furthermore, magnetic materials are integral to electromagnetic propulsion systems, which are essential to develop advanced propulsion technologies in aircraft and spacecraft [158, 159]. To manage the extreme heat and intense magnetic fields generated during operation, high-temperature superconductors and thermal management materials are employed in these propulsion systems. These materials enable high-speed propulsion, making them vital for defense applications [157, 160].

5.3 Automotive industry

Thermal and magnetic materials are vital in the automotive sector, especially for high-power, high-temperature uses such as electric vehicle (EV) motors and power electronics. Magnetic materials, including rare-earth magnets such as neodymium, iron, and boron, deliver high torque density and efficiency, which are critical for developing compact and high-performance electric vehicle motors. Thermal materials manage heat dissipation, ensuring reliability and performance under extreme conditions. These materials improve energy efficiency, reduce losses, and improve the durability of automotive components, supporting the transition to sustainable transportation [161–164].

Advanced thermal materials, such as phase-change materials and thermally conductive polymers, play a critical role in managing heat within electric vehicle batteries and power electronics. By maintaining optimal operating temperatures, these materials improve battery life and overall performance. In addition, high-performance magnets are essential components of electric motors and regenerative brake systems, contributing to improved efficiency and energy recovery in electric vehicles [67, 150, 165].

5.4 Electronics and telecommunications

In the electronics and telecommunications sectors, advanced thermal materials play a crucial role in dissipating heat from high-power semiconductors, which are essential for managing thermal loads in devices. As the 5G infrastructure continues to expand, these materials are increasingly important in ensuring the efficient operation of telecommunication equipment under increasing power demands. In addition, advanced materials are critical in data storage and signal processing technologies, where they contribute to effective heat management and enhanced performance [166, 167].

Thermal and magnetic materials are vital in electronics and telecommunications. Magnetic materials, including ferrites and rare earth magnets, are utilized in transformers, inductors, and motors to improve efficiency and performance in high-power and high-temperature environments. They provide high magnetic permeability and stability across a range of temperatures, ensuring reliable operation. Thermal materials, including thermal interface materials and heat sinks, manage heat dissipation to prevent overheating and maintain device integrity. These materials are essential in power electronics, communication devices, and data centers, where effective thermal management and magnetic performance are vital for sustained operation and energy efficiency [168–170].

5.5 Data storage and signal processing

Magnetic materials form the foundation of numerous data storage technologies, and ongoing research on advanced magnetic materials aims to improve data storage density and speed. These materials are also integral to signal processing devices, such as filters and isolators, where advances are driving significant performance improvements [168, 171, 172]. Specifically, thin-film alloys and spintronic materials are widely used in data storage devices (e.g., hard drives) and signal processing systems. These applications enable high-density data storage and rapid data processing, meeting the growing demands of modern telecommunications [169].

Thermal and magnetic materials are vital for high-power, high-temperature data storage and signal processing applications, ensuring efficiency, thermal stability, and reliability. Magnetic materials, including ferrites, rare earth magnets, and nanocrystalline alloys, are used in hard drives, inductors, and transformers. They provide high magnetic permeability, low energy loss, and thermal stability, essential for high-frequency operations and miniaturization. Advances like high-coercivity rare-earth magnets and soft magnetic composites enhance performance under extreme conditions. Thermal management materials, including thermal interface materials (TIMs), heat sinks, and phase-change materials, are essential for effective heat dissipation in data storage devices such as solid-state drives (SSDs) and hard disk drives (HDDs), as well as signal processing units. SSDs utilize flash memory for rapid data access, while HDDs depend on spinning disks and mechanical parts for data storage. Innovations such as graphene-based TIMs and advanced ceramics improve thermal conductivity and stability, preventing overheating and ensuring the longevity of the device [143, 173, 174].

5.6 Emerging technologies: machine learning and additive manufacturing

Advanced thermal and magnetic materials are pivotal in addressing the challenges posed by extreme operational environments. Machine learning -driven approaches has reduced experimental trial-and-error cycles in designing high-temperature superconductors, enabling rapid discovery of materials with tailored thermal stability and magnetic flux-pinning capabilities [175]. Physics-informed neural networks further optimize magnetic hysteresis loops in electric motors, enhancing efficiency under thermal stress by predicting performance degradation and enabling real-time material adjustments [176].

Additive manufacturing (AM) unlocks novel material architectures such as 3D-printed ceramic-matrix composites (CMCs), offering lightweight, high-strength solutions for aerospace thermal management, withstanding temperatures exceeding 1500 °C while maintaining structural integrity [177, 178]. Laser powder bed fusion enables magnetic components with spatially graded permeability, minimizing eddy current losses in high-frequency transformers operating at elevated temperatures [154, 179]. AM advances thermal and magnetic materials for high-power/high-temperature applications via complex geometries and functional grading [180, 181], integrating functionalities into monolithic structures for aerospace actuators [182] and power electronics [183]. It enhances thermal management through magnetic regenerators [184] and embedded cooling channels [182]. Soft magnetic alloys improve permeability [180], while graded Fe–Co/Fe–Ni alloys ensure microstructural stability at high temperatures [181, 185]. AM-compatible composites like magnetite-polymers and FeSi alloys [186, 187] provide tunable responses. Machine learning synergizes with AM to accelerate material development for energy-dense systems in renewable grids and electric propulsion. Future innovations leverage multi-material processes [188, 189] to address thermal degradation and hysteresis, solidifying AM's role in extreme environments.

Despite their transformative potential, the deployment of advanced thermal and magnetic materials is not without obstacles. Building on the applications discussed, we now address persistent challenges, such as thermal degradation and cost barriers, and outline pathways for future research.

5.7 Emerging materials: 2D magnetic materials, MXenes, and high-entropy alloys

Recent advances in materials science highlight novel material classes for high-power and high-temperature applications. Two-dimensional (2D) magnetic materials (e.g., CrI_3, $Cr_2Ge_2Te_6$), MXenes (e.g., $Ti_3C_2T_x$, where *x* denotes surface termination groups), and high-entropy alloys (HEAs) exhibit unique structural, electronic, and thermal properties for transformative thermal and magnetic systems.

2D Magnetic Materials enable breakthroughs in spintronics and magnetic cooling, such as room-temperature ferromagnetism in MnNCl monolayers for high-temperature sensors and enhanced magnetocaloric effects in iron nanoparticle-TiN films [190–192]. Their compact design supports high-speed spintronic devices in extreme en vironments [193]. MXenes, 2D transition metal carbides/nitrides, excel in electrical/thermal conductivity, electro-magnetic shielding, and hybrid thermal-magnetic composites for power electronics [194, 195]. Their flame-retardant composites, Joule heating capabilities, and 3D-printed heat exchangers leverage high conductivity and adaptability [196, 197]. High-Entropy Alloys (HEAs) (e.g., CoCrFeNiMn, HfNbTaTiZr) provide thermal stability, corrosion resistance, and mechanical strength, addressing thermal degradation and rare-earth dependency [193, 198, 199]. They maintain structural integrity above 1000 °C, ideal for aerospace/nuclear systems [199, 200]. High-entropy ceramics/alloys exhibit extreme thermal stability via configurational entropy [59], while refractory HEAs optimize turbine blade phase stability through atomic size differences [201]. Their multifunctionality enables thermal barrier coatings and corrosion-resistant components [202]. Hybrid systems integrating HEAs, MXenes, and 2D magnets should be prioritized to leverage complementary strengths in energy, aerospace, and electronics.

5.8 Summary table for applications of advanced thermal and magnetic materials for high-power and high-temperature

Table 1 summarizes the opportunities, challenges, and the future direction of AI-driven innovations in electronic materials.

Table 1 Synergistic applications of advanced thermal and magnetic materials for high-power and high-temperature

Material type	Thermal properties	Magnetic properties	Application	Ref
Ceramics	High thermal stability, low thermal conductivity, high melting point	Non-magnetic, except ferrites (ferri-magnetic)	Insulators, sensors, high-temperature coatings	[58, 203]
Composites	Tailorable thermal conductivity, low thermal expansion	Non-magnetic unless magnetic fillers added	Lightweightstructures, thermalmanage-ment, electromagnetic shielding	[63, 203]
Metals and Alloys	High thermal conductivity and melting point	Ferromagnetic (Fe,Ni, Co), high Tc	motors, generators, heat exchangers,magnetic storage	[50, 69, 204]
Carbon Nano-tubes (CNTs)	Extremely high thermal conductivity, low thermal expansion	Diamagnetic, tunable with doping	Thermal interface, sensors, electromag-netic shielding	[71]
Phase Change Materials (PCMs)	High latent heat capacity, low thermal conductivity	Non-magnetic	Thermal energy storage, and regulation	[3, 66, 82, 85]
Soft magnetic materials	Moderate thermal conductivity, high Tc	High permeability, low coercivity and hysteresis losses	Transformers, inductors, electric motors	[48, 69, 81, 82, 88, 92]
Hard magnetic materials	Moderate thermal conductivity, hight-hermal stability	Highcoercivity, remanence, and energy production	Permanentmagnet, sensors, high-tem-perature motors	[48, 69, 116]
High-Temperature Superconductors	Low thermal conductivity in supercon-ducting state, high critical tempera-ture	Zero resistance, high critical magnetic field	power transmission, magnetic levita-tion, high-field magnets	[89, 98, 99]
Nanocrystalline & Amorphous alloys	Low thermal conductivity, high thermal stability up to crystallization tempera-ture	High permeability, low coercivity, low hysteresis losses	Transformers, sensors, magnetic shield-ing	[93, 100, 101, 124, 127]
Ferromagnetic materials	Moderate to high thermal conductivity, high Tc	high magnetization, spontaneous mag-netization below Tc	Motors, generators, magnetic storage devices	[107, 129, 130]

6 Challenges and future perspectives

Developing and implementing advanced thermal and magnetic materials for high-power, high-temperature applications involves significant challenges but offers promising opportunities. These materials are essential for industries like energy, aerospace, automotive, and electronics, where efficiency, reliability, and performance under extreme conditions are critical [37]. By integrating nanostructured thermal materials with high-performance magnetic alloys and superconductors, researchers can address critical challenges in energy efficiency, thermal management, and system miniaturization. Future work should focus on scalable synthesis, multifunctional composites, and real-world validation to bridge lab-scale innovations to industrial adoption. Below is a detailed discussion of future directions in this field.

Advanced thermal and magnetic materials face several significant challenges in high-power and high-temperature applications [88, 89, 107, 120]. One major issue is thermal stability, as operating temperatures often approach the Curie point, leading to demagnetization and reduced efficiency. Additionally, thermal expansion and mechanical stress under high temperatures can degrade structural integrity, while eddy current losses exacerbate heating, necessitating materials with high electrical resistivity. Oxidation and corrosion at elevated temperatures further limit the lifespan of these materials [91, 205]. A key challenge lies in developing materials that retain their desired properties under extreme conditions. This requires overcoming issues such as thermal degradation, loss of magnetic properties, and mechanical stress. Furthermore, the search for cost-effective, with rare-earth-free magnets reduce material costs [65], and scalable manufacturing processes adds another layer of complexity, as does the need to innovate materials that are both efficient and sustainable [34, 88, 206]. Furthermore, the search for cost-effective and scalable manufacturing processes adds complexity, as does the need to innovate materials that are efficient and sustainable [88, 207]. High costs, manufacturing complexities, and material degradation at elevated temperatures remain critical hurdles that must be addressed. Defects and atomic-scale bond changes further complicate modeling efforts, which demand significant computational resources and time [208–211]. Integrating these advanced materials into existing technologies often requires substantial redesign and innovation, highlighting the need for continued research and development [1, 51, 212, 213].

The future of advanced thermal and magnetic materials hinges on the integration of cutting-edge technology, innovative material design, and efficient energy conversion systems. Key areas of focus include enhancing electric vehicle technologies and developing robust solutions for aerospace applications. A significant emphasis is being placed on the creation of smart materials capable of adapting to dynamic conditions, thereby improving performance and reliability in extreme environments [210, 214, 215]. These materials aim to achieve superior thermal stability and magnetic performance while addressing sustainability challenges. The use of machine learning and computational modeling is accelerating the discovery of new materials with tailored properties, enabling break-throughs in high-power and high-temperature applications. Computational techniques, such as density functional theory and physics-informed neural networks, are being employed to model material properties and predict behavior at the atomic level. Additionally, artificial intelligence (AI) is playing a pivotal role in designing energy storage materials, including batteries, alloys, and catalysts [34, 113, 164, 178, 216].

To further advance this field, there is a growing need for advanced characterization techniques that can operate under high temperatures and strong magnetic fields. These techniques are essential for gaining deeper insights into material properties under extreme conditions. Theoretical models that predict material behavior in such environments can guide experimental efforts, bridging gaps in understanding and facilitating the development of novel materials for specific applications. These advancements hold immense promise for optimizing material properties, reducing costs, and improving scalability. By driving innovation in thermal and magnetic materials, they are paving the way for transformative technologies across various industries. In synthesizing the advancements, applications, and limitations of these materials, it becomes clear that their continued evolution is pivotal to overcoming global energy and technological challenges. The concluding remarks summarize these insights and advocate for interdisciplinary collaboration to unlock their full potential.

As a final exit, there needs to be actionable recommendations to address gaps in scalability, sustainability, and performance of advanced thermal and magnetic materials for high-power and high-temperature applications. The one is by accelerating ML-guided material discovery, by establishing open-access databases such as high-temperature Material Genome Initiative (MGI) for training models on thermal and magnetic properties, and deploying generative AI to design rare-earth-free magnets like Mn-Al-C systems [217]. Standardize additive manufacturing by developing protocols for laser powder bed fusion (LPBF) of ceramic–metal composites, optimizing parameters for Fe-Si-B-Nb alloys to achieve low porosity [154, 179], facilitated by industry consortia like the Advanced Manufacturing Collaborative. Scale sustainable production via solvent-free CNT-polymer synthesis for energy reduction [176] and pilot roll-to-roll graphene-enhanced PCMs [218], incentivized by tax breaks for bio-based binders. Enhance recycling infrastructure through hydrometallurgical processes (high Nd/Co recovery) and blockchain-tracked HTS magnet reuse, enforced by Extended Producer Responsibility laws. Foster cross-disciplinary training via graduate programs and funded innovation hubs for ML-driven thermal stress modeling in fusion materials [219].

7 Conclusion

This paper review underscores the pivotal role of advanced thermal and magnetic materials in addressing the demands of high-power and high-temperature applications across industries such as renewable energy, aerospace, automotive, and electronics. Materials like ceramics, carbon nanotubes, and phase-change composites enhance thermal stability and energy efficiency, while magnetic materials, including high-temperature superconductors (e.g., YBCO) and rare-earth-free magnets (e.g., Mn-Al-C systems), enable efficient energy conversion and storage. Innovations such as Fe-Co alloys and nanocrystalline soft magnetic composites improve performance in electric motors and transformers, demonstrating enhanced power density and reduced energy losses. Despite these advancements, significant challenges persist, including material degradation under thermal cycling, reliance on rare-earth elements, and high manufacturing costs. Thermal expansion mismatches and eddy current losses further complicate material reliability in extreme environments. Emerging technologies like machine learning (ML) and additive manufacturing (AM) offer transformative solutions. ML accelerates the discovery of materials with tailored properties, while AM enables the fabrication of complex geometries, such as 3D-printed ceramic-matrix composites and graded magnetic alloys, which optimize thermal and magnetic performance. The integration of thermal and magnetic materials in synergistic applications—such as molten salt-based thermal storage in concentrated solar plants or high-temperature superconductors in fusion reactors—highlights their complementary roles in advancing sustainable technologies. Future research must prioritize scalable synthesis, recyclability, and eco-friendly alternatives to rare-earth elements. Interdisciplinary collaboration, supported by standardized testing and policy frameworks, will be critical to transitioning lab-scale innovations into industrial solutions. By addressing these challenges, next-generation materials can drive a paradigm shift toward resilient, energy-efficient systems, ultimately mitigating environmental impacts and meeting global energy demands. The continued evolution of these materials promises to revolutionize high-power technologies, balancing performance, sustainability, and cost-effectiveness in extreme operational environments.

Author contributions All authors contributed to the design, writing, editing, compiling, and submission of the paper. Wubshet Getachew Mengesha edited the revised manuscript and led the publication process as the main researcher, while Kaveer Nagessar contributed in writing and editing of the paper.

Funding No funding was received for conducting this study.

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Competing interests The authors declare no competing interests.

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