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Sustainable Enhancement of Brake Rotor Durability in Electric Vehicles: Challenges, Innovations, and Future Directions

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Abstract: The widespread adoption of electric vehicles (EVs) has brought about critical challenges in brake rotor performance, primarily attributed to the reduced reliance on conventional friction braking systems. This decreased usage, owing to the predominant application of regenerative braking, has inadvertently increased the susceptibility of brake rotors—particularly those manufactured from grey cast iron (GCI)—to corrosion and non-traditional wear mechanisms due to extended exposure to environmental elements. These challenges are compounded by the global imperative for sustainable transportation solutions, as emphasized in the European Union (EU)'s roadmap for climate-neutral mobility. In this context, the development and implementation of sustainable strategies to improve the wear and corrosion resistance of EV brake rotors have become paramount. This review synthesizes recent advancements in environmentally conscious approaches, including the application of eco-friendly surface treatments, alloying modifications, microstructural engineering, and solid or dry lubrication techniques tailored for GCI rotors. The analysis extends to the evaluation of scalability, cost-efficiency, tribological stability, and environmental compatibility over the rotors' service life. Particular attention is devoted to emergent solutions such as bio-inspired multifunctional coatings, integration of intelligent condition-monitoring technologies, and rotor design optimized through data-driven predictive modelling. The necessity for robust life cycle assessments (LCA) is underscored, aiming to holistically quantify environmental impact from raw material extraction through end-of-life disposal or recycling. Key research gaps are identified, including the limited real-world validation of novel materials under EV-specific load profiles and insufficient understanding of synergistic degradation modes under mixed braking regimes. It is suggested that a multidisciplinary research agenda—merging materials science, tribology, electrochemistry, and intelligent systems—is essential to advance the next generation of high-performance, low-impact braking solutions. In doing so, a comprehensive framework for sustainable brake rotor innovation in EVs can be established, aligning material resilience with broader environmental and regulatory goals.

Keywords: Electric vehicle (EV); Grey cast iron (GCI) rotor; Friction braking; Wear resistance; Corrosion protection; Regenerative braking; Sustainable materials engineering; Bio-inspired coatings

1 Introduction

The rapidly expanding EV market presents distinct challenges and opportunities for automotive component design, particularly for braking systems. GCI remains the predominant material for brake rotors owing to its cost-effectiveness, excellent friction performance, relative ease of manufacturing, thermal conductivity, and high vibration-damping properties [1–4]. However, the operational dynamics of EVs, notably the widespread implementation of regenerative braking, have significantly altered the duty cycles of these components [5, 6]. Regenerative braking prioritizes electric motor deceleration, resulting in reduced reliance on conventional friction brakes. This shift, while enhancing energy efficiency, leads to extended periods of brake rotor inactivity [5, 7], thereby increasing susceptibility to corrosion, particularly in humid or saline environments. Moreover, when mechanical braking becomes necessary, built-up corrosion and modified surface characteristics can intensify wear, potentially jeopardizing the effectiveness of the braking system.

In EVs, brake rotors have significantly different operational requirements compared with those of traditional vehicles powered by internal combustion engines (ICE). Regular mechanical braking in conventional vehicles helps eliminate surface rust and keeps the rotor clean. However, in EVs, the infrequent use of mechanical brakes in conjunction with corrosive agents presents a significant challenge [8, 9]. Brake rotors are particularly susceptible to environmental influences during periods of inactivity. Moisture, salt, and other road contaminants can accumulate on the rotor surface because they are not regularly removed by natural cleaning processes that occur during normal braking events. This situation creates an environment conducive to accelerated corrosion of the rotor surfaces (Figure 1).

Figure 1. Rust development on the friction surface of untreated GCI brake disc mounted on a battery electric vehicle (BEV)

In practical discussions among vehicle owners, it has been observed that even relatively new vehicle rotors can develop significant rust within a short timeframe, particularly in humid and coastal regions. This rusting is attributable to environmental factors such as moisture, road salt, and other elements that induce oxidation. In ICE vehicles, this rust is typically minor and often resolves when brakes are applied during driving, as these vehicles regularly utilize their mechanical or frictional brake systems. However, this is not the case for EVs, which rely primarily on regenerative braking systems. When the friction brakes of EVs are engaged after prolonged inactivity, the accumulated corrosion releases particulates into the environment, raising concerns regarding both performance and environmental impact [10, 11]. Consequently, the corrosion and wear of GCI brake rotors have emerged as critical concerns that require immediate attention. These issues diminish the durability and operational lifespan of brake rotors and compromise the overall safety of vehicles.

Sustainability is a critical focus area of the EU [12]. A summary of the main European Green Deal is shown in Figure 2. Additionally, the EU has initiated a sustainable strategy in the transportation sector, known as the "Sustainable and Smart Mobility Strategy" [13]. This framework was designed to transform the transport sector, aligning it with the goals of the European Green Deal and digital revolution. The strategy aims to create a transport system that is not only environmentally sustainable but also efficient, resilient, and equitable. To effectively address the environmental impacts associated with surface solutions, a comprehensive approach that encompasses the processes, materials, and applications is required. Given the pivotal role of brake rotors in mobility systems, it is crucial to assess sustainable strategies to enhance the wear and corrosion resistance of brake rotors in EVs. To achieve holistic sustainability, all manufacturing processes involved in the production of EV components must align with sustainability objectives. The adoption of sustainable manufacturing practices is essential because they employ commercially viable techniques that minimize negative environmental impacts while conserving energy and other resources, thereby contributing to environmental improvement for future generations [14, 15]. This approach involves creating products through environmentally friendly, economically viable, and socially responsible processes.

Recent research has emphasized the critical need to develop sustainable strategies to address these issues. For instance, advanced surface treatments, such as plasma electrolytic oxidation (PEO) [16–18], have been investigated to enhance corrosion resistance without relying on environmentally deleterious chemicals when compared with other electrochemical processes for metal surface modifications. Ferritic nitrocarburizing (FNC) treatment has been demonstrated to enhance the surface properties of brake rotors, thereby improving their resistance to both wear and corrosion and consequently extending their operational lifespan [3, 19–22]. Concurrently, research is being conducted to investigate sustainable material modifications [23–25], including the integration of recycled materials and corrosion-resistant alloys, to mitigate the environmental impacts associated with brake rotor production.

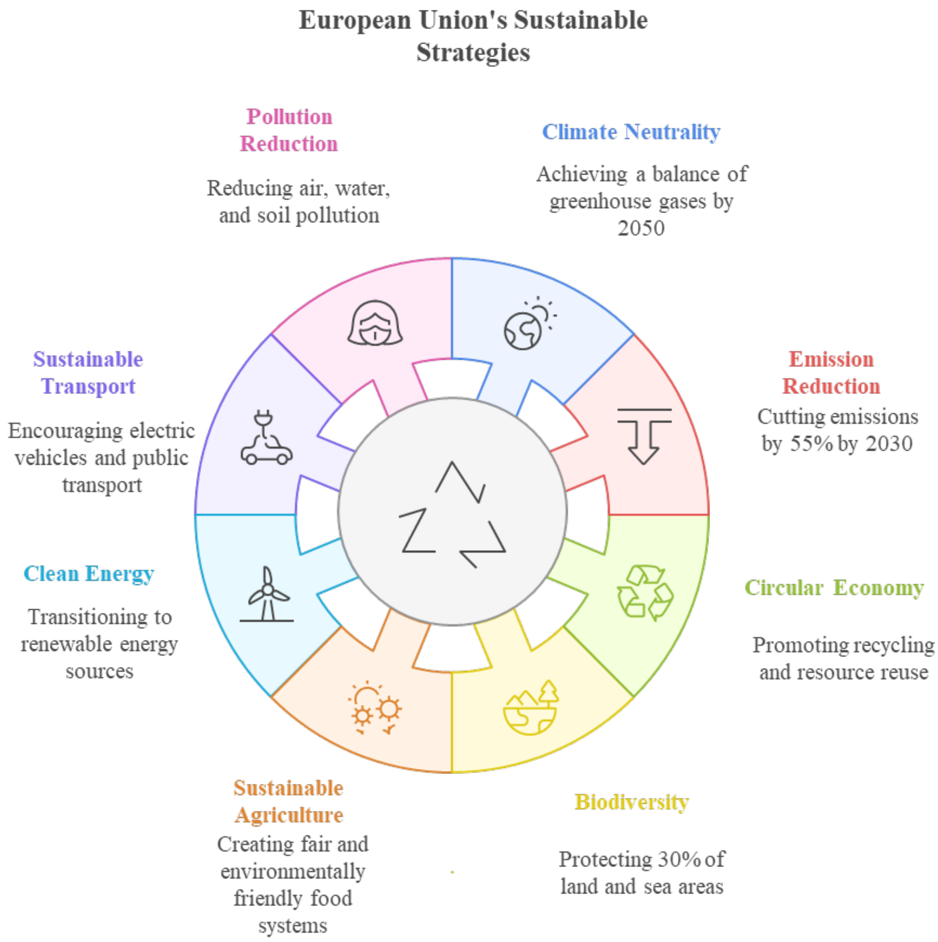

Figure 2. The key components of the EU sustainable strategies [12]

The imperative of this study is underscored by the increasing societal demand for sustainable manufactured goods [26–28]. By investigating more sustainable methods for the production and protection of GCI brake rotors, the EV industry can significantly enhance its contribution to the promotion of an environmentally sustainable automotive sector [13, 29]. This study provides a concise review of sustainable strategies designed to enhance the corrosion and wear resistance of GCI brake rotors in EV applications. It explores existing techniques, identifies the critical challenges associated with their implementation, and outlines promising directions for future research. This review focuses on environment-friendly approaches, emphasizing the need for cost-effective and scalable solutions. By combining recent findings and outlining prospective research avenues, this review aims to contribute to the ongoing development of durable and sustainable EV braking systems.

2 Sustainable Strategies for Improving Corrosion Resistance

The corrosion of GCI brake rotors for EV applications necessitates the development and implementation of sustainable strategies. Traditional corrosion protection methods often rely on hazardous chemicals and energy-intensive processes, prompting a shift towards more eco-friendly alternatives. This section explores several promising sustainable approaches, focusing on surface treatment and material modification techniques.

2.1 Surface Treatments

Eco-friendly coatings have demonstrated significant advancements in terms of enhancing corrosion resistance. Notably, the development of advanced surface treatment technologies has marked a substantial breakthrough in addressing corrosion issues in EV brake rotors. Among the most promising methodologies are FNC with post-oxidation treatment [22, 30] and plasma electrolytic aluminating (PEA) [31, 32]. These approaches offer considerable improvements in corrosion resistance while preserving the essential performance characteristics of brakes. These technologies form protective surface layers that shield the underlying material from environmental exposure without compromising the friction properties necessary for effective braking.

FNC coupled with post-oxidation treatment, notably Nitrex's Smart ONC® technology [19, 20, 30], has emerged as a prominent solution for EV brake rotor applications. This dual-treatment process markedly enhances the corrosion resistance of conventional GCI rotors by forming a protective compound layer. Research has demonstrated that this technology exceeds the traditional corrosion resistance limits while concurrently reducing the particulate emissions associated with EV brake rotors, thereby addressing both durability and environmental concerns [33]. The FNC with Smart ONC exhibited remarkable corrosion resistance, enduring salt spray exposure for up to 120 h without any visible signs of corrosion. This performance signifies a significant enhancement compared to standard FNC treatments. This process involves the diffusion of nitrogen and carbon into the iron surface at temperatures below the transformation point of the material, preserving the ferritic microstructure while forming a hard, wear-resistant compound layer. The subsequent post-oxidation treatment added an additional oxide layer, further augmenting corrosion protection.

PEA is an innovative method for improving the corrosion resistance of brake rotors [31, 32]. This technique generates alumina-based ceramic coatings directly on cast iron substrates via an electrochemical process that protects the underlying substrate from environmental degradation. The process involves the formation of a hercynite ($FeAlO_2$) thin film on the substrate surface, followed by sintering of Al_2O_3 with $FeAlO_2$ [31, 34]. In contrast, cold-spray coatings offer effective corrosion protection owing to their dense structure and low oxide content, thereby enhancing their utility in demanding aerospace and automotive applications [35–37].

Recent comparative analyses of PEA-coated and FNC-treated brake rotors have indicated that PEA technology exhibits superior initial corrosion resistance in electrochemical corrosion assessments [32]. Alumina-based ceramic coatings serve as effective barriers against environmental factors while maintaining suitable friction characteristics for braking applications. A related study evaluated the corrosion resistance performance of a rotor treated with FNC in comparison with that of a rotor subjected to a high-speed laser cladding process (single-layer coating). FNC discs and single-layer coated discs were evaluated for corrosion resistance in accordance with ISO 9227 standards. The discs were rotated 180° daily to ensure a uniform distribution of saline concentration. Single-layer-coated discs demonstrated a resistance of over 504 h in a saline chamber, in contrast to 72 h for FNC-treated discs. This enhanced durability is attributed to the presence of elements such as Cr and Mo in the single-layer coated disc (Figure 3) [38]. It is equally important to note that the FNC coating encompasses all the surfaces of the rotor, whereas the single-layer coating was applied solely to the disc friction surfaces. This necessitates an additional coating to safeguard the non-friction surface of the single-layer coated disc, thereby incurring further costs.

Moreover, laser surface treatments [39–41], including laser alloying and cladding, facilitate precise control over surface modifications, thereby enabling the formation of corrosion-resistant layers with customized compositions. These techniques reduce material waste and energy consumption compared to traditional methods. Laser cladding applies a precise layer of material using a focused laser beam and offers minimal heat input to the substrate, preserving structural integrity and dimensional accuracy. This process resulted in a durable, high-performance coating with excellent corrosion and wear resistance.

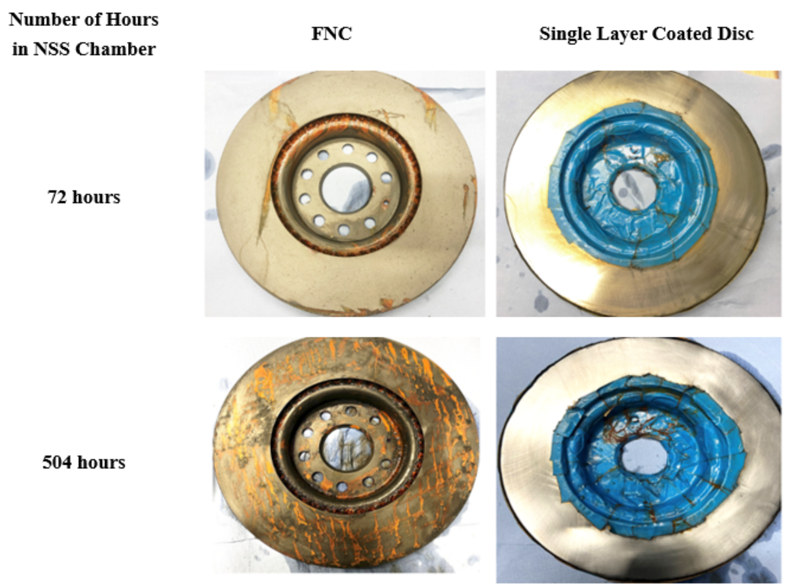

Figure 3. A comparison of brake disc corrosion resistance between FNC and single layer coated disc [38]

2.2 Material Modifications

Incorporating corrosion-resistant elements into GCI is a promising approach for enhancing its durability. The integration of elements such as silicon (Si), nickel (Ni), niobium (Nb), titanium (Ti), and copper (Cu) can significantly improve the resistance of the material to both atmospheric and electrochemical corrosion. For instance, silicon contributes to the formation of a protective silica layer on the surface, whereas copper enhances the electrochemical potential, thereby reducing the corrosion rates [42–44]. Furthermore, the use of recycled materials in GCI production enhances sustainability by decreasing reliance on virgin resources and reducing waste. The integration of recycled iron and steel scrap can diminish the carbon footprint associated with brake rotor manufacturing if the recycling process adheres to environmentally friendly practices [45].

3 Sustainable Strategies for Improving Wear Resistance

In addition to corrosion, wear presents a significant challenge for GCI brake rotors in EVs, particularly owing to altered braking dynamics. To sustainably enhance wear resistance, this section examines surface-hardening techniques, material optimization, and lubrication/friction modification strategies that aim to minimize environmental impact.

3.1 Surface Hardening Processes

Sustainable thermal spray coatings represent a promising strategy for enhancing wear resistance. Conventional thermal spraying (TS) techniques frequently involve the use of hazardous materials and consume substantial amounts of energy [46]. Recent advancements in coating technologies have facilitated the development of environmentally friendly alternatives. For example, cold-spray techniques, which utilize kinetic energy rather than thermal energy for coating deposition, minimize the heat input and reduce the risk of thermal damage to the substrate [35]. Furthermore, the use of recycled coating materials can enhance the sustainability of TS processes [47]. Eco-friendly shot peening is another effective surface-hardening method. This technique involves bombarding the metal surface with small particles, inducing compressive residual stresses that improve wear resistance. In a recent study, the tribological performances of FNC-treated and PEA-coated rotors were evaluated and compared via road vehicle testing [32].

In a series of road vehicle tests involving 1000 braking events at moderate deceleration rates (0.3-0.4 g), brake rotors treated with FNC demonstrated some degradation of the white surface layer while maintaining the integrity of the underlying nitrogen diffusion layer. This subsurface layer shielded the base material from corrosion during testing. However, regions containing graphite flakes on the cast iron surface were exposed to environmental conditions, potentially causing localized corrosion in the later testing stages. This indicates that, although the FNC treatment provides substantial enhancements, the microstructure of GCI may still impose limitations under extreme conditions. The PEA-coated rotors exhibited notable changes during the vehicle testing. A material transfer layer, predominantly from the brake pads, was developed on the PEA-coated surfaces, offering additional protection against abrasive wear. However, when the transfer layer incorporated metallic elements from low-metallic brake pads, electrochemical corrosion resistance measurements indicated diminished performance [32]. This observation highlights the complex interactions between the brake pad and rotor materials, suggesting that optimal performance requires a systematic approach that considers the entire friction couple. Table 1 summarizes the frictional properties and wear resistance associated with the predominant surface treatment processes employed to enhance the durability and tribological performance of GCI brake rotors.

Table 1. Comparative analysis of common surface treatments

Technology	Friction Characteristics	Wear Resistance	Reference
Thermal Spray	Stable CoF (0.31-0.34), minimal wear	Excellent wear resistance, reduced particle emissions	[46, 48]
Cold Spray	Limited data available, but the CoF of 0.38 was observed on an aluminiun substrate	Potential for excellent wear resistance	[1, 46]
FNC-Smart ONC	Stable friction (0.27-0.35 CoF), reduced pad material accumulation	Minimal wear, no delamination or cracking	[19, 30]
FNC + post oxidation	Acceptable stable CoF (0.30-0.39)	Minimal wear, no delamination or cracking	[38]
PEA	Stable CoF (0.31-0.34), minimal wear	Excellent corrosion and wear resistance	[48, 49]
Laser Cladding (WC)	Slightly higher CoF (0.35-0.45), stable friction	Significantly reduced wear, dominant abrasive wear mechanism	[50, 51]

3.2 Material Innovation and Optimization

The pursuit of sustainable brake-rotor solutions has expanded beyond surface treatments to encompass fundamental material innovation and optimization. Optimizing the microstructure of GCI can substantially enhance its wear resistance. Advanced GCI microstructures, characterized by a refined graphite morphology and increased matrix hardness, can improve the resistance of the material to both abrasive and adhesive wear. The incorporation of small amounts of molybdenum (Mo) and niobium (Nb) into the GCI composition can augment its hardness and wear resistance. Recent studies have demonstrated that the addition of 0.3% Nb results in a 27.8% reduction in wear rates compared with conventional GCI [52]. Furthermore, Nb-alloyed GCI subjected to FNC treatment exhibited enhanced corrosion resistance, which is crucial for maintaining braking performance under humid conditions [53].

In recent years, researchers and manufacturers have investigated alternative base materials that inherently provide enhanced wear resistance and reduced environmental impact compared to traditional GCI. Notably, aluminum matrix composites (Al-MCs) and the integration of complementary non-metallic brake pad technologies have emerged as promising developments [54, 55]. Together, these innovations form sustainable friction couples that can be specifically designed for EV applications. Figure 4 shows a typical sustainable aluminum metal matrix composite brake rotor produced using the squeeze casting method. Al-MCs represent a paradigm shift in brake rotor design, offering significant weight reduction while maintaining the necessary performance characteristics. These composites typically combine an aluminum matrix with reinforcing particles to enhance wear resistance and thermal properties. In a related advancement, additive manufacturing was employed to fabricate an aluminum-ceramic brake rotor (AlSi10Mg-SiC), achieving a 67% weight reduction compared to a rotor manufactured from cast iron. The 3D-printed lattice structure depicted in Figure 5 enhances heat dissipation, exhibiting a five-fold increase in thermal conductivity while simultaneously reducing rotational inertia. The incorporation of SiC particles (15-20 vol%) augments the hardness to 120-150 HV, which is comparable to that of GCI. Lifecycle analyses indicated a 45% reduction in CO_2 emissions per kilogram in comparison with conventional rotors, notwithstanding the higher energy requirements for production [56].

Compared with traditional GCI discs, aluminum discs offer several advantages, including superior wear resistance, enhanced thermal conductivity, excellent corrosion resistance, and improved heat transfer capability. Additionally, they do not present noise, vibration, or harshness (NVH) issues, exhibit low particle emissions, and are lighter in weight. The SICAlight disc, being 50–60% lighter than the GCI disc, contributes to improved vehicle ride and handling by reducing the unsprung weight [54, 55], contributing substantially to the overall vehicle efficiency and range extension in EVs. Properly engineered aluminum-based composites can effectively meet the thermal management and wear resistance requirements for automotive braking applications, while also offering superior inherent corrosion resistance compared to ferrous materials. Another critical aspect of material innovation is the development of brake pad materials designed for new rotor compositions. Traditional brake pad formulations for GCI rotors may not perform optimally with aluminum-based composites or surface-treated rotors. This has led to research on sustainable technologies, including metal-free compositions and composite backing plates, to replace steel components. Metal-free brake pads significantly reduce particulate emissions and enhance compatibility with nonferrous rotors by eliminating or reducing the metallic content, thus decreasing the iron-rich emissions typical of conventional systems. Brake wear debris analysis showed that iron compounds dominate emissions from traditional systems, underscoring the environmental benefits of metal-free alternatives. Replacing steel backing plates with polymer composites offers advantages such as 75% weight reduction, corrosion elimination, reduced thermal conductivity, and superior NVH damping [57]. These findings suggest that composite-based technologies provide the necessary durability and substantial sustainability benefits.

3.3 Lubrication and Friction Modification

Sustainable solid lubricants present an environmentally favorable alternative to conventional liquid lubricants, which are known to contribute to environmental pollution. Solid lubricants, including graphite, molybdenum disulfide (MoS2), and boron nitride (BN), function by forming a low-shear-strength film on sliding surfaces, thereby reducing friction and wear, and consequently enhancing longevity and efficiency [58, 59]. The incorporation of bio-derived or recycled solid lubricants can significantly improve the sustainability of lubrication systems, aligning with environmental goals. Although solid lubricants are widely used to reduce friction and wear in engine components, their application in brake systems is limited and requires further investigation. Furthermore, surface texturing techniques, such as laser surface texturing (LST), can alter the frictional properties of GCI by creating microdimples or grooves on the rotor surface. This modification enhanced lubrication retention and reduced abrasive wear by up to 45%. In the context of EVs, rotors treated with LST and paired with low-metallic brake pads demonstrated a 30% reduction in particulate emissions, thereby addressing air quality concerns [60, 61]. These textures can trap wear debris, reduce the contact area, and enhance lubrication, all of which collectively contribute to improved wear resistance. The application of environmentally friendly laser processing techniques can further minimize the environmental impact associated with surface texturing.

Figure 4. A typical sustainable aluminium matrix composite brake disc (SICAlight)

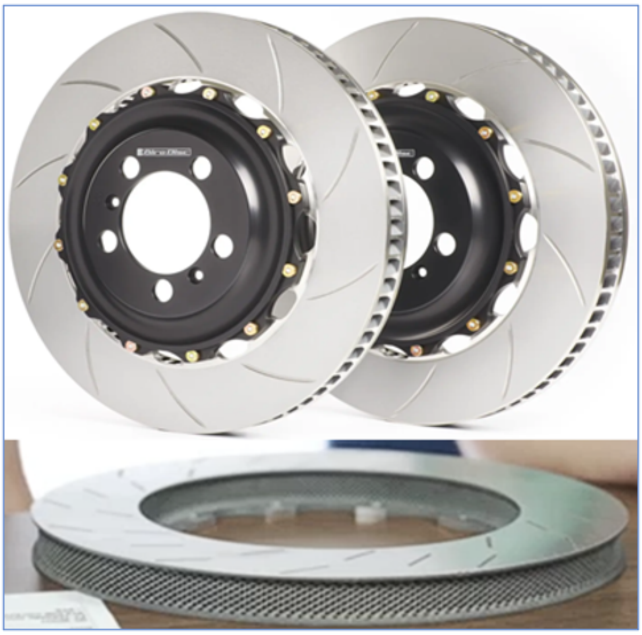

Figure 5. 3D-printed Al-MMC rotor with SiC-reinforced vanes (Source: Ceramic Disc Technologies [56])

4 Challenges and Limitations in Implementing Sustainable Strategies

The shift towards sustainable strategies for enhancing corrosion and wear resistance in GCI brake rotors for EV applications presents several challenges. Although the technologies discussed in this study offer significant potential benefits, several challenges impede the extensive adoption and implementation of sustainable surface treatment processes on an industrial scale.

4.1 Cost-Effectiveness of Sustainable Solutions

One of the principal challenges is the cost-effectiveness of sustainable solutions. Numerous eco-friendly surface treatments, material modifications, and lubrication techniques remain in the developmental phase, leading to elevated production costs compared with conventional methods [28, 62]. TS is a cost-effective method for depositing thick coatings suitable for large-scale industrial applications. However, this process requires significant energy input and generates emissions, which may impact its sustainability [1, 46]. Cold spraying (CS) is an emerging technology that offers lower energy consumption than TS because it operates in the solid state without melting the particles.

This reduces energy costs and environmental impact. However, the initial investment in cold-spray equipment can be higher, and the process may require post-processing steps to achieve the desired properties. PEA is less resource-intensive than TS, and its economic viability is limited by its specialized application and relatively high initial setup costs. PEA are often used in niche industries where corrosion resistance is critical, such as the aerospace and automotive industries [49]. Laser cladding is more expensive than thermal spray and cold spray owing to the high cost of laser equipment, and it is highly efficient for high-value applications in industries such as aerospace and medical devices [47]. This process also reduces material waste, which can offset the initial costs in the long term. Furthermore, the standard FNC process is a mature technology with moderate costs and energy requirements compared to other advanced surface treatment technologies [3, 19–22]. FNC is widely used in automotive and industrial applications, making it cost-effective for large-scale production. However, its environmental impact is higher than that of some newer technologies, such as CS, owing to the use of NH_3 and CO_2 gases in the process. Although the advanced version of the FNC, FNC-Smart ONC, offers improved performance, its economic viability remains under evaluation. The process is less mature than traditional FNC, and its scalability and cost-effectiveness have yet to be fully demonstrated. The initial capital investment necessary for the implementation of novel sustainable technologies and materials poses a substantial challenge, particularly for small-scale manufacturers. Ensuring the economic viability of sustainable solutions is essential for their sustained adoption in the competitive EV market.

4.2 Scalability and Industrial Implementation

The scalability and industrial implementation of sustainability strategies for brake-rotor surface modification present significant challenges. Although numerous promising sustainable techniques, such as advanced PEA processes and FNC-Smart ONC coatings, have been successfully demonstrated at the laboratory scale, their application in large-scale production environments remains challenging. Critical factors, including process control, production rate, and consistency, must be addressed to facilitate the effective integration of these sustainable solutions into existing manufacturing lines. The transition from laboratory prototypes to industrial production necessitates substantial investment in infrastructure and process optimization. In addition, the scalability of these processes to meet the high production demands of the automotive industry is a significant concern. The initial capital investment required for new manufacturing lines, along with potential increases in per-unit production costs, may discourage manufacturers from adopting sustainable solutions [15, 63]. Moreover, the need for rigorous quality control and process optimization to ensure consistent performance adds complexity and expense, all of which must be addressed before sustainable technologies can be implemented at the production level.

4.3 Durability Evaluation and Long-Term Performance in Real-World EV Applications

A significant limitation is the uncertainty regarding the long-term performance and durability of sustainable solutions under actual EV conditions. Although laboratory tests offer valuable insights, they may not fully replicate the complex environmental and operational stresses experienced by braked rotors. Variables such as fluctuating temperature, humidity, road salt exposure, and diverse driving conditions can substantially affect the performance of coatings and material modifications. Specifically, the long-term behavior of bio-based coatings, PEA coatings, and other novel surface modification techniques necessitates a comprehensive investigation to ensure that they can sustain their protective properties throughout a vehicle's lifespan. Accelerated testing methodologies and extensive field trials are crucial for validating the durability and performance of these sustainable strategies, despite being time- and cost-intensive.

4.4 Material Compatibility and Adhesion Issues

One of the primary challenges in the application of surface modification techniques to GCI brake rotors is ensuring material compatibility and adhesion between the coating and the GCI substrate. For example, although thermal spraying effectively reduces particle emissions, adhesion issues may be encountered if the coating material is not meticulously selected or if the substrate preparation is insufficient [46]. Similarly, laser cladding, which provides excellent wear resistance, has been observed to exhibit higher wear rates than untreated GCI in certain applications, potentially owing to differences in material properties [47]. PEA coatings encounter significant challenges in achieving optimal adhesion and corrosion resistance on GCI surfaces. This process necessitates precise control of parameters such as voltage, current density, and treatment duration to ensure a uniform and adherent coating. Even minor deviations from optimal conditions can result in non-uniform coatings, poor adhesion, and diminished corrosion resistance. For example, elevated voltage levels can induce over-oxidation, leading to brittle coatings that are susceptible to cracking [18]. Furthermore, compatibility challenges may emerge with other components, including brake pads, calipers, and electronic control systems. Issues such as thermal expansion mismatch, variations in friction coefficients, and potential interference with sensor readings may occur. Achieving seamless integration and optimal performance necessitates close collaboration among material scientists, engineers, and automotive manufacturers.

4.5 Regulatory and Environmental Constraints

The implementation of sustainable strategies for the surface modification of GCI brake rotors must adhere to stringent regulatory requirements, particularly concerning particulate matter emissions. Achieving compliance with these standards presents challenges, particularly in balancing performance, cost, and environmental impact. For example, the Euro7 particulate emission standards mandate substantial reductions in brake dust emissions, thereby necessitating the development of innovative and compliant surface modification techniques [20, 64]. Moreover, it is imperative to conduct a thorough assessment of the environmental impacts of new sustainable processes to ensure that they provide genuine net benefits. While the primary objective is to reduce the environmental impact, comprehensive LCAs of innovative techniques are essential to confirm their net environmental advantage. Certain 'sustainable' solutions may entail hidden environmental costs related to production, processing, or disposal. For instance, the energy consumption and waste generation associated with specific surface treatment processes require careful evaluation.

4.6 Wear and Emission Trade-Offs

Although surface-modification techniques can substantially mitigate wear and emissions, there is often a trade-off between these two factors. For instance, laser cladding has demonstrated a 90% reduction in the CO_2 footprint compared to the production of virgin GCI rotors; however, it may lead to increased wear rates and particle emissions in specific applications [47]. Similarly, although the FNC treatment is effective in reducing corrosion, it may not offer sufficient wear resistance under extreme braking conditions [20]. Achieving a balance between performance and sustainability is of paramount importance. Although certain surface modification techniques may enhance corrosion and wear resistance, they can potentially compromise other aspects of braking performance, such as the friction coefficient or heat dissipation. For instance, the application of alumina-based coatings with dimples can reduce wear and emissions; however, careful optimization is necessary to maintain braking efficiency [34]. This trade-off highlights the need for a balanced approach for selecting surface modification techniques, considering both environmental and performance requirements.

Table 2. Comparative analysis of GCI brake rotor surface treatment technologies

Surface Treatment Technology	Key Advantages	Limitations
Thermal Spraying	- Reduces particle emissions - Compatible with a variety of materials - Suitable for mass production	- High production costs - Adhesion issues - Requires post-processing - Environmental concerns - High energy consumption
Laser Cladding	- Environmentally friendly - Reduces resource waste - High precision and minimal distortion	- High initial investment - Requires post-processing - Limited production rate - High energy consumption
Cold Spraying	- Low-temperature and eco-friendly - Preserves substrate properties - Suitable for temperature-sensitive components	- Limited scalability - Restricted material options - High-pressure requirements - Requires post-processing
Plasma Electrolytic Aluminating	- Superior wear and corrosion resistance - High hardness and good coating adhesion - Environmentally safe	- High production costs - Limited scalability - Requires post-processing - Specialized equipment required
Ferritic Nitrocarburizing (FNC)	- Enhanced wear and corrosion resistance - Cost-effective - No post-processing needed	- Complex process control - Challenges in layer thickness control - Limited performance under extreme wear conditions
FNC-Smart ONC	- Excellent wear and corrosion resistance - Suitable for mass production - No post-processing needed - Economical surface engineering	- Potential process complexity - Layer thickness control challenges - Limited to pilot-scale testing

Table 2 presents a comprehensive overview of the principal advantages, limitations, and challenges associated with the most promising surface treatment technologies. The implementation of sustainable surface modification strategies for GCI brake rotors presents substantial advantages, including enhanced corrosion and wear resistance, along with a diminished environmental impact. Nevertheless, challenges such as material compatibility, elevated production costs, process complexity, regulatory compliance, environmental concerns, and performance trade-offs must be addressed to facilitate widespread adoption. Addressing these challenges requires a comprehensive approach that considers the interplay between material science, surface engineering, and environmental sustainability. Further research and development are essential to overcome these limitations and develop standardized, scalable, and cost-effective solutions for the automotive industry.

5 Future Directions and Research Opportunities

Overcoming the challenges outlined in the previous section requires dedicated R&D efforts. The future of sustainable GCI brake rotors in EVs depends on innovative approaches and collaborative efforts. Progress in this area demands continuous innovation and exploration of emerging technologies. The following points underscore promising future directions and research opportunities.

5.1 Emerging Materials and Coating Technologies

Future research should prioritize the exploration of innovative materials and coating technologies that offer improved corrosion and wear resistance. This includes the examination of high-entropy alloys (HEAs), which exhibit exceptional mechanical, tribological, and corrosion properties owing to their distinctive atomic configurations [65]. Additionally, the development of advanced ceramic coatings, such as nanocomposites and functionally graded coatings, can provide superior wear resistance and thermal stability. The development of hybrid coatings that integrate organic and inorganic materials to achieve synergistic protection against corrosion and wear is another promising research direction. Furthermore, the development of smart coatings capable of sensing and responding to environmental changes, such as pH or temperature, can facilitate proactive corrosion protection.

5.2 Machine Learning (ML) and Artificial Intelligence (AI) Integration for Optimizing Wear-Resistant Designs and Real-Time Monitoring

The integration of ML and AI can revolutionize the design and optimization of wear-resistant brake rotors. ML algorithms can be used to analyze vast datasets of material properties, operating conditions, and failure modes to predict wear behavior and optimize rotor design [66]. AI-powered simulations can be used to model complex wear mechanisms and predict the performance of different rotor designs under various operating conditions. This approach can accelerate the development of high-performance, durable brake rotors by enabling rapid design iterations and virtual testing. Furthermore, AI can be used for real-time monitoring of rotor wear, enabling predictive maintenance and preventing catastrophic failures.

Integrating smart technologies into GCI brake rotors can enable real-time monitoring of corrosion and wear, allowing for proactive maintenance and performance optimization. The data obtained from these technologies can be used to optimize braking strategies and extend the lifespan of rotors. Smart technologies such as sensors and actuators can provide valuable data on the condition of rotors, enabling predictive maintenance and preventing catastrophic failures [67]. In addition, future research should focus on the application of AI to streamline the brake pad formulation process. This approach aims to reduce raw material waste, decrease costs, and facilitate compliance with environmental and regulatory standards by optimizing formulations in real time.

5.3 Development of Advanced, Bio-Inspired Coatings and Self-Healing Surfaces

Bio-inspired surfaces that mimic natural defense mechanisms offer a promising approach for enhancing brake-rotor durability. Bio-inspired coatings, inspired by the self-healing properties of biological materials, can enhance the wear and corrosion resistance of GCI rotors [68]. These coatings can incorporate self-repair mechanisms, adaptive properties, and enhanced adhesion, thereby improving performance and longevity. Research should focus on developing coatings and surface treatments incorporating self-healing agents, such as microcapsules containing corrosion inhibitors or wear-resistant nanoparticles. Exploration of surfaces with hierarchical structures found in natural materials can enhance lubrication and reduce wear. Bio-inspired surface textures can enhance debris removal and reduce wear.

5.4 Potential of Additive Manufacturing in Brake Rotor Sustainability

Additive manufacturing (AM) has significant potential for enhancing the sustainability of brake-rotor production. AM techniques, such as powder bed fusion and directed energy deposition, enable the fabrication of complex rotor geometries with tailored microstructures [56]. This allows for the optimization of the rotor design for specific EV applications, reducing material waste, and improving performance. AM can also facilitate the integration of functional features, such as integrated sensors and cooling channels, into the rotor design. Furthermore, the use of recycled metal powders in AM can reduce the environmental footprint of brake rotor production. AM can also enable the production of on-demand parts, reducing the need to maintain large stocks of parts, thus reducing waste.

5.5 LCA for Comprehensive Sustainability Evaluation

It is imperative to conduct a comprehensive LCA of all emerging sustainable solutions, such as PEA coatings, CS, and FNC-Smart ONC, to ascertain their net environmental benefits. LCA involves the evaluation of environmental impacts associated with a product or process throughout its life cycle, from the extraction of raw materials to their disposal at the end of its life [69]. This holistic methodology can help identify potential environmental hotspots and inform the development of sustainable solutions.

5.6 Collaboration Between Industry and Academia for Rapid Innovation

Addressing the challenges outlined in this study requires collaboration between industry and academia to expedite the development and implementation of sustainable GCI brake-rotor technologies. Industrial partners can offer valuable insights into practical applications and manufacturing constraints, whereas academic institutions can contribute to advanced research and expertise. Collaborative research projects, technology transfer initiatives, and industry-academia partnerships can promote rapid innovation and facilitate the transition to sustainable EV braking systems.

6 Conclusions

The transition towards sustainable GCI brake rotors in EVs constitutes a pivotal advancement in enhancing both the environmental impact and performance of these vehicles. This brief review examines various sustainable strategies designed to improve corrosion and wear resistance, including environmentally friendly surface treatments, material modifications, and lubrication techniques.

This review underscores the significance of implementing surface treatments such as FNC with post-oxidation, PEA, and laser cladding to reduce corrosion. This highlights the advantages of alloying with corrosion-resistant elements. Furthermore, sustainable strategies to enhance wear resistance, including eco-friendly thermal spray coatings, cold spray coatings, advanced GCI microstructures, and bio-derived solid lubricants, are discussed.

However, the implementation of these strategies presents several challenges. Key obstacles include cost-effectiveness, scalability, long-term performance assessment, environmental impact evaluation, and compatibility with existing EV braking systems. Addressing these challenges necessitates a concerted effort in research and development, which encompasses the exploration of advanced bio-inspired coatings, integration of smart technologies for real-time monitoring, and utilization of additive manufacturing for customized rotor designs.

Future research must prioritize comprehensive life-cycle assessments to ensure the true sustainability of these technologies. Collaboration between industry and academia is essential for fostering rapid innovation and facilitating the transition to sustainable EV braking systems. By addressing these challenges and pursuing future directions, the EV industry can develop more durable and environmentally responsible GCI brake rotors, contributing to the overall sustainability of EVs.

The development of sustainable GCI brake rotors represents not only a technical challenge but also a critical element in the broader initiative to establish a more environmentally sustainable automotive industry. Ongoing research and innovation in this domain are pivotal for shaping the future of sustainable transportation. The findings of this review indicate that a comprehensive approach that incorporates novel materials, surface treatments, and enhancements in braking systems is essential for improving wear resistance, corrosion protection, and environmental compliance.

Data Availability

Not applicable.

Conflicts of Interest

The author declares no conflict of interest.

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