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ALUMINUM MATRIX COMPOSITES ALTERNATIVE FOR BRAKE ROTOR APPLICATIONS

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Abstract. *This literature overview examines the capacity of using aluminum matrix composites (AMCs) rather than conventional grey solid iron in brake rotor packages. Driven by the preference for lighter and more environmentally friendly vehicles, AMCs offer several benefits, including decreased weight, advanced thermal properties, superior put-on resistance, and an optimized breaking system. Studies have concluded that AMCs can gain weight reductions of up to 60% compared to cast iron, resulting in stepped-forward gas performance and automobile management. Besides exhibiting superior thermal conductivity and lower thermal enlargement, it results in better heat dissipation and a reduced danger of warping and cracking. The advantage of using ceramic reinforcements, which include SiC, Al2O3, and B4C, is that they can enhance the damage resistance of AMCs, leading to a longer service life for brake rotors. The review covers various elements of AMC brake rotor development, Starting with manufacturing strategies (stir casting, ultrasonic-assisted stir casting, and squeeze casting), which are powerful techniques for producing extremely good AMC rotors, then the thermal traits, which are so essential due to their thermal conductivity, thermal expansion, and heat dissipation in brake rotor overall performance, Finally, the tribological residences affect load, sliding pace, and floor roughness on the wear and friction of AMC rotors. Brake pad compatibility is so vital in breaking systems, that deciding on suitable brake pad materials, containing non-asbestos organic (NAO) pads, can optimize performance with AMC rotors. These traits can be computationally analysed by using finite element evaluation and different numerical methods to predict the thermal and mechanical behaviour of AMC brake rotors. The review emphasizes that AMCs maintain great promise as next-era manufacturing for brake rotors, offering a balance of weight reduction, stepped-forward thermal control, and more advantageous wear resistance. Further research and improvement are necessary to optimize fabric composition, production strategies, and brake pad compatibility to improve the capacity of AMCs in brake structures.*
Keywords: *Brake Rotors; Aluminum Matrix Composites (AMCs); Tribology; Brake pads.*

1. Introduction

Automobiles use disc brake systems to slow down or stop. The system consists of a disc rotor, a pair of brake pads, and a caliper with a piston. This process is highly efficient and reliable, making disc brake systems the preferred choice for modern automobiles. The frictional heat generated by the rotor and pads is essential in converting the car's kinetic energy into thermal energy, effectively slowing or stopping the vehicle [1].

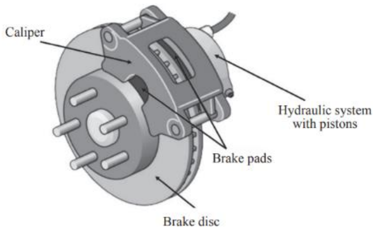

Figure 1 – Hydraulic disc braking system [2].

Gray cast iron is the ideal material for manufacturing brake discs due to its impressive range of properties. It has excellent thermal conductivity, maintains its material stability even at elevated temperatures, and exhibits commendable wear resistance [3]. Gray iron is a practical choice for mass production due to its affordability and the simplicity of the casting process [3].

Gray iron's relatively high density is a major disadvantage as it increases the overall weight of the vehicle, negatively impacting fuel efficiency and CO_2 emissions, as well as the vehicle's handling dynamics, often resulting in poorer performance [4]. However, despite this, gray iron remains a popular choice for its cost-effectiveness and ease of use in manufacturing. The high density of brake rotors is a significant disadvantage as it increases the weight of the vehicle, negatively impacting fuel efficiency, CO_2 emissions, and handling dynamics, often resulting in poorer performance. The weight of the brake rotors is a crucial factor in both conventional and electric vehicles as it significantly contributes to the overall weight of the chassis. The automotive industry is confidently researching and adopting lighter materials for disc brake rotors to significantly improve efficiency and performance. This decisive shift aims to enhance vehicle efficiency and handling by reducing unsprung weight to expertly meet the evolving demands of modern transportation [5, 6].

Aluminum alloys are an excellent choice for manufacturing due to their unique physical properties, including low density, minimal thermal expansion, high thermal conductivity, and strong corrosion resistance [7, 8]. Aluminum alloys are a highly valued choice for the automotive industry due to their high specific strength and excellent corrosion resistance, making them cost-effective and ideal for high-volume production. Our research and development in aluminum-based metal matrix composites (AMCs) have shown great promise for use in brake rotors. This is because traditional cast-iron brake rotors have a major limitation of relatively low resistance to scuffing and seizing, as noted in Reference 6. Our AMCs are a confident alternative to address these challenges [9].

AMCs offer significant benefits over gray cast iron for brake rotor applications, particularly in terms of thermal conductivity, density, and specific strength. Their superior properties make AMCs an appealing option that can potentially improve brake rotor performance and efficiency. Ongoing research and development in this area suggests that AMCs will soon become a more common material in brake rotor manufacturing, offering a balance between strength, weight, and thermal properties [10]. To improve resistance to galling and seizure, AMCs are strengthened with hard synthetic ceramic materials, such as SiC, Al_2O_3, B_4C, SiO_2, and TiO_2. The integration of these ceramic reinforcements with the base aluminum matrix is optimized for various automotive applications, ensuring their effectiveness [11, 12].

Hybrid aluminum-metal matrix composites (HAMCs) outperform single-reinforced AMCs, especially in mechanical and tribological aspects. HAMCs incorporate secondary reinforcements, such as industrial by-products or agricultural wastes like fly ash, red mud, sugarcane bagasse ash, rice husk ash, bean ash, and cow dung ash, providing numerous advantages. HAMCs are the superior choice for automotive applications due to their lower density, reduced manufacturing costs, and lighter weight compared to primary reinforcements. They combine the desirable properties of AMCs with the added benefits of cost-effectiveness and sustainability [9].

2. Methods for Creating Aluminum Matrix Composite Rotor Discs

Aluminum is the ideal material for manufacturing rotor discs due to its ease of casting and suitability for large-scale production (Chebolu et al., 2022). The stir casting process is a highly effective and efficient method for producing low-cost, high-quality aluminum matrix composite (AMC) brake rotors. This technique involves mechanically stirring molten metal to uniformly distribute ceramic particles that are either micron- or nano-sized throughout the aluminum matrix. Aluminum is the ideal material for manufacturing rotor discs due to its ease of casting and suitability for large-scale production [13]. The stir casting process is an effective and efficient method for producing low-cost, high-quality aluminum matrix composite (AMC) brake rotors. This technique involves mechanically stirring molten metal to uniformly distribute micron- or nano-sized ceramic particles throughout the aluminum matrix [14, 15].

Mohanavel and colleagues improved stir casting techniques to produce aluminum alloy AA 7178/Si_3N_4 composites. The study found that the distribution of Si_3N_4 within the matrix plays a critical role in determining the composite's properties, particularly its tensile strength. To optimize the mechanical characteristics, it is imperative to uniformly distribute Si_3N_4 particles throughout the AA7178 alloy matrix. This will significantly improve the strength and performance of the composite [16]. Ul Haq et al. demonstrated that adding silicon nitride (Si_3N_4) in proportions ranging from 0–8 wt% to AA7075 aluminum alloy significantly improves its hardness, compression strength, and wear resistance. At an 8 wt% Si_3N_4 level, the alloy showed up to a 20% increase in hardness and a 50% boost in compression strength. Additionally, wear resistance improved significantly, with a 37% reduction at 10 N loads and a 61% decrease at 50 N loads. The coefficient of friction (CoF) ranged from 0.10 to 0.30. It increased with Si_3N_4 content up to 4 wt% and then decreased. These results demonstrate that AA7075-Si_3N_4 composites, particularly those with higher Si_3N_4 content, are highly suitable for brake rotor applications [17].

Stir casting has made significant advancements in recent years [18], especially with the introduction of ultrasonic-assisted techniques and the use of nano-sized ceramic particles as reinforcements [16]. The application of ultrasonic waves during the casting process has been found to greatly improve the uniform distribution of these nanoparticles within the molten aluminum alloy [19]. This breakthrough holds immense potential for enhancing the quality and performance of AMC brake rotors [13, 14]. Ultrasonic-assisted stir casting has been extensively researched in the field of materials science and has been proven to enhance mechanical properties and wear resistance. This technique has shown promise in brake rotor manufacturing, an area traditionally dominated by die casting, which has been the industry standard for many years [20, 21, 22].

Researchers have explored a new manufacturing method called ultrasonic squeeze-assisted stir casting [20] instead of conventional methods. This method was successfully used to produce aluminum matrix composite (AMC) brake discs, as demonstrated in a specific study (shown as Figure 2). The technique described in this study combines ultrasonic stirring and squeeze casting principles to confidently produce superior AMC brake discs [23].

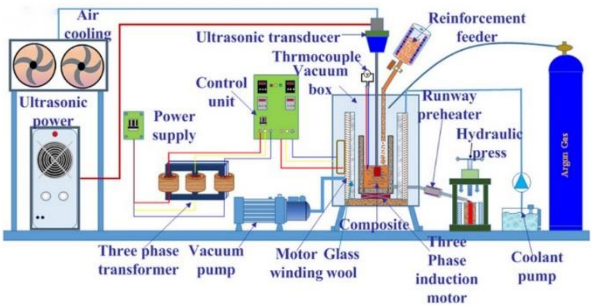

Figure 2 –Recommended stir casting furnace design [23].

The use of ultrasonic vibrations in the stir casting process results in a more uniform distribution of reinforcing particles in the aluminum matrix, leading to better bonding between the matrix and the reinforcement. The end product's mechanical characteristics are significantly enhanced. The squeeze casting process achieves a denser and more refined microstructure in the brake discs, enhancing their performance and wear resistance. The combination of squeeze-assisted stir casting and ultrasonics represents an innovative approach that significantly advances the field of automotive braking systems. This approach produces high-quality aluminum matrix composite (AMC) disc brakes that are more efficient and have a longer lifespan [24].

Lo et al. presents advanced methods for improving aluminum metal matrix composite (Al MMC) brake rotors using squeeze casting (SC). This technique improves reinforcement incorporation, high temperature performance and potentially reduces cost. SC increases the maximum operating temperature (MOT) of Al MMCs by using specific aluminum alloys, more reinforcement, and magnesium alloying. Al MMCs offer over 60% weight reduction compared to cast iron, along with superior thermal conductivity, reducing stress and hot spots. AMCs exhibit superior resistance to thermal shock and fatigue due to their low modulus and thermal expansion. They also exhibit superior tensile strength, damping, and wear resistance compared to cast iron, making them an excellent choice for brake rotor applications.

Kumar conducted a stir-casting research study to produce an aluminum hybrid metal matrix composite (AlHMMC) consisting of 3% alumina and 3% graphite. The objective of the study was to determine the wear resistance of AlHMMC compared to the base alloy for automotive applications. Based on the analysis of various factors such as load, sliding velocity and distance, the study confirms that AlHMMC has superior wear resistance compared to the base alloy. Although the wear rate of AlHMMC increases with load and distance, it is still lower than that of Al6061. This result shows that AlHMMC has various advantages over Al6061 in different tribological applications. Furthermore, the study showed that the wear rate of AlHMMC decreases with increasing sliding velocity up to 4.18 m/s. However, it increases with distance. These results demonstrate the potential of AlHMMC for use in various automotive applications due to its superior wear resistance. As the sliding distance increases, the wear resistance of AlHMMC improves significantly, ranging from 20% to 50% compared to the Al6061 alloy. This improvement is attributed to the combined effects of applied load and sliding velocity. The key to this performance improvement is the integration of hard ceramic reinforcements (Al_2O_3) and soft solid lubricants (graphite) into the AlHMMC composition [25].

The results of the next study are highly significant for the automotive industry, especially for disk applications. These results demonstrate the competence and expertise of the researchers in this field. The results clearly demonstrate that hybrid metal matrix composites (HMMCs) can significantly improve wear properties and facilitate weight reduction in brake systems. The HMMCs are expertly produced by a two-step stir-casting process in which aluminum alloy (AA2219) is melted and reinforcing materials such as SiC, Al_2O_3 and wollastonite are added. The resulting mixture is then poured into sand molds to form the composites [26].

Madan and his team are investigating the use of radial functional grading to improve disk performance. This technique, although not extensively covered in the existing literature, has been shown to be effective in improving disk performance. The study uses a powder metallurgy process to fabricate Al-SiC-based discs with three and five layers in which the concentration of SiC particles varies radially. Finite element analysis is used to thoroughly investigate the stress distribution in these wafers. The fabrication of the functionally graded material was successful. The uniform distribution of SiC and the seamless transition between layers without cracks or voids demonstrate the success of the process. The material also exhibits reduced grain size and increased hardness with a higher SiC content, making it an ideal candidate for use in various types of machines, such as power transmission and energy storage devices. This study presents a powder metallurgy method for producing functionally graded materials that have significant advantages for various industrial applications [27].

A metal matrix composite (MMC) has been successfully synthesized using the stir-casting technique. The composite consisted of an LM13 aluminum alloy base reinforced with silicon nitride (Si_3N_4) and graphite (Gr). The wear rate was significantly reduced as the sliding distance increased, demonstrating the superior performance of the composite. The LM13/Si_3N_4/Gr MMC was fabricated using the LM13 aluminum alloy for its superior wear resistance properties. Si_3N_4 and graphite were selected as reinforcing agents for their high temperature stability and lubricating properties, respectively. LM13 was melted in a controlled argon atmosphere to avoid unwanted atmospheric reactions during the manufacturing process. The LM13 alloy was melted, and 12 wt% Si_3N_4 and 3 wt% graphite, preheated to 250°C, were carefully added to the melt. The mixture was stirred at a constant speed of 200 rpm for five minutes to ensure uniform distribution of the reinforcements throughout the alloy. Once uniform dispersion was achieved, the molten composite was poured into a preheated mold 20 mm in diameter and 100 mm long. It was then allowed to cool and solidify at room temperature [23].

3. Components for Aluminum Matrix Composite Rotor Discs

3.1. Aluminum Matrix Substances:

3.1.1 Aluminum Metal Matrix composite AMC:

Aluminum alloys are an excellent choice for the automotive industry due to their low density, high strength-to-density ratio, and remarkable thermal conductivity. They are particularly favored for various vehicle components where weight reduction and heat management are essential. Despite these advantages, there are challenges associated with using aluminum alloys for brake disc applications. To make these alloys a viable alternative to grey cast iron, it is crucial to improve their maximum operating temperature and wear resistance. While grey cast iron is often preferred due to its cost-effectiveness and performance under high-stress conditions, these alloys have the potential to surpass it with the right improvements. It is worth noting that the original text is supported by sources [28, 29].

Rettig and his team developed a new hyper-eutectic aluminum alloy named EDERALSI using a unique low-pressure die-casting technique. The composition of this innovative brake disc is detailed in Table 1. The high strength of this alloy is primarily attributed to its evenly distributed high silicon content. The uniform distribution of silicon particles and consistent grain sizes contribute significantly to the inherent strength of the alloy. This composition does not require post-processing temperature treatments or fiber incorporation to enhance its strength characteristics, simplifying the manufacturing process and making it an environmentally sustainable option. Moreover, the durability of the alloy obviates the necessity for supplementary surface treatments, underscoring its eco-friendly attributes and streamlining the manufacturing process [30]. The EDERALSI alloy offers three significant advantages over traditional grey cast iron used in brake discs. Firstly, it achieves a substantial weight reduction of up to 60%, which is a crucial factor in automotive design as lower weight can lead to improved fuel efficiency and overall vehicle performance. Secondly, this alloy maintains consistent frictional properties across a broad range of temperatures, ensuring reliable braking performance under varying operating conditions.

Table 1 – the material properties of Ederalsi and grey cast iron [30].

Elements	Weight %
Silicon	16-20
Magnesium	0.2- 0.7
Copper	0.3
Titanium	0.06- 0.1
Iron	0.2
Strontium	0.001
Aluminium	Balamce

Mann and colleagues confidently utilized the stir casting process to successfully produce a new hyper-eutectic AMC brake rotor material. This study showcases the competence and expertise of the researchers in developing a superior brake rotor material. The material, which consisted of LM 30 alloy as the matrix and was reinforced with natural mineral corundum (Al_2O_3) particles measuring 74 μm, demonstrated an average stable wear rate 7% lower than that of traditional cast iron brake materials at a contact pressure of 1.8 MPa. The corundum particles played a crucial role in enhancing the strength of the AMC. They acted as a barrier to fracture propagation and reduced surface delamination, resulting in a significant increase in the wear resistance of the AMC brake disc material. Moreover, brake rotors made from this AMC material were approximately 60% lighter than their cast iron counterparts, which can greatly improve overall vehicle efficiency. This technical advancement represents a practical improvement in automotive design [31].

3.1.2 Aluminum Metal Matrix composite AMC:

Singh et al. introduced Al6061/SiC/Gr, an advanced metal matrix composite material, to enhance the efficiency of conventional car braking systems. Our team confidently assessed the performance and effectiveness of these rotors through detailed finite element analysis. The simulation results clearly indicate that the hybrid Al6061/SiC/Gr composite brake rotor has the potential to replace traditional cast iron brake discs. Table 2 presents the material properties of the composites used in the finite element analysis for a comprehensive understanding [32].

Table 2 – Material properties of new AI based HMMC and cast iron.

	Density (kg/m^3)	Young's Modulus E (MPa)	Poisons Ratio	Specific Heat (J.Kg^{-1}.K^{-1})	Thermal Conductivity (W/m ºC)	Thermal Expansion Coefficient (K^{-1})	Hardness by Vickers (N/mm2)
AL/SiC$_{12\%}$/Gr$_{5\%}$	2815	114	0.24	820	125	2.3$^{-0.5}$	101.7
Cast Iron	7150	119	0.27	460	52	1.2$^{-0.5}$	225

Ferraris and colleagues conducted a study on the feasibility of using aluminum alloys and composites as a substitute for cast iron or steel in the manufacturing of disc brake rotors. The study found that brake discs made from SiC/Al composites exhibited highly promising results, demonstrating their potential as a wear-resistant layer for brake discs in passenger cars. The study confirms that SiC/Al discs can withstand applied stresses and maintain an acceptable coefficient of friction (CoF). Furthermore, their heat dissipation behavior is comparable to that of conventional rotor materials. The significance of silicon (Si) in aluminum alloys utilized for rotor discs is also emphasized. Alloys containing silicon are ideal for this application because they can withstand high temperatures without experiencing galling or seizure. Additionally, silicon's high thermal conductivity enhances heat dissipation from the brake surface, significantly reducing the likelihood of warping and cracking even in the most extreme conditions [33].

Awe et al. explores the potential of a lightweight SICAlight rotor as a replacement for traditional, gray-cast iron brake discs in future electric vehicle applications. The composite, consisting of AlSi9Mg0.6 and 20 wt% SiC particles, exhibits positive braking performance, minimal wear, low corrosion, reasonable durability, and favorable noise behavior. Extensive testing, including dynamometer and vehicle evaluations, demonstrates the benefits of the SICAlight rotor, such as lower particulate emissions compared to standard gray-cast iron rotors. In collaboration with disc and pad manufacturers, the study evaluates the performance of the aluminum rotor with compatible pads under electrified vehicle conditions. Comparisons with reference cast iron rotors show reduced PM10 emissions (78% reduction) for SICAlight rotors, highlighting potential benefits for battery electric vehicles, including weight reduction, reduced unsprung mass, and lower energy consumption. The corrosion resistance of SICA discs is also superior, indicating a reduced potential for noise, vibration, harshness, and PM emissions compared to GCI discs [34]. Where Sangeethkumar develops hybrid metal matrix composites (HMMC) for automotive rotor disc applications. The composites reinforce aluminum alloy AA2219 with silicon carbide (SiC), aluminum oxide (Al_2O_3), and wollastonite ($CaSiO_3$) to significantly improve wear properties and reduce the weight of cast iron disc brake rotors. The researchers conducted pin-on-disc wear tests and hardness tests to evaluate the tribological performance of the composites. The results clearly demonstrate that increasing the SiC and wollastonite content in the composite leads to a lower wear rate and improved wear resistance. Moreover, the composites with higher SiC and Al_2O_3 content exhibit superior wear characteristic [26].

Kumar’s study analyzes AA5052/ZrB_2 composites and highlights a proportional increase in wear as sliding distance increases, a key consideration for brake rotor life. The study also identifies significant variations in the coefficient of friction, which is critical for consistent brake performance. A notable discovery is the escalation of wear rate and coefficient of friction with increasing sliding speed and load, marking a shift from mild to severe wear under extreme conditions. This finding is critical for the design of robust brake rotors capable of handling high-speed, high-load situations. In addition, the study suggests that tailoring the ZrB_2 content in composites can fine-tune their wear and friction characteristics, making them suitable for demanding applications such as brake rotors [35].

3.1.3 Titanium alloy

Qu’s research clearly demonstrates that the oxygen diffusion (OD) process significantly improves the friction and wear properties of Ti-6Al-4V titanium alloys for truck disk brake rotors. In fact, the results indicate that OD-treated Ti-6Al-4V (OD-Ti64) outperforms other titanium materials, including untreated Ti-6Al-4V, titanium-based metal matrix composites (MMCs), and thermally spray-coated titanium alloys. OD-Ti64 maintained an optimal friction coefficient of 0.35-0.50, even at high disk surface temperatures near 600°C, and displayed enhanced wear resistance, surpassing both untreated Ti-6Al-4V and titanium-based composites in durability [36].

In another search, Blau et al focused on two commercial titanium alloys, four experimental titanium-based composites with hard particles, and a titanium alloy that had undergone thermal spray coating [37]. The study found that the friction coefficients were influenced by the type of counter face material, whether semi-metallic or highly metallic, and by the temperature of the friction-induced wear track, which in some cases exceeded 800°C. Interestingly, the wear rates for the titanium metal matrix composites were higher than those of conventional cast iron but significantly lower than those of two of the titanium alloys tested. Of the materials tested, the thermally spray-coated titanium disk showed the least wear, highlighting its potential as a viable option for a lightweight, corrosion-resistant brake rotor material. This finding suggests a promising direction for future research and development in the field of automotive braking systems [38].

3.2 Reinforcement materials

Reinforced aluminum matrix composites (AMCs) offer several improved properties over monolithic aluminum alloys [39]. The effectiveness of AMCs, particularly in brake rotor applications, is largely influenced by the type of reinforcement used [40]. Various reinforcements such as SiC, Al_2O_3 and B_4C as well as natural minerals rich in alumina, silica and aluminum silicate are commonly used to improve the mechanical and tribological properties of AMC brake discs [41].

Hybrid AMCs (HAMCs) with dual reinforcement outperform single particle reinforced AMCs, especially in terms of wear resistance, thermal conductivity, and mechanical properties. The reinforcing particles primarily reinforce the matrix phase. Typically, a concentration of 5–10% is effective for micron-sized reinforcing particles. Even the addition of 5% nanoparticles can result in significant improvements in both mechanical and tribological properties. [42]. SiC is the most used synthetic reinforcement material in AMC rotor disks due to its effectiveness in improving the overall performance of the composite [43].

Sadagopan and his team developed an AMC brake disc made of AA6061 reinforced with 20% SiC. To improve its strength, hardness and wear resistance, the fabricated AMC brake disc was subjected to a meticulous three-step heat treatment process including solution annealing, quenching and age hardening. The AMC disc material exhibited a uniform wear pattern on its contact surface, resulting in a lower wear rate and coefficient of friction (CoF) compared to traditional cast iron discs. A notable feature of these discs was the varying concentration of SiC particles in different layers, which contributed to their improved performance. The AMC disc showed superior braking efficiency and heat dissipation compared to conventional gray cast iron. The study analyzed the discs and found a lower temperature distribution, indicating the potential for longer brake disc life. This underscores the effectiveness of the AMC material in improving brake disc performance and durability [44].

Venkatachalam and colleagues investigated the use of dual reinforcement in AA6082, specifically combining 5 wt% SiC with 5 wt% fly ash and 5 wt% basalt. Their results showed that the Al/SiC/basalt composites have great potential as Hybrid Aluminum Matrix Composite (HAMC) materials for brake disc applications. The effective wetting of the reinforced particles within the aluminum alloy is critical to the performance and integrity of the composite. This property is responsible for the potential of the material [45].

Bracamonte and his team developed a novel sandwich structure for AMC brake rotors. The structure includes a thin, wear-resistant Al-SiC composite surface layer and an underlying aluminum alloy known for its high thermal conductivity. Their research showed that the tribological properties of the AMC surface layers were significantly affected by the temperature-pressure profile used during the manufacturing process. The process played a critical role in achieving a uniform distribution of Al and SiC particles or the formation of a distinctive mottled or vein-like microstructure. When compared to traditional cast iron rotors, the AMC brake rotors showed remarkable performance improvements. These improvements included minimal wear, no dust emissions, significantly reduced temperatures during braking, and extended service life. These advances highlight the potential of AMC brake rotors as a superior alternative in terms of both environmental friendliness and operational efficiency [46].

The interaction between the solid matrix and the reinforcement in composites can be explained by two types of bonding [47] : chemical and physical bridging. Physical bonding is characterized by relatively low bonding energy and involves hydrogen bonding and van der Waals forces [40]. On the other hand, chemical bonding provides high bonding energy due to processes such as chemical reactions and diffusion. These processes create a distinct interface. The strength of an aluminum matrix composite (AMC) is determined by three main factors: load carrying capacity, dislocation density, and the Orowan strengthening mechanism. In addition, the strength of AMCs can be improved by processes such as quenching and work hardening, which modify the properties of the material and contribute to its structural integrity [48].

Natarajan introduced a motorcycle brake rotor made of a 20% silicon carbide (SiC) reinforced aluminum matrix composite (AMC) combined with Al 6061. The goal of this combination is to reduce heat generation and unsprung mass, which in turn improves vehicle handling. The rotor has increased strength, stiffness and improved high temperature performance. After being cast, machined, and heat treated, the mechanical and thermal properties of the AMC rotor are proven to be suitable for motorcycle applications. Wear tests have shown that the AMC rotor outperforms traditional cast iron (CI) rotors. Notably, the AMC rotor is 56% lighter than its CI counterpart, resulting in improved braking efficiency and reduced risk of brake fading. This makes it a promising option for high performance applications [44].

The metal-ceramic hybrid brake disc, weighing 4.8 kg, is a novel invention that combines carbon-silicon-carbide (C/SiC) friction segments with an aluminum backing. The design of this disc was created by Opel et al using Finite Element Analysis (FEA) and has proven to be effective in bringing a 1.8-ton vehicle to a complete stop from a speed of 200 km/h. This disc requires less C/SiC material than standard C/SiC brake discs, making it more efficient and lightweight. The disc was tested with LowMet, C/SiC, and C/C pads during emergency conditions and it was found that C/SiC pads had the best balance of coefficient of friction and wear rate, making them the most suitable choice [49, 50]

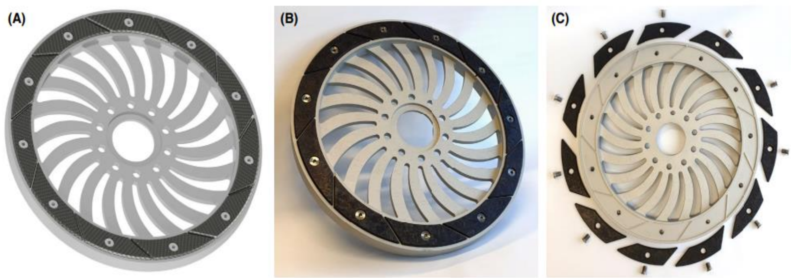

Figure 3 – final design of the metal- ceramic hybrid brake disc (outer diameter = 410): (a) rendering of cad design, (b) photo of built prototype, (c) carrier body with friction segments and correspondent screws [50].

In one hand, Fan et al. investigated the importance of selecting appropriate filler materials for friction blocks in high-speed train brakes. The goal was to optimize wear characteristics and minimize noise and vibration. Three different fillers were used sequentially: a Cu-based powder metallurgy material, a composite material, and a Mn-Cu damping alloy. The results showed that the filler material has a significant effect on the wear behavior at the brake interface and the friction-induced vibration characteristics. The Mn-Cu damping alloy was found to be particularly effective in reducing friction-induced vibration and noise in the brake system, resulting in the lowest noise levels compared to other systems. The wear debris behavior of the fill materials and the interface wear characteristics are the primary influencers of friction-induced vibration and noise in the brake system [51].

Su et al introduce a novel SiCp/Al-20Si-3Cu functionally graded material (FGM) for brake disks. It demonstrates superior wear and friction properties compared to traditional cast iron (HT250) under various loads and speeds. Our research is significant due to its innovative material composition, detailed analysis of wear mechanisms, and potential to enhance brake system performance and safety in the automotive industry. It offers insights into how the distribution of SiC particles affects performance, shows a transition in wear mechanisms with changing conditions, and highlights the FGM's potential as a more effective and durable material for brake disk applications [52].

Singhal and his team also researched the performance of SiC particle-reinforced functionally graded material (FGM) for brake disk applications. The study demonstrates the impact of SiC particle distribution on performance, revealing a shift in wear mechanisms under varying conditions. The findings underscore the potential of FGM as a superior and long-lasting material for brake disk applications. The composites were fabricated with a porosity level of approximately 1.74%. The HAMCs with Sn and Gr demonstrated wear resistance within 6% of the commercial grey cast iron commonly used in automotive brake rotors [53].

The liquid metallurgy method was used to develop a hybrid composite consisting of LM13, 12 wt.% silicon nitride (Si_3N_4), and 3 wt.% graphite (Gr). The wear behavior of the composite was evaluated using a pin-on-disc tribometer, which revealed that the wear rate increased with both the load and sliding velocity. This increase in wear rate was attributed to the stress induced by the load causing the Si_3N_4 particles to fracture and damaging the aluminum matrix. Silicon nitride was chosen as the primary reinforcement due to its exceptional ability to maintain structural integrity even at high temperatures. Additionally, graphite was selected as the secondary reinforcement for its outstanding thermal and electrical conductivity. The morphological analysis depicted in Figure 4 revealed that the average size of silicon nitride particles was 5 μm, while that of graphite particles was 2 μm. A higher wear rate was observed with an increase in sliding velocity, primarily due to the abrasive action caused by the dislodged Si_3N_4 particles [54].

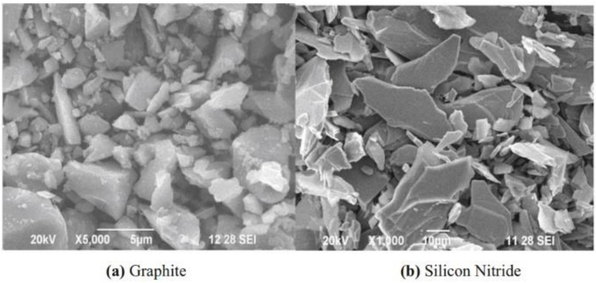

Figure 4 – SEM morphology (a) Graphite, (b) Silicon nitride [54].

Omran and colleagues researched sustainable material science by incorporating recycled elements into their work. They focused on hindalium, a recycled Al-Mg-Si alloy, and enhanced its properties by adding silicon carbide (SiC) particles. The investigation revealed a significant improvement in the alloy's mechanical properties. The addition of SiC particles to the hindalium alloy at a concentration of 15% increases the material's hardness by 14%. The research notes a 17% reduction in wear rate in comparison to the original hindalium alloy, which sets a precedent in the utilization of recycled materials for high-end applications, marrying sustainability with technological advancement [55].

This study of Du et al. addresses the critical issue of reducing vehicle mass to lower fuel usage and greenhouse gas emissions in automotive engineering. The creation of aluminum metal matrix composite (Al-MMC) brake discs that are lightweight and high-performing is examined. The investigation focuses on Al-Si alloys fortified with varying proportions and dimensions of silicon carbide particles (SiCp). Lanthanum (La) and Cerium (Ce) are incorporated into the Al-MMC to fortify the aluminum matrix and enhance the brake discs' ability to withstand high temperatures, such as those encountered during prolonged braking periods. The creation of intermetallic phases through the addition of La and Ce further strengthens the composite. The inclusion of SiCp particles in larger sizes and a broader range enhances thermal endurance and ease of processing of the composite. The material demonstrates a twofold increase in compression peak strength while retaining its malleability [56].

In the other hand, Wang et al. found that the incorporation of nano-sized particles of silicon carbide (n-SiC) by powder metallurgy significantly improves the peak hardness and the aging hardening process of 2014 Al alloy composite materials. This discovery has important implications to produce automotive components, particularly brake rotors. Transmission electron microscopy (TEM) was used to accurately identify key precipitation phases, including $Al_5Cu_2Mn_3$ and θ' (Al_2Cu), as well as the rarely seen Ω phase in aluminum metal matrix composites without silver (Ag). The higher dislocation density resulting from the thermal expansion coefficient mismatch between n-SiC and the 2014 Al matrix can be confidently attributed to the increase in aging kinetics and peak hardness. Composite materials have great potential to produce high-performance automotive parts, such as brake rotors, due to their ability to provide improved hardness and aging properties [57].

In the study of Lei and his team [58], the team compared three carbon/carbon (C/C) composites with varying compositions for brake rotors. The composites included rough laminar pyrocarbon, resin-derived carbon, and a mixture of both. The study clearly demonstrated that resin-derived carbon significantly increased wear rate without notably affecting friction coefficient, which had a negative impact on rotor durability and maintenance. The composites exhibited consistent friction coefficients at different speeds, but wear rates varied. However, it is important to note that the rough laminar pyrocarbon composite exhibited the least wear, indicating greater durability and a potentially longer service life. On the other hand, the carbon composite derived solely from resin wore down the fastest [59], suggesting a shorter lifespan in brake rotors.

4. Thermal Characteristics

Thermal analysis is critical in assessing the reliability of systems and components, especially those subjected to temperature cycling and thermal stress. In the case of aluminum metal matrix composites (AMCs), thermal analysis focuses on investigating the thermal behavior and response of the material to temperature changes, such as temperature distribution, heat transfer, and heat flux [60].

During braking, friction generates heat that raises the temperature of the brake rotor [61]. The ability of a material to rapidly dissipate heat is critical for effective high-temperature braking. Therefore, brake rotors must have high thermal conductivity, high thermal deformation resistance, and a low coefficient of thermal expansion [62]. Evaluation of these thermal properties is critical for any brake rotor disc alloy or composite. However, there are few studies that focus on these critical thermal properties of brake rotors [63].

Thermal conductivity is the rate at which heat passes through a material per unit thickness per unit area for each unit of temperature difference [64]. It can be evaluated using thermal or laser flash analyzers. The coefficient of thermal expansion, which indicates how a material's dimensions change with temperature changes, can be measured with a dilatometer. This instrument is essential for investigating the thermal properties of brake rotors, including thermal strain and thermal expansion [65].

In their study of the thermal dissipation capabilities of a high aluminum matrix composite (HAMC) brake disc, Gupta and colleagues used an LM27 alloy reinforced with 15% rutile and sillimanite as shown in table 3. Their research focused on thermal conductivity, strain, and coefficient of expansion. The disc produced by HAMC showed significant resistance to thermal expansion due to the effective interfacial bonding between the matrix and the reinforcements. As a result, it exhibited superior thermal conductivity and lower thermal strain and expansion coefficient compared to rotors made of traditional gray cast iron [66].

Table 4 –Thermal properties of density of LM27 alloy, DRP-15 composite, and the commercial material.

Property	Materials		
	LM27 alloy	DRP- 15 compositr	Commercial brake rotor material
Thermal conductivity at 25 ºC, k (W/ mK)	154.42 ± 0.36	141.65 ± 0.81	55.82 ± 0.31
Thermal strain ε_t (* 10^{-3})	1.01 ± 0.17	0.57 ± 0.17	0.37 ± 0.08
Coefficient of thermal expansion CTE (* 10^{-6} /ºC^{-1})	18.95 ± 0.17	11.09 ± 0.017	7.12 ± 0.08
Density (g/ cm^3)	2.77 ± 0.004	2.82 ± 0.006	6.92 ± 0,005

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Adebisi and her team conducted a study of a passenger car braking system, analyzing a stir-cast AMC brake rotor made of AA6061 alloy with 20% SiC and comparing it to a cast iron rotor using thermal imaging. The rotors were mounted on a stand and monitored with an IR thermal camera for thermographic analysis. The AMC rotor showed uniform thermal dispersion and a 25% higher heat dissipation rate at brake pressures ranging from 1.5 to 2.0 MPa compared to the cast iron rotor. This was attributed to the superior thermal conductivity of the AMC material [69].

Separately, Jayaraj and colleagues investigated the thermal properties of an LM9 alloy reinforced with multi-walled carbon nanotubes (MWCNTs) at various weight fractions. The thermal conductivity of the stir-cast composites was evaluated using the hot disk technique. The MWCNTs present in the matrix acted as foreign particles, creating thermal barriers that impeded heat movement and reduced the thermal conductivity of the AMCs [70].

In the study conducted by Singh et al, they performed transient thermal analysis on brake disks to study heat flow and temperature variations. The results showed that while the cast iron heated up to a lower temperature of 98°C, the Al6061/SiC/Gr composite reached a higher temperature of 230°C. However, it is important to note that the maximum operating temperature of Al6061/SiC/Gr was below the maximum tolerance of the composite, which was 525°C. The Al6061/SiC/Gr material has high thermal conductivity, which allows for effective heat dissipation and reduces hot spot formation. This results in better temperature uniformity and can help minimize or eliminate thermal failures in brake pads and rotors, ultimately increasing their operational reliability compared to cast iron [32]. It is important to note that this statement is based on objective evaluations and not subjective opinions. This results in better temperature distribution and can help minimize or eliminate thermal failures in brake pads and rotors, ultimately improving their operational reliability compared to cast iron [26]

In their study, Firouz and colleagues [71] developed automotive brake rotors using Al-9Si-SiC and Al-12Si-SiC composites. The composites were reinforced with 10 or 20 weight percent SiC particles by stir casting. The resulting rotors exhibited a uniform distribution of SiC particles and a refined grain structure, which improved their overall microstructure. When exposed to temperatures ranging from room temperature to 350°C, the Al-12Si composites exhibited significantly lower coefficients of thermal expansion and minimal residual strain. In addition, the research included thermal fatigue testing of these composites against conventional cast iron rotors over 80 cycles. Analysis after these cycles, including hardness evaluation, microstructural examination, and X-ray diffraction, indicated that the composite rotors maintained consistent strain and temperature profiles during both the heating and cooling phases without hysteresis loops or residual strain. The crystalline structure of the composite rotors improved with thermal cycling, while that of the cast iron rotors deteriorated over time. This study highlights the potential of AlSi-SiC composites as superior materials for automotive brake rotors due to their improved thermal stability and fatigue resistance compared to standard cast iron options.

Sharma et al. analyze the impact of heat treatment on the LM30 aluminum matrix composites reinforced with sillimanite. The composites had varying sillimanite content (3–15 wt.%) and particle sizes. They were treated through T4 and T6 methods. The increases in sillimanite content led to an improvement in hardness. Both T4 and T6 treatments resulted in better wear resistance and reduced friction. Specifically, the T6-treated composite with 15 wt.% sillimanite at 200°C showed a significant reduction in wear rate and friction coefficient by 70% and 52%, respectively, which is clear to show in figure 5. The composites had wear properties like those of grey cast iron. This suggests that they could serve as a lightweight alternative to heavy-cast iron in automotive parts like brake rotors [72].

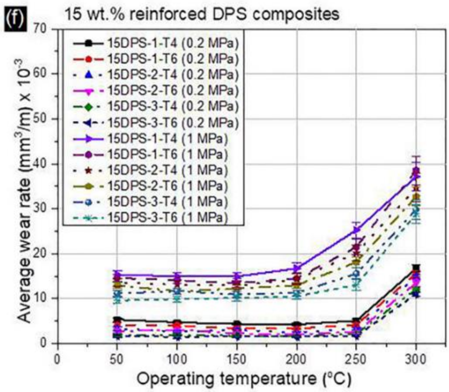

Figure 5 – Average wear rate versus operating temperature for heat treated 15DPS AMCs [72].

5. Tribological properties

Understanding the tribological behavior of Aluminum Matrix Composite (AMC) brake rotors is critical because it is influenced by several factors. The most important of these are the applied load and the sliding speed, both of which have a significant impact on the efficiency of the brake rotor. As a result, numerous studies have focused on these parameters to evaluate the wear and coefficient of friction (COF) rates of AMC brake rotors. The equation used to calculate the wear rate is.

$$K = \frac{\Delta m}{\rho F_n D}$$

Wear is the gradual degradation of material caused by continuous relative motion between two contacting surfaces. It is quantified as wear loss, which is the volume or mass loss of a material during a test period. The rate of wear can be determined using a specific formula. The wear rate 'r' is calculated from the mass loss before and after the wear test (Δm), the density of the material (ρ), the applied normal load (F_n) and the sliding distance (D). This calculation is critical for evaluating the durability and efficiency of AMC brake rotors under various operating conditions [24].

In a tribological evaluation using a small-scale dynamometer, Alnaqi and colleagues compared rotors made of AMC and gray cast iron. The study focused on Al6082 and AMC (Al6061/40% SiC) rotors, the latter having an alumina coating applied by plasma electrolyte oxidation. This coating increased the hardness of the AMC rotors and reduced their wear rates, resulting in a coefficient of friction (COF) in line with industry standards [73].

Lyu et al investigated the friction properties of an Al-SiC AMC brake disc using a pin-on-disc tribometer and non-asbestos organic (NAO) brake pads. They found that this AMC disc exhibited similar friction characteristics to conventional cast iron discs due to a self-generated protective tribo-layer that improved wear resistance [28].

Ahmad et al evaluated the wear and friction characteristics of AMC and cast-iron brake discs using a pin-on-disc tribometer. The AMC samples, consisting of AA242 with 30% Al_2O_3, showed a slight variation in CoF that was more pronounced at higher loads. This difference was attributed to the softer nature of the aluminum alloy compared to cast iron, resulting in increased surface roughness and wear [74].

Daoud and colleagues evaluated the wear and friction characteristics of A359-20 vol% SiC AMC rotors against commercial brake pads. They found that AMCs consistently outperformed cast iron in terms of CoF, which is critical for effective braking. The addition of SiC and Si to the AMC rotors contributed significantly to their superior strength, hardness, and wear resistance. This is due to the ability of the SiC particles to carry most of the wear load and increase the overall toughness of the composite. The reference remains unchanged [75].

Tan and colleagues conducted dynamometer tests on hybrid aluminum metal matrix composite (HAMC) brake rotors for rail vehicles. The results of the study suggest that HAMC brake rotors could be a promising alternative to conventional brake rotors in the rail industry. The discs, consisting of an A357/SiC MMC top layer fused to an AA6082 aluminum alloy base by friction stir processing, exhibited superior wear and friction performance. Capable of withstanding temperatures as high as 240°C, these rotors provide a consistent coefficient of friction, demonstrating their potential to replace traditional heavy iron and steel rotors on trains operating at 120 km/h. The presence of Third Body Films (TBFs) plays a critical role in reducing direct disc-pad contact, thereby reducing the incidence of cracking and debris generation. This resulted in fewer surface grooves, less AMC layer degradation and less wear loss, which ensured a stable coefficient of friction [76].

Jiang and his team investigated the friction and wear characteristics of SiC3D/Al brake disks paired with graphite (G)/SiC brake pads using a smaller-scale dynamometer designed for high-speed train applications. They found that SiC3D/Al-G/SiC tribocouples outperformed traditional iron-steel pairs by offering lower operating temperatures, stable friction, and improved durability. The mechanically mixed layer formed during the sliding process significantly affected the wear and friction properties of the tribocouple, leading to its improved performance [77].

Baig et al. conducted a study of the tribological behavior of an aluminum composite reinforced with submicron Al_2O_3 particles used as a brake rotor material. The study compared the friction and wear properties of this composite with those of conventional gray cast iron rotors under dry sliding conditions with semi-metallic brake linings, as shown in the figure. The results indicate that the Al_2O_3-reinforced composite exhibits lower wear rates than gray cast iron, particularly at lower braking force intensities. In addition, the use of Al_2O_3 reinforcement results in reduced brake pad wear even at higher intensities due to its superior heat dissipation. The inclusion of submicron Al_2O_3 particles increase the wear resistance of the rotor and extends its life. In addition, the Al_2O_3 particles improve the friction and stability characteristics of the material, potentially lowering the coefficient of friction for smoother braking. The fine particles provide a more uniform distribution within the aluminum matrix, resulting in consistent friction behavior. In addition, the Al_2O_3 reinforcement aids in heat dissipation, improving the thermal stability of the rotor and maintaining performance during extensive braking [5].

6. Influence of Brake Pads on Aluminum Matrix Composite Disc

The effect of brake pad materials on the performance of Aluminum Matrix Composite (AMC) rotors is a critical factor in brake system performance [2]. Research indicates that Non-Asbestos Organic (NAO) pads are more suitable for use with aluminum rotors than low-steel or semi-metallic pads [78]. NAO materials are particularly notable for their ability to develop protective third body tribological layers under higher loads, resulting in a lower coefficient of friction and consistent wear rate [28, 30].

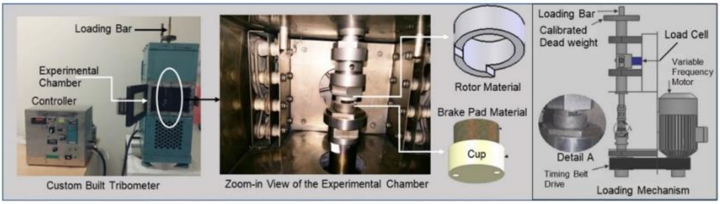

Figure 6 – Photograph of the Tribometer with Pad-on-Disc wear test configuration used in the wear experiments along with the schematic of the loading mechanism [5].

Nakanishi et al. aimed to improve fuel efficiency by reducing vehicle weight through the use of aluminum metal matrix composite (Al-MMC) brake rotors and pads [79]. They ensured that the braking performance and wear resistance of the Al-MMC system matched those of conventional cast iron systems by optimizing the amount and particle size ratio of hard particles in both the rotor and pad [80]. The researchers rigorously tested the wear resistance of the newly developed brake pad. The evaluation consisted of repeating 1000 braking cycles at different temperatures, starting from an initial speed of 50 km/h and a deceleration rate of 1.5 m/s^2 as shown in figure 7. To measure the changes in thickness of the pad need to evaluate its wear resistance [81]. The results were compared with those obtained with a conventional ferrous cast (FC) brake rotor and pad combination [82].

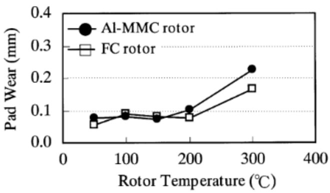

Figure 7 – Pad wear per 1000 braking times[79] .

Zhang and his team have developed a brake rotor composite that consists of 56% foam ceramics and 44% aluminum alloy. They have conducted rigorous tests on an Optimal SRV machine using a phenolic resin brake pad to thoroughly investigate the impact of temperature and load, between 32 N to 128 N, on friction and wear. The composite has shown predictable friction fade with increasing temperature, followed by remarkable over recovery on cooling [41]. The wear rates have also increased with temperature. The tests were meticulously carried out at both 100°C and 250°C. At 250°C, both friction and wear were significantly higher than at 100°C. Scanning electron microscopy has revealed that the wear was mainly caused by two-body wear [83].

Agbeleye investigates the properties of brake pads made from aluminum 6063 alloy blended with 5–30% clay (Al-clay composites), produced through stir casting. Clay particle size in the composites is 250 microns. Using Denison T62HS pin-on-disc tests, the study assesses the composites' wear behavior under dry sliding conditions. Results show that composites with 10–25% clay content significantly enhance tensile strength, hardness, and wear resistance, with optimal performance at 15% clay. The wear rate is influenced by both load and sliding speed [84]. These Al-clay composites, especially with 15–25% clay, exhibit wear and friction characteristics on par with conventional semi-metallic brake pads [85].

Österle et al. present in their research a detailed analysis of frictional interfaces and coatings on a semi-metallic polymer matrix composite (PMC) brake pad. The focused ion beam (FIB) technique is expertly employed to examine the topmost layers at the micro-contact regions of the brake pad. The frictional material of the brake pad is a blend of a metallic polymer matrix composite and is expertly paired with a cast iron rotor as shown in the next figure. The brake pad is composed of up to three distinct layers [41], each with its own unique composition. These layers consist of a thin friction film made of metal oxides and a sulfur-rich amorphous phase, a layer filled with wear debris, and a heavily distorted layer, especially when a metal particle is used as the base [86]. The analysis confidently indicates the accumulation of iron oxide particles from wear and the adhesion of copper and sulfur on the pad's surface. Furthermore, it highlights the transfer of zinc onto the cast iron rotor [87].

The research of Venugopal et al. investigates the use of magnesium (Mg) composites reinforced with Ni-P-coated alumina and silicon carbide microparticles for brake pad applications [88]. These composites are produced using a special stir-squeeze process. To test their suitability for brake systems, the study uses a tribometer in which the Mg composite acts as a pin against a stainless-steel disk, mimicking the brake pad-rotor interaction. Key findings show that coating the reinforcements significantly reduces the porosity of the composite and increases its hardness and compressive strength. The wear resistance of these Mg composites is comparable to that of conventional brake pad materials, highlighting their potential as effective friction materials in automotive braking systems working in conjunction with rotors [41].

The study of et al. Darmawan examines the wear rates of brake pads in the LRV Series 1100, utilizing both regenerative and pneumatic braking systems. Its goal is to forecast brake pad longevity and uncover reasons for wear rate disparities between motor and trailer bogie brake pads. Through linear regression of maintenance and field data, it predicts brake pad life spans—2039 for McA and McB bogies and 2029 for trailer bogies—noting that braking method impacts wear rates. The findings underline how braking force and friction influence pad durability, which is crucial for optimizing maintenance and enhancing safety. This analysis aids the rotor desk in strategic planning for maintenance and replacements, potentially lowering costs and ensuring safety by adapting maintenance to actual wear trends.[89, 20].

7. Impact of Surface Texture (R_a) on Rotor Disc

In tribological studies, it is critical to understand the effect of surface roughness, commonly referred to as R_a, on the performance of Aluminum Matrix Composite (AMC) brake rotors [75]. To evaluate the wear rate and friction characteristics of the disc materials, it is necessary to measure the surface roughness of both the disc and pad material before and after tribological testing. To evaluate the wear rate and friction characteristics of the disk materials, it is necessary to measure the surface roughness of both the disk and pad material before and after tribological testing. This helps us to obtain accurate and reliable results. Prior to testing, it is important to ensure that the AMC brake disc and pad material have consistent R_a values [90].

Research has shown that the surface roughness of AMC brake rotors tends to increase significantly after being subjected to dynamometer testing [73]. This increase is attributed to the weakening of the alloy matrix at the contact surface due to the high temperatures experienced during testing. It is also useful to measure the surface roughness of the protective tribofilm formed on the disk. This helps to verify the consistency of the coefficient of friction (CoF) under varying load conditions. Understanding the effect of surface roughness on AMC discs is critical to optimizing brake performance and durability. This is discussed in reference [28].

Biswas et al. investigated the development, characterization, and application of Al-Mg_2Si composites in motorcycle disc brake rotors. The performance of Al-Mg_2Si composites was compared with traditional materials such as cast iron and stainless steel using the Digital Logic Method (DLM) for material selection. In a simulated motorcycle disc brake scenario, the Al-20wt% Mg_2Si composite and steel rotors were evaluated. The technical performance index of the Al-Mg_2Si composite was 73.65, slightly lower than that of steel at 78.10. However, the Energy Efficiency Index (EEI) of the composite was significantly lower at 31.79 compared to 100 for steel. Notably, the composite had significantly lower CO_2 and CO emissions of 0.087 and 0.0026 g/km, respectively, compared to steel's 0.276 and 0.0082 g/km [91].

Alnaqi studied the effects of alumina coatings applied via plasma electrolytic oxidation (PEO) on AA6082 aluminum alloy (Al-Alloy) and 6061/40SiC aluminum metal matrix composite (Al-MMC) brake rotors, focusing on friction and high-temperature performance. The PEO process improves adhesion, uniformity, and surface hardness, with Al-Alloy achieving higher micro-hardness (1400 HV) than Al-MMC (980 HV). Al-Alloy rotors show superior thermal and frictional performance, handling over 500°C, while Al-MMC rotors have reduced heat tolerance. Coated rotors maintain acceptable friction coefficients (0.28 to 0.34). Al-Alloy rotors keep consistent coating thickness, unlike Al-MMC. Both rotor types develop a 2–4 mm transfer layer. However, alumina-coated Al-Alloy rotors fail above 550°C due to mechanical and thermal stress. Improvements could involve metallurgical changes or design modifications like ventilated discs [73].

In a novel study, laminate composite brake material designed for high-speed train braking systems was developed using powder metallurgy. This material has a bilayer structure consisting of prefabricated tribofilm (PTF, oxide-based) and metal-based materials. We evaluated the friction and wear performance of this brake pad, focusing on variations in PTF layer thickness, against a steel rotor disk. Tests were conducted using a TM-I type dynamometer at initial braking speeds (IBS) ranging from 50 to 350 km/h. The results showed that the PTF pad maintained stable friction and wear rates over a wide range of IBS (50–250 km/h) suitable for high-speed train applications. Key to its performance is the protective friction film formed on the pad's worn surface during braking, which is enhanced by the PTF layer, providing a larger, flatter contact area compared to metal-based materials. This film contributes to the pad's consistent friction performance and wear rate [92].

Synák et al. study the automotive brake components (rotors and pads) at different price points to determine if they effectively convert kinetic energy into thermal energy without overheating. It combines driving and laboratory tests to evaluate stopping distance, deceleration, steering effort, braking force, temperature, and corrosion resistance. The results show that while all brakes perform well under standard conditions, the least expensive brakes may underperform under intense or prolonged use [93].

8. Computational Examination of Aluminum Matrix Composite Brake Discs

Numerical analysis is used in brake system design to predict thermal aspects such as friction pressure distribution, surface heat flow, brake temperature distribution, radial surface temperature, and thermal stress [94]. Effective management of the conversion of kinetic energy to frictional heat at the disc can improve braking efficiency. This can be achieved through ideal rotor design and the use of superior heat dissipating materials. Heat transfer in brakes is primarily by conduction and convection, with radiation playing a minor role (5-10%). Research typically includes analysis of both transient thermal and structural aspects. However, the integration of fluid analysis for heat convection with thermal simulations provides a more comprehensive approach, especially under different braking conditions, such as prolonged, single emergency, and repeated braking events [95].

Pranta and colleagues conducted innovative research to redesign ventilated disc brake rotors. They incorporated unique curved vents, holes, and slots (as shown in

Figure 10) using Solidworks. Their analysis in ANSYS showed that these novel designs outperformed conventional disc brake rotors in terms of performance, achieving higher braking forces while avoiding cracking and buckling during operation [96].

Ali et al. analyzed the thermo-mechanical dynamics of brake rotors and pads during braking using ANSYS finite element software. They examined both full and vented disk interfaces within the braking system. The results showed a rapid temperature increase followed by a decrease after sustained braking, which was attributed to the disc brake design. Despite variations in friction coefficients, the deformation of the disc pad remained largely unchanged [97].

Nong and colleagues recommend the use of aluminum metal matrix composites (AMCs) in brake discs, especially for high-speed train applications where energy efficiency is a priority. They first determined heat convection coefficients using Solidworks 2014 flow simulation, which informed their CFD-based design. The subsequent thermal analysis used these coefficients as initial conditions. The study analyzed the use of radially vented SiC3D/Al alloy brake rotors, which were found to significantly improve airflow around and through the rotor. This improved airflow effectively dissipated frictional heat, resulting in a temperature reduction of up to 14%. The high thermal conductivity of the discs also resulted in a more uniform temperature distribution across the rotor. A peak temperature of 471.08°C was recorded at the 70-second mark near the outer regions of the friction surface, as shown in Figure 11. This underscores the suitability of the material for high-speed rail applications [98].

This study analyzes disc brake rotors, using finite element analysis (FEA) to compare aluminum alloy and aluminum matrix nanocomposite (AMNC) rotors at 70 km/h emergency braking. Key findings include: AMNCs' superior strength-to-weight ratio, aluminum alloy's max heat flux at 8 W/mm² versus AMNC's 16.28 W/mm², aluminum alloy's max deformation at 0.19 mm compared to AMNC's 0.05 mm, and AMNC's max von Mises stress at 184 MPa, slightly higher than aluminum alloy's 180 MPa. This suggests AMNCs as a viable alternative for disc brake rotor materials, Results of the ANSYS modal analysis are presented for the aluminum alloy and AMNC discs [99, 100].

Kumar et al use the grey relational analysis (GRA) to improve the specific wear resistance and friction coefficient of AlHMMC. Using the Grey Relational Analysis (GRA) approach, the study reveals distinct influences on the friction coefficient of Al6061 alloy and its hybrid composite, AlHMMC. For Al6061, the sliding distance, followed by sliding velocity and applied load, are key factors in that order. Conversely, for AlHMMC, the order of influence is applied load (43.67%), sliding velocity (42.51%), and then sliding distance [35].

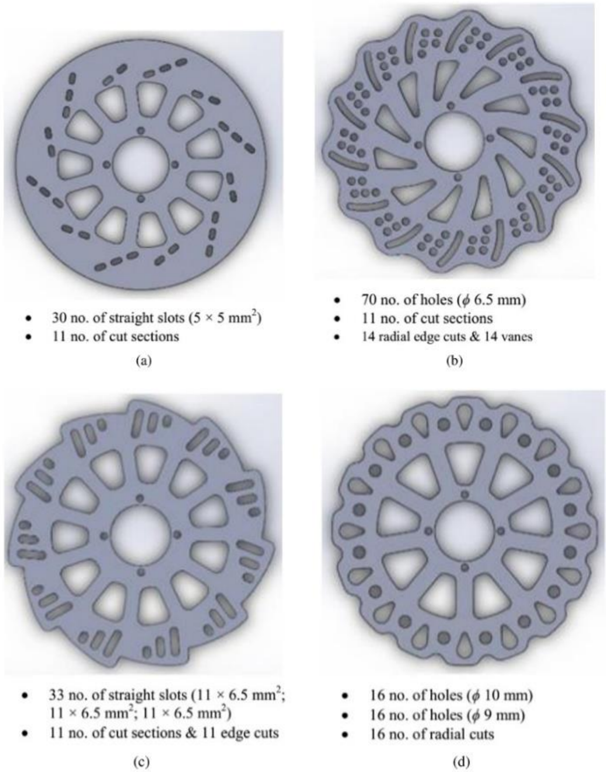

Figure 8 – Diagramof(a)Basemodel, (b)modifiedmodel1(MM1), (c)modifiedmodel2(MM2) and(b)modifiedmodel3 (MM3) with description [98].

The specific wear rate in another study analysis using GRA-ANOVA highlights that sliding velocity impacts Al6061 and AlHMMC by 39.57% and 42.51%, respectively. However, the applied load has a more pronounced effect on AlHMMC for all sliding distances. In summary, while both Al6061 and AlHMMC are influenced by similar factors, the order and magnitude of these influences differ significantly between the two materials [45].

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АЛЬТЕРНАТИВНЕ ЗАСТОСУВАННЯ АЛЮМІНІЄВИХ МАТРИЧНИХ КОМПОЗИТІВ ДЛЯ ГАЛЬМІВНИХ ДИСКІВ

Анотація. *У цьому огляді літератури розглядається можливість використання алюмінієвих матричних композитів (АМК) замість звичайного сірого чавуна в пакетах гальмівних дисків. Керуючись перевагою більш легких та екологічних транспортних засобів, АМК пропонують кілька переваг, включаючи зменшену вагу, покращені теплові властивості, чудову стійкість до корозії та оптимізовану систему руйнування. Дослідження дійшли висновку, що АМК можуть зменшити вагу до 60% порівняно з чавуном, що призводить до поступового підвищення продуктивності газу та управління автомобілем. Крім того, що він демонструє чудову теплопровідність і менше теплове збільшення, він призводить до кращого розсіювання тепла та зменшує небезпеку деформації та розтріскування. Перевага використання керамічних підсилювачів, які включають SiC,* Al_2O_3 *і* B_4C*, полягає в тому, що вони можуть підвищити стійкість до пошкоджень АМК, що призводить до більш тривалого терміну служби гальмівних* *дисків. Огляд охоплює різні елементи розробки гальмівного диска АМК, починаючи з виробничих стратегій (лиття з перемішуванням, лиття з перемішуванням за допомогою ультразвуку та лиття під тиск), які є потужними технологіями для виробництва надзвичайно хороших дисків АМК, потім теплові характеристики, які є такими важливими через їх теплопровідність, теплове розширення та розсіювання тепла в загальному циклі експлуатації гальмівного диска, нарешті, Трибологічні показники впливають на навантаження через швидкість ковзання та шорсткість поверхні на знос та тертя дисків АМК. Сумісність гальмівних колодок настільки важлива для систем тертя, що вибір відповідних матеріалів гальмівних колодок, наприклад, які містять неазбестові органічні (НАО) речовини, може оптимізувати експлуатаційну продуктивність дисків АМК. Ці характеристики можуть бути проаналізовані обчислювальним шляхом використання оцінки кінцевих елементів та різних чисельних методів для прогнозування теплової та механічної поведінки гальмівних дисків АМК. В огляді підкреслюється, що АМК зберігають великі перспективи як виробництво гальмівних дисків наступної ери, пропонуючи баланс зниження ваги, ступінчастий термоконтроль і більш вигідну зносостійкість. Необхідні подальші дослідження та вдосконалення для оптимізації складу структури, стратегій виробництва та сумісності гальмівних колодок для покращення експлуатаційних показників АМК в гальмівних конструкціях.*

Ключові слова: *гальмівні диски; алюмінієві матричні композити (АМК); трибологія; гальмівні колодки.*