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Comprehensive Review on Brake Friction Materials

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Abstract

Automobile manufacturers are currently dedicated to enhancing vehicle speeds for the purpose of saving travel time. However, achieving this objective necessitates the use of friction materials capable of handling high-speed braking. In this article, we will delve into the historical evolution of materials utilized for brake pads and drums. In the past, asbestos stood out as the most widely employed brake lining material due to its effectiveness. Unfortunately, its carcinogenic properties led to its prohibition by health and environmental agencies. Consequently, endeavors were undertaken to create brake friction materials devoid of asbestos. Presently, non-asbestos organic brake pads have become the most prevalent choice, despite the generation of harmful wear debris. To drive progress, scientists are energetically involved in developing environmentally sustainable brake friction materials that can perform effectively in high-speed braking under various weather conditions. They are exploring options like natural fibers or materials derived from agricultural waste as potential alternatives for brake pads. When it comes to brake discs and drums, cast iron has historically been the conventional choice. Nonetheless, more recent materials such as aluminum matrix composites, carbon-carbon composites, and ceramics are gaining popularity. Among these, aluminum matrix composite is particularly promising due to its low density and improved braking stability. Consequently, it is considered a potential future material for brake discs or drums.

Keywords: Brake Pad, Brake Disc, Brake Drum, Metal Matrix Composites, Non-Asbestos Materials.

INTRODUCTION

The braking system holds immense significance in all vehicles, being responsible for the essential task of slowing down or halting them completely. The reliability and consistent efficiency of this system, regardless of varying atmospheric conditions, are of utmost importance. In the realm of braking systems, two primary friction materials are commonly employed: disc brake pads and drum brake linings. Disc brake pads play a crucial role in disc brakes, finding widespread use in both automotive and industrial applications. A visual comparison of these liners and pads is depicted below in [Figure 1]. The pads are designed with steel backing plates that hold the friction material, which comes into contact with the disc brake rotor. Conversely, drum brakes operate by pressing a pair of shoes outward against a rotating, cylindrical brake drum [1].

The significance of the braking system extends to all types of vehicles, encompassing cars, buses, trains, airplanes, and more, as its failure could result in catastrophic consequences. The system operates on the principle of energy conservation. When brakes are engaged, the kinetic energy of the vehicle is transformed into heat energy through friction between the braking material and the moving body, rather than relying on contactless processes [2]. Two braking systems exist based on

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contact nature: direct-contact braking and contactless braking systems. In [Figure 2] displays different types of braking systems are used in Vehicles and Machinery's. Direct Contact braking mechanism that involves pressing a stationary frictional material, like brake pads or shoes, directly against a rotating or moving component, such as a brake rotor or drum, with the aim of reducing speed or halting the component's motion. This braking system is widely employed in vehicles and machinery to facilitate deceleration or come to a complete stop [3]. In [Figure 3] Displays Disc brakes assembly unit found in vehicles and machinery, feature a flat metal rotor connected to the wheel. When braking is initiated, brake pads press against the rotor, creating friction to halt wheel rotation. This design excels in heat dissipation, making disc brakes ideal for high-performance and heavy-duty applications, frequently seen in modern automobiles for superior stopping power and fade resistance [4]. Direct-contact braking systems utilize a brake disc or brake drum as the rotating component, whereas contactless braking systems operate without direct contact between the braking mechanism and the moving device. In contactless systems, electromagnetic devices generate braking force without any physical connection to the rotating device. Applying a magnetic flux to a conducting material produces eddy currents, which generate a force that opposes the motion of the rotating device [5]. The contactless braking systems function by inducing eddy currents in a conducting material, resulting in a counteracting force that transforms the rotational energy of the device into heat energy, ultimately bringing the device to a halt. These systems present various advantages over direct-contact braking systems, including enhanced efficiency, uniform braking force, and reduced replacement frequency.

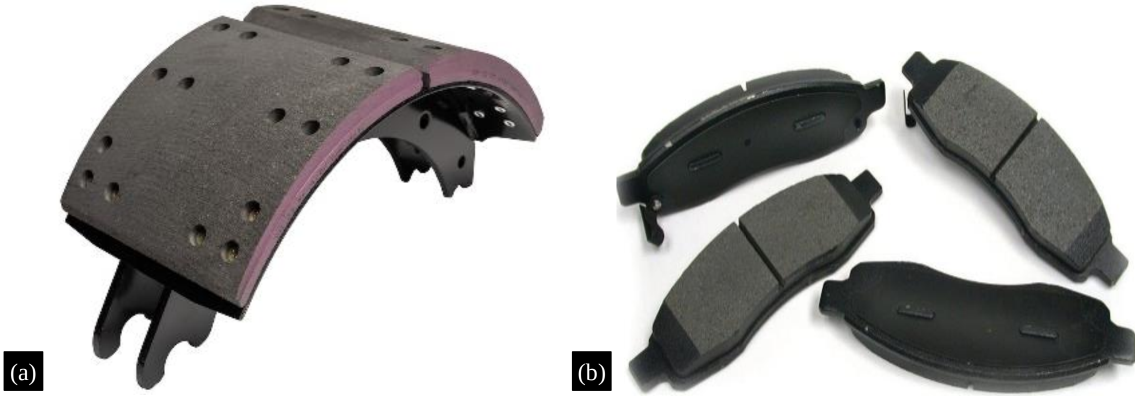

Figure 1. Difference between Liners and Pads. (a) Brake Liners with shoe, (b) Brake Pads.

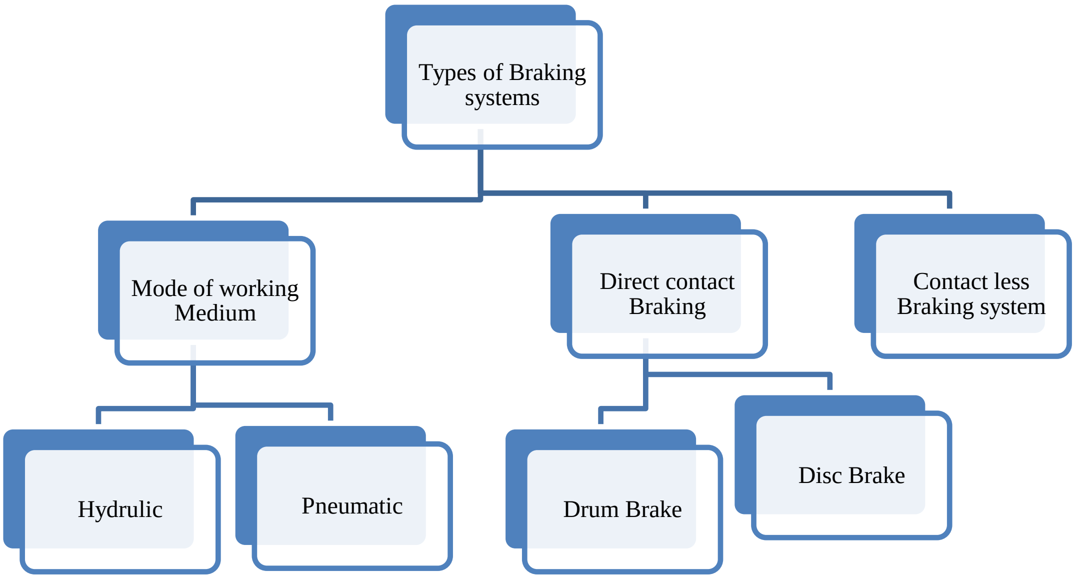

Figure 2. Types of the braking system.

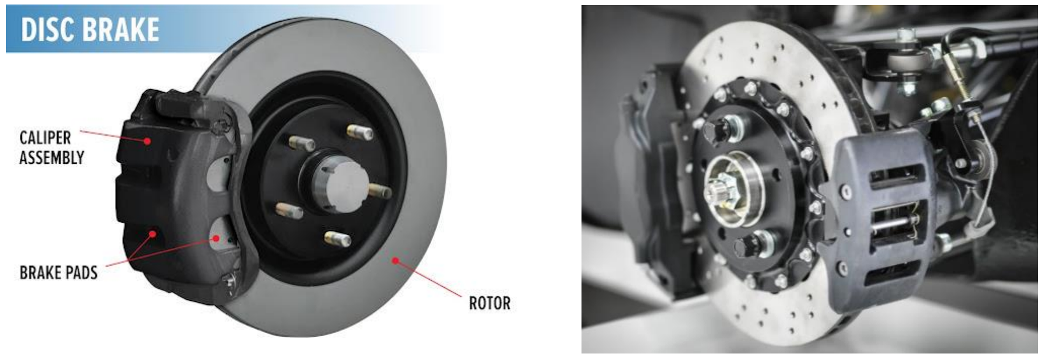

Figure 3. Assembly of Disc Brake Unit.

However, it's worth noting that contactless braking systems are not suitable for petroleum-fueled vehicles and may be susceptible to abrupt failure, potentially leading to accidents. On the other hand, direct-contact braking systems experience continuous wear of brake components like brake pads and discs/drums. Regularly replacing worn-out pads and discs/drums is crucial in minimizing the risk of sudden braking system failure. Adequate maintenance of brake system components is imperative to ensure their dependable operation, as this directly impacts vehicle safety [6]. Direct-contact braking systems depend on mechanical engagement, enhancing their dependability compared to contactless braking systems. Due to this and other contributing factors, the utilization of contactless braking systems is constrained. The initial brake lining material, developed by Herbert Frood in 1897, involved cotton soaked in a bitumen solution [7].

BRAKE FRICTION MATERIALS

Herbert Frood is renowned for his invention of the first brake lining materials in 1897, as documented by Nicholson in 1995. The Indian automotive market has witnessed the advent of high-speed capable vehicles, necessitating continuous technological advancements in brake systems to ensure public safety. Over the years, significant strides have been made in the development of superior brake friction products, thereby enhancing the effectiveness of braking systems. Additionally, there have been notable improvements in the technology and materials used for brake friction parts.

As a result of these advancements, the Indian aftermarket for brake friction products has flourished, offering a wide array of high-quality components and cutting-edge technology, thereby making them easily accessible to customers. Consequently, this has significantly contributed to improved vehicle safety. By utilizing top-notch brake friction products, drivers can ensure that their braking systems remain highly efficient and reliable, thereby elevating the overall driving experience.

To uphold the safety standards, it is imperative for customers to prioritize brake system maintenance, including regular inspections. This diligence ensures that the brakes remain in optimal working condition, allowing for a safer driving experience. As the Indian automotive market continues to progress, further advancements in brake technology and materials will play an instrumental role in enhancing overall vehicle safety.

DISC BRAKE

Elmer Ambrose Sperry, an American inventor and entrepreneur, introduced disc brakes in 1889. The design was later refined and patented by William Lanchester in 1902. However, it wasn't until the 1950s that disc brakes gained widespread popularity and became a standard feature in most passenger vehicles. This innovative braking system involves firmly attaching a metal or composite disc to the rotating wheel, while a brake pad made of frictional material is applied against it. Through the friction between the brake disc and pad, a force is generated that opposes the rotation, effectively slowing down the vehicle. This introduction of disc brakes marked a ground-breaking advancement in the field

Figure 4. Various materials used for fabrication brake materials.

of braking technology. As time progressed, in 1903, automotive companies Renault and Mercedes introduced drum brakes as a variation to the existing disc brake design. Drum brakes feature a hollow cylindrical drum, which is rigidly attached to the rotating wheel. Brake pads are applied against the inner circumference of the drum. Drum brakes come with several advantages over disc brakes, including increased contact area for friction materials, cost-effectiveness, and the requirement of less input force. The subsequent sections will delve into an in-depth examination of the various materials utilized over the years for both brake pads and brake discs/drums.

BRAKE FRICTION MATERIALS INGREDIENTS

A brake pad is an essential element within a vehicle's braking system, serving the critical purpose of converting kinetic energy into thermal energy through friction against the moving vehicle. This interaction occurs with the cast iron disc surface, and its complexity arises from the unique morphology of the contact plateaus. These plateaus play a significant role in determining the friction behavior of the surfaces as they engage. Various materials are commonly used to manufacture brake pads, including asbestos, SM material, NAOs, low-steel, and low-carbon materials. Among these, NAO stands out as a widely used material in automotive brake pads. Brake friction materials, typically located in brake pads and shoes, are crucial elements for ensuring effective braking performance. They encompass a heat-resistant binder, which may consist of synthetic or natural materials, that binds together friction-inducing components, including graphite, metallic powders (such as copper and iron), abrasive particles like aluminum oxide, fillers like clay or barite, reinforcing materials (commonly steel fibers), sensitizing agents, and heat transfer layers. These compositions vary according to their intended use, aiming to achieve an optimal balance between friction, wear resistance, heat tolerance, and noise reduction to guarantee the effectiveness and safety of braking systems. The composition of the brake pad material plays a pivotal role in its overall performance, durability, and noise levels during operation. Therefore, selecting the most appropriate material for the brake pad is of utmost importance to ensure the vehicle's safety and achieve optimal braking performance [8, 9]. Here are the properties of the brake pad components. [Figure 4] represents various materials used for fabrication for brake disc materials.

Reinforcing Fiber

Various reinforcing fibers, such as copper, brass, steel, carbon fiber, aramid fiber, and glass fiber, play a crucial role in enhancing the wear resistance and heat dissipation characteristics of the brake pad. As a result, the brake pads become highly efficient and durable. The selection and quantity of these reinforcing fibers are tailored to suit the particular application and specific demands of the brake pad.

Binder

The adhesive strength of the brake pad's components relies on a binder that is required to exhibit excellent thermal stability. For improved damping characteristics, a common approach involves incorporating phenolic resin along with rubber crumb.

Abrasive

Abrasives play a crucial role in controlling frictional properties and ensuring stability in braking situations. Some common examples of abrasives used for this purpose are zircon, zirconium oxide, and alumina.

Lubricants

Solid lubricants, including graphite and several metal sulphides, are utilized to maintain a stable coefficient of friction at high temperatures of the contacting surfaces.

Fillers

Brake pads often integrate fillers to improve their manufacturability and cost-effectiveness. Several types of fillers have been employed in the production process, including barite ($BaSO_4$), vermiculite, mineral silicates, and potassium titanate. These fillers serve the purpose of enhancing the overall performance of the brake pads while also contributing to cost reduction.

REINFORCING FIBER

Glass fiber

Glass fibers have been utilized as reinforcing fibers since the mid-1970s due to their physical strength and compatibility with resin bonding. These fibers are well-suited for reinforcing applications due to their thermal resilience [10]. Compared to typical glass, which has a melting point of 1430 °C, glass fibers exhibit a relatively low thermal conductivity of 0.04 W/m K. This conductivity value is even lower than that of asbestos, which is 0.15 W/m K [11], and significantly lower than that of metallic fibers.

Metallic Fiber

Reinforcing fibers like steel, brass, and copper, commonly referred to as metallic fibers, find widespread use in various applications. These fibers are typically utilized in the form of chips or granules to enhance the strength of materials. However, there is a significant drawback associated with the use of steel fibers-their susceptibility to rust, especially when exposed to extended periods of rest or moist environments. Rust formation on steel fibers leads to a decrease in their ability to withstand stress, which ultimately compromises their effectiveness as reinforcement. To overcome the problem of rusting, manufacturers have found a solution for brake pads. They incorporate metals such as zinc into the friction lining. This strategic arrangement creates a sacrificial anode, where the zinc becomes the primary site for rusting rather than the steel fibers. As a result, the steel fiber’s integrity and performance are preserved, ensuring better and longer-lasting reinforcement in brake pads and similar applications [12].

Aramid Fiber

Aramid fibers, such as Kevlar fibers, are commonly utilized as reinforcing fibers. Kevlar fibers are produced through condensation polymerization, where isophthalic or terephthalic acids and m-or p-phenylenediamine chemically combine by eliminating water molecules. The resulting polymer solution is spun into continuous fibers using a spinneret and solidified. These strong, heat-resistant Kevlar fibers find diverse applications in body armor, industrial materials, and aerospace components [13]. Aramid fibers are known for their lightweight nature and exceptional thermal stability. They possess an excellent stiffness-to-weight ratio, making them highly suitable for reinforcement applications. In terms of fade resistance, aramid fibers have been found to exhibit superior properties compared to asbestos, as highlighted by Smith and Boyd of R.K. Carbon Fibers [14].

Ceramic

In comparison to metallic fibers like steel, ceramic fibers are a relatively new raw material in friction products. These fibers are typically composed of different metal oxides, including alumina (aluminum oxide), carbides, and silicon carbide. Ceramic fibers are renowned for their high thermal resistance, boasting melting points that range from 1850 to 3000°C [15].

BINDERS

The primary role of a binder within a friction product is to uphold its structural integrity when subjected to mechanical and thermal stresses. Its crucial function lies in securely holding together the various components and preventing any potential separation or disintegration. The mentioned specific values pertain to typical characteristics associated with the particular binder. Selecting the appropriate binder for a friction product is of utmost importance. If the binder fails to maintain its structural integrity during braking, it can lead to the deterioration of other components, such as reinforcing fibers or lubricants. Hence, an excellent heat resistance is imperative for the binder to endure the high temperatures generated during braking. Silicone and epoxy modified resins are widely considered as ideal binders for most braking applications due to their superior heat resistance properties. It is essential to acknowledge that there might be other binders suitable for specific applications, as long as their limitations do not compromise their effectiveness. Precise selection of the binder is essential to align with the distinct needs and expectations of individual applications. Careful tailoring ensures that the binder chosen is a perfect match for the specific requirements of each unique use case. [16].

Phenolic Resin

Phenolic resin is widely favored as the primary resin binder in brake friction materials. This unique polymer is created through a condensation reaction involving phenol and formaldehyde, resulting in an efficient matrix that effectively binds different substrates together. Depending on whether acidic or alkali catalysts are used, the condensation reaction gives rise to different classes of phenolic resins. Once cured, these resins undergo a transformation from a thermoplastic state to a tightly compacted, cross-linked thermoset matrix, providing remarkable heat resistance [17].

FILLERS

Fillers play a crucial role in friction products, offering various benefits like improved manufacturability and cost reduction for brake pads. These fillers encompass a wide range of substances used in significant proportions within the friction material. While not as critical as reinforcing fibers and other components, fillers still hold vital importance in tailoring specific properties of friction products. The selection of fillers depends on the composition of the friction material and the desired outcome. For example, when dealing with metallic brake pads that are notorious for producing braking noise, the addition of fillers like cashew and mica becomes essential as they act as noise suppressors. On the other hand, for semi-metallic brake pads that blend metallic and organic compounds with differing thermal expansion coefficients, a substantial amount of molybdenum trioxide might be necessary to prevent lining cracking. The choice of fillers varies based on the constituents and characteristics of the friction material. For instance, brake products containing ample quantities of graphite or antimony sulfide as lubricants might not require the use of alkali metals as fillers. Each type of filler serves a specific purpose and contributes to the overall performance of the friction product, demonstrating the importance of thoughtful filler selection in friction material formulation [18].

Inorganic Fillers

Barium sulfate is a widely used filler in friction products due to its ability to enhance heat stability while also contributing to the friction characteristics of the material. Calcium carbonate is considered an alternative to barium sulfate as it shares similar functional properties, providing heat stability to the friction material and improving brake fade properties. While calcium carbonate is a more economical option, it is less stable at higher temperatures compared to barium sulfate [18, 19].

Organic Fillers

Organic fillers such as cashew dust and rubber dust are commonly employed in friction products due to their advantageous viscoelastic properties, primarily aimed at reducing brake noises [20]. Cashew particles, however, have a tendency to detach from the friction surface, resulting in the formation of larger pores that may eventually lead to cracking [21].

FRICTIONAL ADDITIVES

Frictional additives play a crucial role in friction product materials as they help in fine-tuning the friction coefficients and wear rates. These additives can be categorized into two main types:

lubricants, which are responsible for lowering friction coefficients and minimizing wear rates, and abrasives, which enhance friction coefficients and wear rates. It is important to note that in certain cases, when certain frictional additives are present in higher quantities, they may also be regarded as fillers by some manufacturers [16].

Lubricants

Graphite plays a significant role in brake friction materials because of its rapid formation of a lubricating layer on the opposing counter friction material. This property makes graphite a widely used component in such materials, contributing to their effective performance in braking systems. Graphite used in these materials can be sourced from natural or synthetic origins and can be found in flake or powder form. Flake graphite offers enhanced lubrication properties [22], while powder graphite effectively dissipates heat generated during braking However, it is important to note that the bonding strength between graphite and phenolic resin is relatively weak, restricting the excessive use of graphite in phenolic resins and resulting in lower shear strengths [23].

Abrasives

The presence of abrasives in friction product materials serves to increase the friction coefficient while also accelerating the wear rate of the counter face material. These abrasives effectively remove iron oxides and undesirable surface film layers that form during the braking process. However, it is important to note that friction materials with higher abrasive content may exhibit a greater variation in friction coefficient, leading to instability in braking torque. Abrasives are composed of hard particles consisting of metal oxides and silicates. These particles need to possess sufficient hardness to effectively abrade the counter friction material, such as cast iron. Typically, abrasives have Mohs hardness values ranging from 7 to 8. Some commonly used examples of abrasives include zirconium oxide, zirconium silicate, aluminum oxide, and chromium oxide [24].

MATERIALS USED FOR BRAKE DISC/DRUM

The brake disc/drum plays a critical role in the braking system, as approximately 70% of brake wear initiates from this component. It is essential for the brake disc/drum material to possess several key characteristics, including high strength, wear resistance, thermal conductivity, low thermal expansion, and thermal stability. Modern composites utilized in the manufacturing of brake discs and drums include various materials such as carbon composites, carbon-ceramic composites, and other advanced metal alloys. [Figure 5] Displayed below is Brake Drum used in Heavy Automobiles and Machinery. These materials offer improved performance, reduced weight, and enhanced heat resistance, contributing to more efficient and durable braking systems in contemporary vehicles. According to data from Science Direct, cast iron and steel remain the most commonly used materials, accounting for approximately 70% of brake disc/drum production. However, there is an increasing trend in the use of ceramic-based, Carbon Composite and aluminum-based materials for manufacturing brake discs/drums [25]. [Figure 6] is a Brake Disc used in Commercial Vehicle's and Especially in Sports Cars for More Breaking Efficiency.

Figure 5. Brake Drum.

Figure 6. Brake Disc.

CAST IRON

Gray cast iron was the initial choice for manufacturing brake discs/drums, and remarkably, it remains one of the most preferred materials even after several centuries [26]. Although numerous alternative materials have been developed over the past 100–120 years to replace cast iron in brake discs, cast iron continues to dominate the market [27]. This preference for cast iron can be attributed to its advantages, including low cost, low wear rate, reduced noise, consistent friction coefficient, high thermal conductivity, long lifespan, and satisfactory corrosion resistance [28]. It's important to highlight that, despite its relatively modest inherent strength, high-carbon gray iron alloyed with molybdenum and niobium is the chosen material for brake discs in heavy trucks and passenger cars The use of high-carbon gray iron as a base material offers good wear resistance and superior heat dissipation capabilities. This is crucial for brake discs, as they endure significant friction and heat during braking. The high carbon content in the iron aids in effectively absorbing and dispersing heat, preventing overheating and ensuring consistent braking performance. The addition of molybdenum and niobium to the alloy further enhances the material's mechanical properties, such as strength and durability. These alloying elements contribute to the ability of the brake discs to withstand the substantial stresses and demands placed upon them in heavy trucks and passenger cars. In summary, while high-carbon gray iron alloyed with molybdenum and niobium may not be the strongest material in isolation, its combination of properties makes it an excellent choice for brake discs in heavy vehicles, ensuring reliable and efficient braking performance under demanding conditions. [29]. However, there is a potential alternative to gray iron known as compact graphite iron (CGI), which is being employed as a brake disc material in European railroads [30]. CGI shows promise as a superior alternative to gray iron in the manufacturing of brake discs.

The high density of cast iron, which is commonly used in brake discs and drums, poses a significant challenge. The weight of the unsprung mass in the brake assembly is substantially increased due to this high density. As a result, the dynamics of braking are heavily influenced by the unsprung mass, leading to poor brake dynamics [31]. This issue has prompted researchers to focus on developing lightweight materials for brake discs/drums right from the start in order to enhance brake dynamics. Another drawback associated with gray cast iron discs is the reduction in the coefficient of friction when operating under wet conditions [32]. This reduction in friction can potentially contribute to accidents. Therefore, there is a need to develop a braking material that can perform effectively in both dry and wet conditions, ensuring reliable braking performance in all scenarios.

STEEL

Steel is a widely utilized material for brake discs and drums due to its remarkable properties, as highlighted in various studies [33]. The material's unique blend of qualities, including exceptional strength, corrosion resistance, thermal stability, and remarkable wear resistance, renders it perfect for rigorous applications like aircraft, trains, and trucks. Its robust structural strength enables it to withstand heavy loads and extreme stresses, crucial in aerospace and transportation. Moreover, its resistance to corrosion ensures longevity amid various conditions, while thermal stability and wear resistance make it ideal for components subjected to high temperatures and friction. These attributes collectively establish it as the preferred choice for demanding, heavy-duty applications where durability, safety, and performance are of utmost importance. [34]. Researchers have investigated the occurrence of hot spots in forged steel, specifically the 28CrMoV5-08 steel used in railway brake discs [35]. Thermal distortion resulting from frictional heat is believed to be the primary cause of hot spot formation. Therefore, it is crucial for the brake disc material to possess high thermal resistance to prevent brake failure. The study was analyzed the wear characteristics when a sintered metal matrix composite brake pad interacts with the 28CrMoV5-08 forged steel brake disc, commonly employed in railway applications.

Sintered Metal Matrix Composite Brake Pad: This specialized brake pad, used in railway systems, is crafted via sintering, a process involving compacting and heating metal particles into a solid piece.

The study aims to comprehend how this composite brake pad endures wear and tear during its operational lifespan.

28CrMoV5-08 Forged Steel Brake Disc: A crucial component in railway braking, this brake disc is constructed from 28CrMoV5-08 forged steel, produced through a heating and shaping process. The research evaluates how this specific brake disc fares when exposed to the associated brake pad.

Their findings revealed the formation of a third body during the braking process, which acts as a barrier between the brake disc and drum. Consequently, the wear behavior is primarily influenced by the properties of this third body. Overall, steel demonstrates its suitability as a brake disc material through its strength, corrosion resistance, thermal stability, and wear resistance, making it an ideal choice for demanding applications. Researchers continue to explore and analyze various aspects related to steel brake discs to enhance their performance and reliability [36].

CARBON-BASED MATERIALS

Carbon-based materials are widely utilized for manufacturing brake discs, known for their exceptional properties [37]. These materials exhibit high thermal resistance and wear resistance, making them particularly suitable for applications in aircraft and racing cars [38]. The carbon-carbon brake systems can provide satisfactory performance for twice the number of aircraft landings compared to steel brake systems [39]. Carbon-carbon brake discs are renowned for their exceptional properties, one of which is their low coefficient of friction when operating at temperatures below 400°C to 500°C. This property is significant because it allows for efficient and controlled braking in a variety of applications. To further improve the coefficient of friction and wear resistance in specific conditions, such as high-performance or extreme braking scenarios, reinforcements like silicon carbide (SiC) are introduced into the carbon matrix. This innovative approach results in the creation of C-C/SiC brake discs. These composite brake discs offer superior properties compared to traditional carbon-carbon discs and find extensive use in the production of brake discs for high-speed trains and racing cars.

Low Coefficient of Friction: Carbon-carbon brake discs have a unique characteristic of providing low friction levels at temperatures below 400°C to 500°C. This makes them ideal for applications where controlled and gradual braking is required, such as in most typical driving conditions. The low coefficient of friction prevents abrupt stops and provides smooth, consistent braking.

Reinforcements with SiC: In certain situations where higher friction and enhanced wear resistance are necessary, carbon-carbon brake discs are reinforced with silicon carbide (SiC) particles. Silicon carbide is known for its exceptional hardness and resistance to wear and heat. By incorporating SiC into the carbon matrix, the resulting C-C/SiC composite material benefits from SiC's properties.

C-C/SiC Brake Discs: The introduction of SiC into the carbon matrix transforms the material into C-C/SiC brake discs. These discs offer improved friction characteristics, making them suitable for high-performance applications such as racing cars, aircraft, or heavy machinery. The SiC particles enhance wear resistance, reduce heat buildup, and increase the coefficient of friction, allowing for more effective and reliable braking at elevated temperatures.

The carbon-carbon brake discs possess a low coefficient of friction at moderate temperatures, making them ideal for standard braking requirements. However, for applications demanding higher friction and improved wear resistance, the addition of silicon carbide (SiC) reinforcement results in the development of C-C/SiC brake discs, which are well-suited for high-performance or demanding conditions where efficient braking is crucial. The remarkable thermal resistance and wear resistance of carbon-based materials contribute to their popularity in brake disc applications. Ongoing research and advancements continue to refine and expand the capabilities of carbon-based brake systems, ensuring their effectiveness and reliability in demanding environments [40].

The detailed explanation of the comparative study conducted to evaluate the thermal and wear behavior of C-C/SiC (carbon-carbon/silicon carbide) brake discs and gray cast iron brake discs against a Metal Matrix Composite (MMC) brake pad is as follows:

Comparative Study Objective: The study aimed to assess and compare the performance of two different types of brake discs, C-C/SiC and gray cast iron, when paired with a Metal Matrix Composite (MMC) brake pad. The key performance aspects under scrutiny were thermal behavior, wear characteristics, and friction coefficient. These factors are crucial for understanding how the braking system functions and determining which materials provide the best overall performance.

Thermal Behavior: One important finding of the study was related to the thermal behavior of the brake systems. When using a carbon-based C-C/SiC disc in conjunction with the MMC brake pad, the system generated significantly higher levels of heat compared to the system employing a gray cast iron disc. This indicates that the C-C/SiC-based brake system has a greater capacity to absorb and dissipate heat, which can be advantageous in high-performance or demanding braking scenarios. The ability to manage heat effectively helps prevent issues like brake fade and ensures consistent performance.

Wear Characteristics: The study also examined wear characteristics. However, the provided information does not specify the results regarding wear behavior for the two types of brake discs and the MMC brake pad. Typically, wear resistance is a critical aspect to consider, as it affects the longevity and durability of the braking system.

Friction Coefficient: The study did provide important insights into the friction coefficient. It revealed that the C-C/SiC-based brake system exhibited a higher and more consistent friction coefficient compared to the system with the gray cast iron disc. This finding indicates that the C-C/SiC-based braking system offers more reliable and effective braking, ensuring consistent stopping power. The friction coefficient is crucial for safety and performance, and the higher and consistent values suggest better control and predictability during braking.

In the comparative study demonstrated that the braking system using C-C/SiC brake discs in combination with an MMC brake pad exhibited superior thermal behavior, generating higher heat levels but effectively managing it. Additionally, it demonstrated a higher and more consistent friction coefficient, suggesting better braking performance and control. These findings are valuable for selecting suitable materials for various braking applications, considering factors like heat management and friction characteristics [41].

ALUMINIUM BASED MATERIALS

To enhance brake dynamics, there is a rising interest in the advancement of low-density brake disc materials utilizing aluminum alloys, in contrast to the higher density materials like cast iron or steel [42]. A recent investigation focused on the utilization of two specific aluminum alloys, namely Duralcan (AS10G) and hyper-eutectic alloy (AS18UNG), for the production of a brake disc. To improve wear resistance, the study incorporated SiC as a reinforcing element [43]. Additionally, the researchers examined the impact of post-processing techniques, such as annealing and aging, on the wear properties of the manufactured composites. Encouraging results were obtained from these experiments, pointing towards the potential development of aluminum-based brake discs and brake drums.

A study was carried out to investigate the influence of incorporating metal fiber reinforcement into a non-asbestos organic brake pad on the wear properties of both cast-iron and aluminum-based brake discs. The research aimed to assess the performance of these brake pads with metal fiber reinforcement and understand their effects on the wear behavior of two different types of brake discs: cast-iron and aluminum. This study provided valuable insights into the potential improvements in wear resistance and overall braking performance, offering valuable information for brake system design and material selection in the automotive industry [44]. Aluminum-based discs were produced by incorporating 20% SiC into A356 aluminum alloy. The wear trends observed in the aluminum-based discs were found to be similar to those of cast-iron discs. The aluminum-based discs exhibited maximum high-temperature fade resistance when combined with copper-fiber reinforced brake pads. In another investigation brake discs made of aluminum matrix composites reinforced with 13% SiC/B4C were utilized [45]. The research focused on the wear characteristics of these custom-made brake discs, which were analyzed alongside phenolic resin-based brake pads. During the study, a noteworthy phenomenon was observed: the development of a well-formed transfer layer between the composite brake discs and the phenolic brake pads. This transfer layer played a crucial role in diminishing the wear rates of the braking components. The formation of this compact transfer layer acted as a protective barrier, mitigating the direct friction and wear between the brake discs and pads. By serving as a sacrificial surface, the transfer layer absorbed some of the wear and tear, effectively reducing the overall wear rates of the braking system. This phenomenon can have significant implications for the automotive industry, as it offers a potential avenue for extending the lifespan and enhancing the efficiency of brake components. The study's findings shed light on a promising approach to optimize braking systems by harnessing the protective qualities of transfer layers. Furthermore, developed aluminum matrix composites reinforced with varying amounts of SiC with the aim of replacing cast iron in brake discs [46]. The study examined how aluminum matrix brake discs performed when paired with polymer matrix composite brake pads, focusing on their wear behavior. During this investigation, the interaction between the brake pad and the disc resulted in the creation of a tribo-layer, and this layer had a notable impact on the wear characteristics of the braking components. The study was conducted to understand how aluminum matrix brake discs perform in terms of wear when paired with polymer matrix composite brake pads. Wear behavior is a critical factor in the assessment of braking systems, as it directly impacts the longevity and effectiveness of the components.

Interaction and Tribo-Layer Formation: During the study, researchers observed the interaction between the brake pad and the brake disc. This interaction resulted in the formation of a layer known as a tribo-layer. Tribo-layers are created when two materials come into contact and undergo friction and wear. In this case, the tribo-layer was formed due to the contact and friction between the polymer matrix composite brake pad and the aluminum matrix brake disc.

The study highlighted that the formation of the tribo-layer had a significant impact on the wear behavior of the braking system. This influence could manifest in several ways

Wear Rate: The tribo-layer might affect the rate at which the brake pad and disc wear down during use.

Friction Coefficient: The presence of the tribo-layer can influence the friction coefficient, which, in turn, affects the braking performance and efficiency.

Wear Pattern: The tribo-layer can also impact the wear pattern on the brake disc's surface, which can provide insights into the overall performance and durability of the system [47]. These studies contribute to the understanding of the wear characteristics and performance of aluminum-based brake discs in combination with different brake pad materials. The thermal expansion of aluminum brake drums was found to be higher when using a non-asbestos brake liner, likely due to increased heat generation. The statement mentions two key findings related to brake systems, specifically the influence of using a non-asbestos organic brake liner and a comparative study investigating the tribological behavior of three brake disc materials in trucks.

Steady-State Temperature with Non-Asbestos Organic Brake Liner: One observation note that when a non-asbestos organic brake liner is used in a brake system, it results in a lower steady-state temperature. The steady-state temperature is the equilibrium temperature reached during continuous or prolonged braking. This finding is noteworthy because it indicates that the non-asbestos organic brake liner may have specific qualities that contribute to improved heat dissipation and thermal management within the brake system. Lower temperatures are generally desirable because excessive heat can lead to brake fade, reduced performance, and even damage to brake components. Therefore, a lower steady-state temperature is a positive outcome for brake system efficiency and longevity.

Comparative Study on Brake Disc Materials

The second part of the statement highlights a comparative study that investigated the tribological behavior of three different brake disc materials: cast iron, steel, and aluminum alloy. Tribology is the science and engineering of interacting surfaces in relative motion, which includes the study of friction, wear, and lubrication. In the context of brake systems, it's crucial to understand how different brake disc materials perform in terms of friction, wear, and heat generation. The study examined these materials in the context of their use in trucks, which are typically subjected to heavy loads and demanding operating conditions. The goal of this comparative analysis was likely to determine which of the three materials offers the best balance of performance characteristics, including efficient braking, durability, and resistance to wear and heat. This information is essential for selecting the most suitable brake disc material for heavy-duty truck applications to ensure safety and reliability. The study revealed that aluminum alloy brake discs exhibited minimal deformation and the lowest maximum temperature rise. This suggests that aluminum alloy can potentially replace cast iron as a material for truck brake discs, resulting in a substantial reduction of approximately 58% in brake disc weight [48].

CERAMIC-BASED MATERIALS

A composite material composed of a porous ceramic mixture (56%) and aluminum alloy (44%) as a potential substitute for cast iron in brake rotors [49]. The wear behaviour of this composite brake rotor was evaluated against phenolic resin brakes, revealing higher wear rates and friction coefficients compared to cast iron rotors. The SiC brake discs or ceramic brake discs outperformed carbon-fibre composite brake discs in military helicopter and heavy-duty applications due to their lower wear rates and minimal spark generation [50]. The tribological behavior of two ceramic brake discs made of C/SiC/Si material. These discs had different compositions, with one containing 53.1% SiC/Si and the other containing 17.7% SiC/Si. The investigation was carried out under specific conditions involving water spray.

Ceramic Brake Disc Material (C/SiC/Si):

C/SiC/Si stands for Carbon/Silicon Carbide/Silicon, and it is a composite material used for brake discs. These materials are known for their high-temperature stability, wear resistance, and lightweight properties. The two brake discs under investigation had different compositions. One had a higher proportion of SiC/Si (53.1%), while the other had a lower content (17.7%). This difference in composition likely impacts their tribological behavior

Tribological Behaviour

Tribological behavior relates to how materials interact when in relative motion, encompassing aspects like friction, wear, and lubrication and in the context of brake discs, tribological behavior is crucial as it affects the braking system's efficiency, durability, and safety

Water-Spray Conditions

The study involved testing the tribological behavior of these ceramic brake discs under water-spray conditions. This implies that the discs were subjected to conditions where water was sprayed onto them and testing under such conditions is valuable because it simulates scenarios where the brake discs may be exposed to wet or rainy conditions during vehicle operation **[**51].

Ceramic brake discs containing 53.1% SiC/Si displayed a notably higher coefficient of friction, measuring at 0.5, which indicates their suitability for efficient performance in damp or wet conditions. Additionally, this statement introduces the topic of a review focusing on materials employed in railway applications for both brake discs and brake pads [52]. The statement highlights the choice of disc brake materials based on train speeds and underscores the shift towards ceramic materials in the context of high-speed train development. Here's an in-depth explanation:

Disc Brake Materials for Different Train Speeds: The statement differentiates between two categories of disc brake materials, primarily based on train speeds:

Low-Speed Trains (Below 200 km/h): For low-speed trains, such as those traveling at speeds below 200 km/h, cast iron and aluminum alloy-based disc brakes are found to be suitable. These materials are effective at these lower speeds and are commonly employed in such train applications. The choice of these materials may be due to their cost-effectiveness, reliability, and satisfactory performance under moderate braking demands.

High-Speed Trains (Above 400 km/h): In contrast, high-speed trains, which typically operate at speeds above 400 km/h, employ ceramic and steel brake discs. These materials offer high thermal and wear resistance, making them crucial for braking systems in high-speed train applications. The emphasis on these properties is due to the intense demands placed on brakes at high speeds, as efficient braking and safety are paramount.

Focus on High-Speed Train Development: The statement acknowledges that many countries are directing their efforts towards developing high-speed trains and vehicles. The central objective behind this emphasis is to reduce travel time significantly. High-speed transportation is an appealing concept for its potential to make travel faster, more efficient, and attractive to commuters and travelers.

Ceramic Materials as the Future for Braking Systems: The statement concludes by suggesting that ceramic materials are considered the future for braking systems. This signifies a growing trend in the transportation industry towards the utilization of ceramics, especially in high-speed train systems. The choice of ceramic materials is primarily attributed to their exceptional thermal and wear resistance properties.

High Thermal Resistance: Ceramics can withstand high temperatures generated during braking, ensuring consistent and reliable performance.

High Wear Resistance: They are less prone to wear and offer durability, making them suitable for high-speed and heavy braking applications.

The transition to ceramic materials in braking systems aligns with the ongoing development of high-speed transportation to enhance efficiency and reduce travel times, emphasizing the importance of selecting materials that can meet the specific demands of different train speeds.

The tribological properties of SiC/Al ceramic brake discs in combination with C/SiC brake pads used in high-speed trains [53]. The study's outcome establishes the suitability of the SiC/Al-C/SiC tribo-couple for use in high-speed train emergency braking systems. This particular material combination, consisting of Silicon Carbide (SiC), Aluminum Carbide (Al-C), and Silicon Carbide (SiC), exhibits properties and performance characteristics that render it well-suited for the critical function of emergency braking. High-speed trains, which operate at significantly elevated speeds, demand reliable and efficient braking mechanisms, especially in emergency situations where swift and forceful stops are essential. The study's conclusion underscores the significance of selecting appropriate materials for these braking systems, ensuring the safety and effectiveness of emergency stops in high-speed rail applications, a critical aspect of passenger and crew well-being.

METAL MATRIX COMPOSITE BRAKE PADS

Due to health concerns, asbestos-based materials are being phased out, and non-asbestos organic pads have limited thermal resistance. As a result, Metal Matrix Composite (MMC) brake pads are being developed for heavy-duty applications [54]. An aluminum matrix composite brake pad reinforced with boron carbide (Al/B4C) [55]. The study demonstrated that Al/B4C exhibited high wear resistance and did not experience fading behavior at high temperatures. In a comprehensive research study, the performance of Metal Matrix Composite (MMC) brake pads was evaluated by subjecting them to wear tests involving two different brake disc materials: conventional Gray cast iron and advanced C-C/SiC (Carbon-Carbon/Silicon Carbide). The research aimed to gain insights into how these MMC brake pads interact with various disc materials, shedding light on their wear behavior, friction characteristics, and compatibility in diverse braking conditions. This investigation holds the potential to inform the selection of optimal brake pad and disc material combinations for specific applications, contributing to the design of efficient and reliable braking systems tailored to varying vehicle types and operational demands [56].

The temperature rise was significant when using the MMC pad with the C-C/SiC brake disc; however, the coefficient of friction remained high and consistent. Thus, the MMC brake pad can be a suitable alternative to the C-C/SiC brake pad when used with C-C/SiC brake discs. The impact of SiC and graphite additions on the wear behavior of metal matrix composite brake pads against C-C/SiC brake discs [57, 58]. The research findings indicated that the SiC-reinforced Metal Matrix Composite (MMC) brake pad displayed a notably low coefficient of friction. This quality implies that the brake pad produces minimal resistance during contact with the braking surface, potentially contributing to smoother and more effective braking performance. This observation highlights the brake pad's potential for enhancing the efficiency and control of braking systems, making it a valuable consideration for various applications. Interestingly, the coefficient of friction increased with the addition of graphite, despite graphite's solid lubricant properties. Thermal stresses generated during the braking process in a system employing a metal-ceramic brake pad and a cast-iron disc exemplify the impact of heat buildup and its influence on the mechanical components [59]. The study's results exposed the correlation between the considerable heat produced during braking and the consequential thermal stress encountered by the brake components. Additionally, the research delved into the tribological behavior, or the surface interactions, of a sintered metal matrix composite brake pad when utilized in conjunction with a forged steel brake disc. Such investigations are crucial for gaining insights into the functionality and longevity of braking systems, as they provide a deeper understanding of how these components react to the thermal and frictional forces generated in the braking process. [60]. They observed that the formation of a third body layer significantly influenced the wear behavior. The wear behavior of an aluminum matrix composite brake drum against a copper matrix composite brake pad reinforced with graphite [61]. The incorporation of copper in brake pad applications offers significant benefits, primarily attributed to its remarkable thermal conductivity. Copper's ability to efficiently dissipate heat generated during braking leads to a notable reduction in temperature rise within the brake system. Additionally, in these brake pad applications, an aluminum matrix composite reinforced with SiC (Silicon Carbide) is employed, further enhancing the thermal characteristics and performance of the braking components [62]. This study focused on understanding how the weight fraction of SiC (Silicon Carbide) influences the wear behavior of brake pads composed of an aluminum matrix with SiC reinforcement, known as Al/SiC brake pads. The researchers sought to determine the optimal balance between aluminum and SiC content in these composite brake pads to minimize wear rates, a critical factor in brake pad performance. Through a series of experiments and analyses, it was discovered that when the Al matrix composite contained 10% SiC, the wear rate reached its lowest point. This implies that a specific weight fraction of SiC, in this case, 10%, provides the ideal blend of material properties, offering effective wear resistance without compromising other aspects of brake pad performance. These findings have practical implications for the design and manufacturing of brake pads, allowing for the optimization of their composition to enhance durability and performance in braking systems.

CONCLUSIONS

Due to its cancer-causing properties, the utilization of asbestos in friction components such as brake pads and linings has been prohibited. Hence, researchers are now channelling their research efforts into the development of asbestos-free materials as substitutes for conventional brake components, aiming to ensure both effective braking performance and safety by eliminating the health risks associated with asbestos usage. A commonly employed substitute is non-asbestos organic (NAO) materials, but their thermal stability is somewhat limited, making them suitable primarily for light-duty vehicles. On the other hand, for applications in railways and airplanes, where higher thermal stability is required, Metal Matrix Composites (MMCs) or ceramic brake pads prove to be more effective. With the global emphasis on high-speed train development, there is now a growing demand for ceramic or MMC brake pads.

Traditionally, brake discs and drums are manufactured using high-density cast iron or steel. Nonetheless, the weight of this unsprung rotating mass has a detrimental impact on the dynamics of the braking system. To tackle this issue, aluminum matrix composites (AMCs) are being considered as a promising material for brake discs and drums due to their lightweight nature, high strength, and exceptional wear resistance. The implementation of AMCs in these components effectively reduces the overall weight of the braking system, thereby leading to improved brake dynamics.

REFERENCES

1. S. Venkatesh et.al, Scoping Review of Brake Friction Material for Automotive, Materials Today: Proceedings,2019, (16), 927–933.
2. Blau PJ, Meyer III HM. Case Study: Characteristics of wear particles produced during friction tests of conventional and unconventional disc brake materials. Wear. 2003;255(7-12): 1261–1269.
3. Gowthami et.al, Designing and Analysis of Brake Drum. International Journal for Research in Applied Science & Engineering Technology. 2016;4(9): 135–142.
4. Chandgude et.al, Review on development of composite material for disc brake pad [JETIR]. J Emerg Technol Innov Res. 2016;3(5):63–5
5. Rao RU, Babji G. A Review paper on alternate materials for Asbestos brake pads and its characterization. International Research Journal of Engineering and Technology. 2015;2(2): 556–562.
6. Lee K, Park K. Optimal robust control of a contactless brake system using an eddy current. Mechatronics. 1999;9(6): 615–631.
7. Maluf O et.al, Development of materials for automotive disc brakes. Minerva. 2007;4(2): 149–158.
8. Santhosh Kumar, Subrata Kumar Ghosh, Particle emission of organic brake pad material: A review, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 2019; (234):1213–1223
9. Eriksson M and Jacobson S. Tribological surfaces of organic brake pads. Tribol Int 2000; 33: 817–882
10. Marzocchi, A., Jannarelli, A. E. and Garrett, D. W. Friction materials for brake linings and the like. US Pat. 3967037, 1976 (United States Patent and Trademark Office).
11. Holman, J. P. Heat Transfer, 8th edition, pp. 641–642 (McGraw-Hill, Singapore).
12. Hell, M., Jaworek, W., Huppatz, W. and Wieser, D. Friction lining, especially for brakes and clutches, and a method for producing a friction lining. US Pat. 6481555, 2002 (United States Patent and Trademark Office).
13. Okubo, H. S., Albertson, C. E. and Nibert, R. K. Asbestos-free friction materials. US Pat. 4446203, 1984 (United States Patent and Trademark Office).

14. Smith, W. N. and Boyd, P. Carbonaceous friction materials. US Pat. 5965658, 1999 (United States Patent and Trademark Office).
15. Warren, R. Ceramic-Matrix Composites, 1992, p. 2 (Blackie, New York).
16. D.Chan and G W Stachowiak Review of automotive brake friction materials Proc. Instn Mech. Engrs Vol. 218,p 953–965.
17. Critchley, J. P., Knight, G. J. and Wright, W. W. Heat-Resistant Polymers, 1983, pp. 21–29 (Plenum Press, New York)
18. Komori, T., Miyake, S. and Senoo, Y. Brake friction material. US Pat. 4954536, 1990 (United States Patent and Trademark Office).
19. Ohya, K. and Kimbara, H. Disc brake pad. US Pat. 4944373, 1990 (United States Patent and Trademark Office).
20. Kamioka, N., Tokumura, H. and Yoshino, T. Friction material containing BT resin dust. US Pat. 5384344, 1995 (United States Patent and Trademark Office).
21. Kinouchi, S., Hara, Y. and Yamaguchi, J. Friction material composition, production of the same and friction material. US Pat. 6372817, 2002 (United States Patent and Trademark Office).
22. The exfoliation of vermiculite. Report 23, Western Australian Mining and Petroleum Research Institute, 1989
23. Komori, T., Miyake, S. and Senoo, Y. Brake friction material. US Pat. 4954536, 1990 (United States Patent and Trademark Office)
24. Kobayashi, M. Non-asbestos friction materials. US Pat. 6413622, 2002 (United States Patent and Trademark Office).
25. Hulskotte JHJ, Roskam GD, Denier van der Gona HAC. Elemental composition of current automotive braking materials and derived air emission factors. Atmospheric Environment. 2014;99: 436–445.
26. Maluf O, Angeloni M, Milan MT, Spinelli D, Filho WWB. Development of materials for automotive disc brakes. Minerva. 2007;4(2): 149–158.
27. Belhocine A, Bouchetara M. Temperature and Thermal Stresses of Vehicles Gray Cast Brake. Journal of Applied Research and Technology. 2013;11: 674–682.
28. Lyu Y, Olofsson U. On black carbon emission from automotive disc brakes. Journal of Aerosol Science. 2020;148: 105610.
29. Mackin TJ. Thermal Cracking in Disc Brakes. Engineering failure Analysis. 2002;9: 63–76.
30. Cueva G, Sinatora A, Guesser WL, Tschiptschin AP. Case Study: Wear resistance of cast irons used in brake disc rotors. Wear. 2003;255: 1256–1260.
31. Natarajan N, Vijayarangan S, Rajendran I. Fabrication, testing and thermal analysis of metal matrix composite brake drum. Int J Vehicle Design. 2007;44: 339–359. 810 Naveen Kumar, Ajaya Bharti, H.S. Goyal, Kunvar Kant Patel
32. Blau PJ, McLaughlin JC. Effects of water films and sliding speed on the frictional behavior of truck disc brake materials. Tribology International. 2003;36: 709–715.
33. Blanco C, Bermejo J, Marsh H, Menendez R. Chemical and physical properties of carbon as related to brake performance. Wear. 1997;213: 1–12.
34. Xiao Y, Zhang Z, Yao P, Fan K, Zhou H, Gong T, Zhao L, Deng M. Mechanical and tribological behaviors of copper metal matrix composites for brake pads used in high-speed trains. Tribology International. 2018;119: 585–592.
35. Panier S, Dufrénoy P, Weichert D. An experimental investigation of hot spots in railway disc brakes. Wear. 2004;256: 7764–7773.
36. Desplanques Y, Roussette O, Degallaix G, Copin R, Berthier Y. Analysis of tribological behaviour of pad–disc contact in railway braking Part 1. Laboratory test development, compromises between actual and simulated tribological triplets. Wear. 2007;262: 582–591.
37. Ma X, Fan S, Sun H, Luan C, Deng J, Zhang L, Cheng L. Investigation on braking performance and wear mechanism of full-carbon/ceramic braking pairs. Tribology International. 2020;142: 105981.

38. Tayeb NSME, Liew KW. Effect of water spray on friction and wear behaviour of noncommercial and commercial brake pad materials. Journal of Materials Processing Technology. 2008;208: 135–144.
39. Blanco C, Bermejo J, Marsh H, Menendez R. Chemical and physical properties of carbon as related to brake performance. Wear. 1997;213: 1–12.
40. Stadler Z, Krnel K, Kosmac T. Friction and wear of sintered metallic brake linings on a C/C-SiC composite brake disc. Wear. 2008;265: 278–285.
41. Blanco C, Bermejo J, Marsh H, Menendez R. Chemical and physical properties of carbon as related to brake performance. Wear. 1997;213: 1–2.
42. Samal P, Vundavilli PR. Dry Sliding Wear Performances of AA5052 Hybrid Composite Brake Disc Materials Reinforced with In Situ Synthesized TiC and Multi-Walled Carbon Nanotube. ASME Journal of Tribology, 2023; 145:1–15.
43. Samal P, Surekha B, Vundavilli PR. Experimental Investigations on Microstructure, Mechanical Behavior and Tribological analysis of AA5154/SiC Composites by Stir Casting. Silicon. 2022; 14:3317–3328.
44. Jang H, Ko K, Kim SJ, Basch RH, Fash JW. The effect of metal fibers on the friction performance of automotive brake friction materials. Wear. 2004;256: 406–414.
45. Shorowordi KM, Haseeb ASMA, Celis JP. Velocity effects on the wear, friction and tribochemistry of aluminum MMC sliding against phenolic brake pad. Wear. 2004;256: 1176–1181.
46. Uyyuru RK, Surappa MK, Brusethaug S. Effect of reinforcement volume fraction and size distribution on the tribological behavior of Al-composite/brake pad tribo-couple. Wear. 2006;260: 1248–1255.
47. Samal P, Vundavilli PR, Meher A, Mahapatra MM. Influence of TiC on dry sliding wear and mechanical properties of in situ synthesized AA5052 metal matrix composites. Journal of Composite Materials, 2019; 53:4323–4336.
48. Gowthami K, Balaji K. Designing and Analysis of Brake Drum. International Journal for Research in Applied Science & Engineering Technology. 2016;4(9): 135–142.
49. Zhang SY, Qu SG, Li YY, Chen WP. Two-body abrasive behavior of brake pad dry sliding against interpenetrating network ceramics/Al-alloy composites. Wear. 2010;268: 939–945.
50. Podratzky A, Bansemir H. Design and experimental characterization of modern helicopters rotor brakes. Aerospace Science and Technology. 2007;11: 360–369.
51. Bian G, Wu H. Friction performance of carbon/silicon carbide ceramic composite brakes in ambient air and water spray environment. Tribology International. 2015;92: 1–11.
52. Günay M, Korkmaz ME, Özmen R. An investigation on braking systems used in railway vehicles. Engineering Science and Technology, an International Journal. 2020;23: 421–431.
53. Jiang L, Jiang Y, Yu L, Yang H, Li Z, Ding Y, Fu GF. Fabrication, microstructure, friction and wear properties of SiC3D/Al brake disc−graphite/SiC pad tribo-couple for highspeed train. Trans Nonferrous Met Soc China. 2019;29(9): 1889–1902.
54. Meher A, Mahapatra MM, Samal P, Vundavilli PR. A review on manufacturability of magnesium matrix composites: Processing, tribology, joining, and machining. CIRP Journal of Manufacturing Science and Technology. 2022; 39:134–158.
55. Chapman TR, Niesz DE, Fox RT, Fawcett T. Wear-resistant aluminum-boron-carbide cermets for automotive brake applications. Wear. 1999;236: 81–87.
56. Kermc M, Kalin M, Vizintin J. Development and use of an apparatus for tribological evaluation of ceramic-based brake materials. Wear. 2005;259: 1079–1087.
57. Stadler Z, Krnel K, Kosmac T. Friction behavior of sintered metallic brake pads on a C/C–SiC composite brake disc. Journal of the European Ceramic Society. 2007;27: 1411–1417.
58. Stadler Z, Krnel K, Kosmac T. Friction and wear of sintered metallic brake linings on a C/C-SiC composite brake disc. Wear. 2008;265: 278–285.
59. Samal P, Vundavilli PR, Meher A, Mahapatra MM. Recent progress in aluminum metal matrix composites: A review on processing, mechanical and wear properties. Journal of Manufacturing Processes. 2020; 59: 131–152.

60. Desplanques Y, Roussette O, Degallaix G, Copin R, Berthier Y. Analysis of tribological behaviour of pad–disc contact in railway braking Part 1. Laboratory test development, compromises between actual and simulated tribological triplets. Wear. 2007;262: 582–591.
61. Tayeb NSME, Liew KW. Effect of water spray on friction and wear behaviour of noncommercial and commercial brake pad materials. Journal of Materials Processing Technology. 2008;208: 135–144.
62. Abhik R, V. U, Xavior MA. Evaluation of Properties for Al-SiC Reinforced Metal Matrix Composite for Brake Pads. Procedia Engineering. 2014;97: 941–950.