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The Mechanical &Thermal Properties of Various Brake Rotors Materials: A Review

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Abstract

The brake system is an important part of an automobile. It plays a vital role in helping the driver to reduce the speed of an automobile or to stop the automobile. Initially, when automobiles were first introduced, they were equipped with drum brakes. These drum brakes were cheap, easy to install and atmospheric agents cannot hinder their performance. Despite these advantages, the major disadvantage of the drum brake system is the poor heat dissipation. To tackle this problem, the automotive engineers came up with the disc brake system. The brake rotor is one of the most critical components of the disc brake system. The brake rotor is made up of a pure metal or a metal with certain reinforcements. These brake rotors are circular with perforations made in a particular manner to enable faster dissipation. These perforations help to reduce the weight of the disc brake rotor. The disc brake rotor is fixed to the wheel hub with brake calipers. In this review article, I will be critically analyzing various research articles on the thermal and mechanical properties of various brake rotor materials used in automobiles.

Keywords: *Automobiles, Brake Rotor, Cast Iron, Layered Steel, Aluminium, High Carbon Steel, Carbon Ceramic*

1. Introduction

The automobiles were first introduced with drum brakes. These drum brakes were affordable, simple to install and their performance could not be hindered by various atmospheric agents. The lack of ventilation in the brake drum is the major reason behind the poor heat dissipation in the drum brake system. To improve the heat dissipation from the braking system, the automotive industry started to work towards developing another braking system that could replace the drum brakes. They came up with a superior braking system called the disc brake system. The disc brake system has been mass-produced and used in a majority of automobiles since 1955. The disc brake system has four main functional parts.

They are:

I. Brake Pad
II. Brake Rotor
III. Brake Calipers
IV. Caliper Support

Brake rotors are circular discs that are connected to the wheels of an automobile. They play a vital role in converting kinetic energy to thermal energy. The large surface area of the rotor creates friction when the brake pads squeeze them. The brake rotors are classified into four types based on the presence of holes or slots. They are as follows:

I. Blank and Smooth Brake Rotor
II. Drilled Brake Rotor
III. Slotted Brake Rotor
IV. Drilled and Slotted Brake Rotor

The desirable properties of a brake rotor material are good thermal conductivity, low wear rate, long durability, high vibration resistance, heat resistance, and fast cooling rate. The six materials commonly used to manufacture are as follows:

I. Grey Cast Iron
II. Steel
III. Aluminium
IV. Aluminium Metal-Matrix Composite
V. Titanium Alloy
VI. Ceramic Matrix Composites (CMC)

In this review article, I will be critically analyzing various research articles on Mechanical & Thermal Properties Of Brake Rotors Materials. The main properties analyzed in the review article are:

I. Tensile Strength
II. Deformation
III. Compressive Strength
IV. Wear rate
V. Ductility
VI. Thermal Expansion
VII. Coefficient of Friction

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2. Literature Survey On The Mechanical &Thermal Analysis Of Brake Rotor Materials

2.1 Grey Cast Iron and Steel

Cast Iron is a group of Iron-Carbon alloy with carbon content greater than 2% by weight. Carbon can be either be present as free carbon or Iron-Carbide (Fe_3C) in cast iron. The four types of cast iron are grey cast iron, white cast iron, malleable cast iron, and spheroidal graphite iron. Cast iron is used to produce brake disc rotors not only because of its low manufacturing cost but also has an excellent thermal conductivity that plays a vital role in dissipating the heat due to friction between the brake rotor and brake pad. It also has very good vibration damping properties (Prof. R. K. Pohane et al,2016).

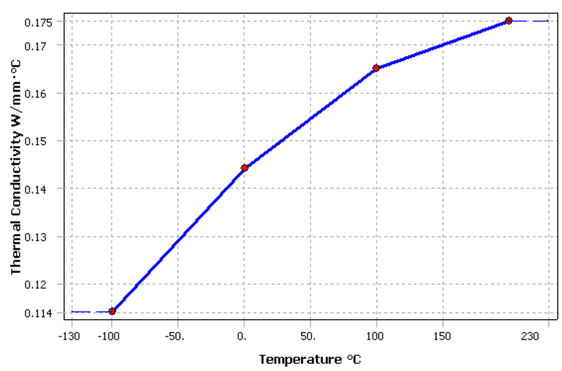

Fig 1: Thermal Conductivity v/s Temperature(S. Venkata Saidutt et al,2015)

In the research paper titled "Modeling and Analysis of Disc Brake" by S. Venkata Saidutt, A. Bala Chandrasekhar, Y. Vamsi, R. Jyothu Naik, K. Sandeep Kumar, and O. Jithendra(S. Venkata Saidutt et al,2015) brake rotors made up of Aluminium alloy, titanium alloy, and grey cast iron was designed on Catia V5. The above-designed rotors were tested for their ability to withstand heat at temperatures less than 40 degrees celsius using ANSYS Software under steady-state conditions. From the ANSYS simulation, it was found out that the grey cast iron rotor has the least thermal expansion as compared to the titanium alloy rotor and Aluminium alloy rotor. It was also found that the grey cast iron rotor has the least temperature flow as compared to the titanium alloy rotor and Aluminium alloy rotor. In this research paper titled "Manufacturing of Gray Cast Iron Automotive Disc Brake" by Masoud I. M., Al-Jarrah J. A and Abu Mansour T(Masoud I. M. et al,2014), two types of grey cast iron alloy with different percentages of carbon and silicon were used to manufacture disc brake rotors using casting. The brake rotors made from two alloys are named D1 and D2. The microstructure, Non-Destructive Testing, wear resistance test, and hardness test was conducted on the brake rotors made from two alloys are named D1 and D2. Rotor D1 has a higher wear rate than Rotor D2 because of the lower carbon content and higher silicon content than Rotor D2.In the research paper "FEA Analysis of coupled thermo-mechanical response of grey cast iron material used in brake discs" by Ali Belhocine and Asif Afzal(Ali Belhocine et al,2019), FEA Analysis and experimental analysis of the ventilated rotor disc and full disc made up of three types of grey cast iron namely FG 15, FG20, and FG25AL was conducted. From the ANSYS analysis, it was concluded that ventilated brake rotor made up of FG15 recorded a maximum temperature of 345.4 degrees Celsius while the ventilated brake rotor made up of FG20 and FG25AL recorded a maximum temperature of 351.5 and 380.2 °C respectively. This is because FG15 has higher thermal conductivity as compared to the other materials. In the research paper titled "Selection of material through "Thermal-Stress" analysis on Fusion 360 for a brake rotor" by Gaurav Maurya(Gaurav Maurya,2021), the four brake rotors made up of Grey Cast Iron (ASTM A48 Grade 30), Ti-6Al-4V (Grade 5) alloy, Stainless Steel 440C & Al 6061 alloy were designed using Fusion 360 software. The Finite Element Analysis(FEA) of the above-mentioned four brake rotors was done using the Fusion 360 software. From the FEA results, it was found out that Grey Cast Iron had the highest deformation amongst all the selected materials. In the research work titled "THE EFFECTS OF MOLYBDENUM, CHROMIUM, AND NIOBIUM ON GRAY IRON FOR BRAKE ROTOR APPLICATIONS" by Matthew Hasbrouck(Matthew Hasbrouck,2021), the researcher proposed 12 chemistries of varying Chromium, Molybdenum, and Niobium composition with six of them having high carbon equivalent grey iron, and the rest six were low carbon equivalent grey iron. Various micro metallurgical tests and mechanical properties were analyzed. It was found out that a higher carbon equivalent has a lower Brinell Macro Hardness number. The presence of Molybdenum and Niobium tends to increase the Brinell Macro Hardness number of the Grey Cast Iron but Nb has a higher impact on the Brinell Macro Hardness number as compared to that of Mo. It was also found that Nb reduces the wear rate. It was also concluded that Niobium has a predominant impact in improving the mechanical and thermal properties of the grey cast iron as compared to Molybdenum and Chromium. Thereby it was concluded that Niobium is the best dopant for grey cast iron to produce a brake rotor. In the research paper titled "TRANSIENT THERMAL ANALYSIS OF DISC BRAKE ROTOR GRAY CAST IRON F12801" by Hredey Mishra and Vikas Mishra(Hredey Mishra et al,2017), a brake rotor made up of grey cast iron was designed on CREO and the transient analysis was conducted on ANSYS Workbench. The transient analysis concluded that the longer the duration of contact between the grey cast iron rotor and the pad greater will be heat released. Therefore, there will be greater plastic deformation of the grey cast iron rotor. In the research paper titled " Thermo-mechanical performance of automotive disc brakes" by Daanvir Karan Dhir(Daanvir Karan Dhir,2016), three brake rotors made up of grey cast iron were designed on Solid Works. The three brake rotor discs were named Disc 1, Disc 2, and Disc 3. Disc 1, Disc 2, and Disc 3 were solid discs without any holes, with holes, and with aerofoil-type slots. The ANSYS steady-state analysis was conducted on the brake rotor discs at an ambient temperature of 295K and with a load moment of 101 N-m applied on one of the faces of the brake rotor. It was found that the highest deformation was seen in Disc 3. It was found that the geometric variations in the grey cast iron brake rotor design will tend to induce alternating stresses that might further cause the cracking of the brake rotor. In the research paper titled "Thermal analysis on car brake rotor using cast iron material with different geometries" by Ashish Kumar Shrivastava, Rohit Pandey,

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Rajneesh Kumar Gedam, Nikhil Kumar, and T. Ravi Kiran(Ashish Kumar Shrivastava et al,2021),three-disc brake rotors with three different geometries namely Solid Rotor, Drilled Rotor and Drilled & Slotted Rotor made up of grey cast iron were designed using CATIAV5R20 software. The FEM analysis was conducted on ANSYS R20 software. From the FEM analysis results, it was concluded that the drilled and slotted disc brake rotor has the highest heat flux as compared to the other two geometries.

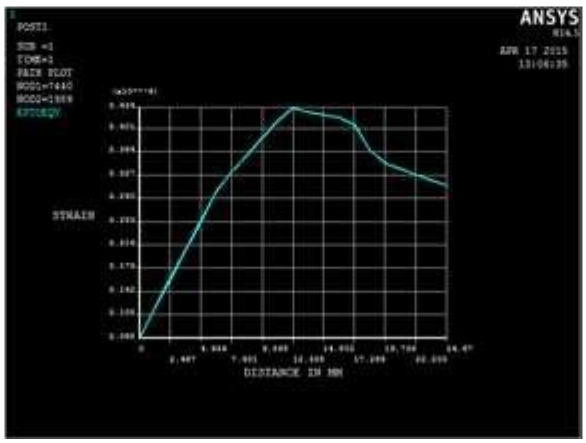

Fig 2: Strain graph of Ductile Cast Iron(V. V. Prathibha Bharathi et al,2016)

In the research paper titled "ANALYSIS AND OPTIMIZATION OF DISC BRAKE ROTOR" by V. V. Prathibha Bharathi, Busi Ashok Kumar, and Ajay Kodliwad(V. V. Prathibha Bharathi et al,2016), two brake rotors of 240 mm diameter,5mm thick and 18 holes with 7mm diameter made up of Grey Cast Iron & Ductile Cast Iron have been designed on Pro-E software. The brake rotors were analyzed using ANSYS. It was found out that the Ductile Cast Iron brake rotor has a lesser stress concentration as compared to the Grey Cast Iron brake rotor. The deformation of the grey cast iron brake rotor is approximately double the deformation of the ductile cast iron brake rotor. In the research paper titled "Effect of Slotted holes on performance of Disc Brake" by Ch. Indira Priyadarsini(Ch. Indira Priyadarsini,2018), two slotted brake rotors made up of stainless steel and cast iron was designed on Solidworks 2016. The thermal analysis of the two rotors was conducted using ANSYS 16.0 software. It was concluded that 33% of reduction in temperature in the cast iron brake rotor. The maximum deformation of the stainless steel rotor was found to be 2.7255 times greater than the maximum deformation of the cast iron brake rotor. In the research paper titled "FINITE ELEMENT ANALYSIS OF DISC BRAKES OF STEEL AND GARY CAST IRON FOR THERMAL EFFECTS" by VINAY SHAH(Vinay Shah,2020), FEM analysis of the ventilated and solid brake rotor disc made from stainless steel and cast iron was conducted on ANSYS. It was found that ventilated grey cast iron is the best suited for the disc brake system.

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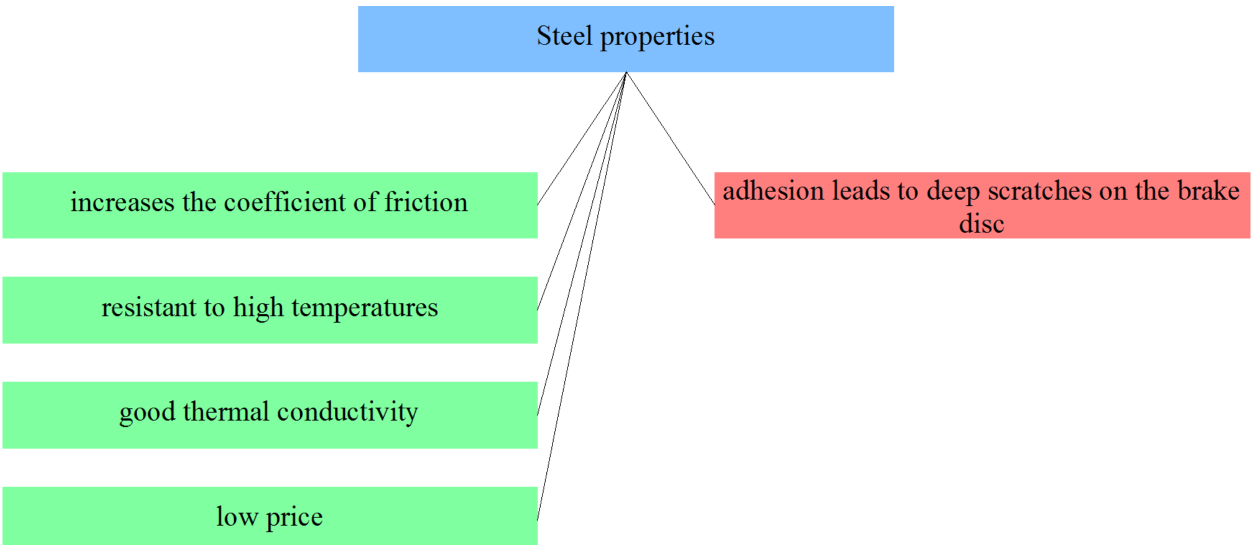

Fig 3: Properties of Steel((Borawski, Andrzej,2020)

Steel is an alloy of Fe(Iron) and C(Carbon) with a carbon content percentage of less than 2.11%. It is also a friction material with a high-temperature resistance with an ability to stabilize the coefficient of friction(Incesu A et al,2013). Stainless steel is a corrosion-resistant alloy containing iron, chromium, nickel, carbon, and other elements(aperam.com).In the research paper titled “Thermal Analysis of Disc Brake” by Mr. Sumeet Satope, Mr. Akshaykumar Bote, and Prof. Swapneel D. Rawool(Mr. Sumeet Satope et al,2017), brake rotors made up of cast iron and stainless steel was designed on Solidworks 15 software while the thermal analysis was conducted on ANSYS 14.5. It was found that the maximum temperature rise for the grey cast iron rotor was less than that of the stainless steel rotor. Grey cast iron rotors are susceptible to corrosion and therefore stainless steel is the best material for the brake rotor.

2.2 Aluminium and Aluminum Metal Matrix Composites

Aluminium is a silvery-white material with a density less than iron. It is the third most abundant chemical element on Earth after silicon and oxygen(aluminiumleader.com).In the research paper titled “Comparative Analysis of Disc Brake Model for Different Materials” by Vikas Gupta, Kuldeep Saini, Ashok Kumar Garg, Gopal Krishan, and Om Parkash(Vikas Gupta et al,2016), four brake rotors made up of cast iron, mild steel,aluminium, and Ceramic Al_2O_3 (99.5%) was designed to conduct the FEA analysis under tragic braking condition using COSMOL MULTIPHYSICS. The rate of dissipation of heat is the least in the case of the aluminium rotor as compared to the

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other materials. Despite aluminum being a light material as compared to stainless steel and grey cast iron, it is not suitable to make brake rotors because of its low operating temperatures i.e. less than 400 degrees Celsius (Marc Retting et al,2020). Therefore there is a need for reinforcement with metal matrix composites for aluminium to increase its working temperature. Metal Matrix Composites (MMCs) are composite materials with two or more constituents and one of them is metal while the other constituent may or may not be metallic (Madhusoodhanan Geethakumari Akhil et al, 2021).

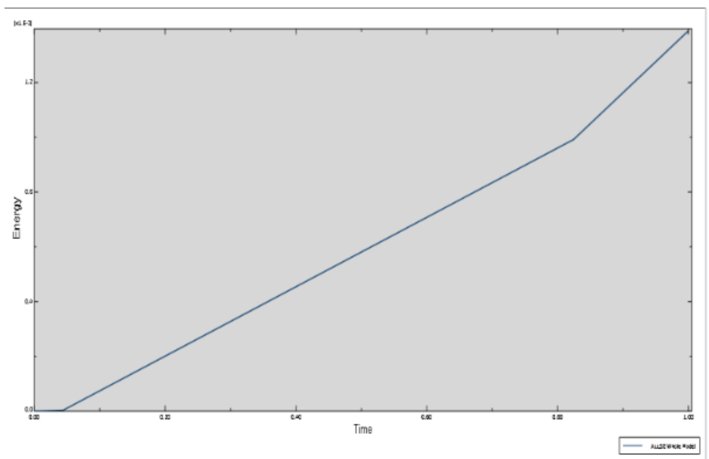

Fig 4: Strain Energy Curve For Al Composite(S. Dhiyaneswaran et al,2014)

In the research paper titled "Comparative Study of Disc Brake Materials through Computer-Aided Engineering" by S. Dhiyaneswaran and Dr. K. S. Amirthagadeswaran(S. Dhiyaneswaran et al,2014), the thermal and mechanical properties of two brake rotors made up of grey cast iron and aluminium composite with SiC[20%] reinforcement has been analyzed using Abaqus software package. It was found that the aluminium composite brake rotor with SiC[20%] reinforcement can store higher strain energy than the grey cast iron rotor. In the research paper titled "Coupled Thermo-Mechanical Analysis of an Automobile Disc Brake" by Suraj S. Rana and Dr. W.S. Rathod(Suraj S.Rana et al,2016), the transient coupled thermal-mechanical analysis of five brake rotors made up of stainless steel, grey cast iron, silicon carbide, carbon composite, and Aluminum metal matrix composite containing 58% volume fraction of Silicon Carbide [Al-MMC Rotor] was conducted on ABAQUS/CAE 6.12. It was found that the Al-MMC rotor had a better temperature distribution concerning the radial distance as compared to the other materials. The thermal conductivity of Al-MMC Rotor was found to be thrice the thermal conductivity of grey cast iron. In the research paper titled "Design and Analysis of Automobile Brake Disc by Using Al/SiC MMC" by M.Govindan and B.Viji(M.Govindan et al,2017), the FEM analysis of four brake rotors made up of grey cast iron, Al/SiC MMC with 5% SiC, Al/SiC MMC with 10% SiC and Al/SiC MMC with 12.5% SiC using ANSYS 15.0 software. It was found out that the brake rotor had a very uniform temperature distribution as compared to other materials. In the research paper titled "Investigation On Thermal Behaviour Of Aluminium Alloy Metal Matrix Nano Composite For Brake Drum Of An Automobile." by S.A.Srinivasan, A. Karthik, R.Surendran, and P.Mayilsamy(S.A.Srinivasan et al,2015), aluminium has been reinforced with nano-alumina particles of 40nm reinforced in three different percentage (1%, 1.5%, 2.5%) by weight. These samples are subjected to stability tests at various temperatures using the Differential Thermal Analysis (DTA) to simulate the working conditions of a brake drum. It was found that aluminium reinforced with 1.5% of nano alumina is the best material to replace the standard conventional cast-iron brake rotors because of their thermal stability. The research paper titled," Metal Matrix Composite Brake Rotor: Historical Development And Product Life Cycle Analysis " by A.A. Adebisi, M.A. Maleque, and M.M. Rahman(A.A. Adebisi et al,2011), proves that stir casting is the best method to produce Al-MMC brake rotors as the method provides ease of operation and better quality brake rotors. In the research paper titled "Designing a Composite Material for Use in Brake Applications" by Jason Lo(Jason Lo,2005), it's proven that nearly 60% of the weight reduction in the brake rotor can be obtained by replacing cast iron with Al MMC. In the research paper titled "Development of Disk Brake Rotor Utilizing Aluminum Metal Matrix Composite by Nobuyuki Oda, Yukihiro Sugimoto, Takahiro Higuchi, and Kouji Minesita (Nobuyuki Oda et al,1997), dynamometer and vehicle tests were used to understand the performance of the Al-MMC i.e Aluminium Silicon Carbide brake rotor. It was found that the maximum operating temperature of the Aluminium Silicon Carbide brake rotor is 450 degrees Celsius beyond which the rotor is susceptible to scoring. In the research paper titled "Designing a Composite Material for Use in Brake Applications" by Jason Lo(Jason Lo,2005), the author proposes the Squeeze Casting(SC) method to produce the Al-MMC brake rotors to increase the maximum operating temperature.

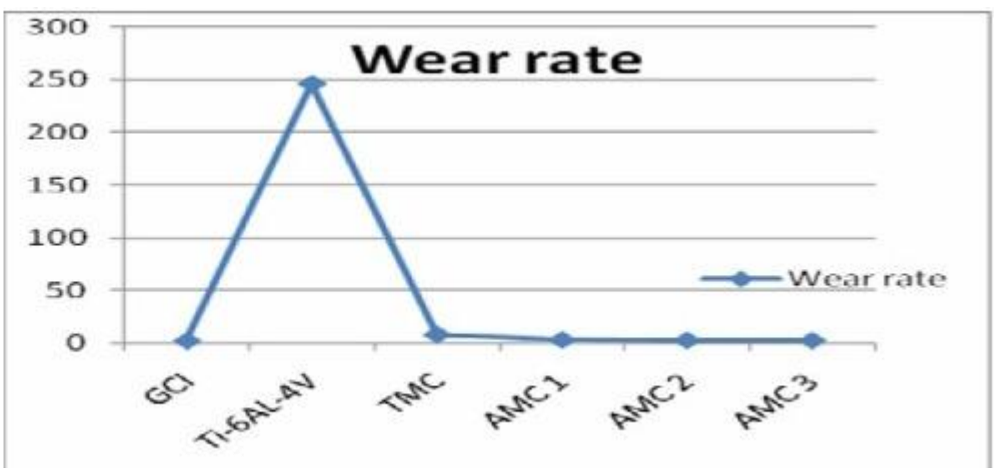

Fig 5:Wear Rate of various materials(Shaik Himam Saheb et al,2017)

In the research paper titled "Manufacturing And Testing Of Braking Material-Amc 3" by Shaik Himam Saheb And M.Naveen Kumar(Shaik Himam Saheb et al,2017), brake rotors made up of grey cast iron (i.e conventional material), Ti-alloy, 7.5 wt% WC and 7.5wt% TiC reinforced Ti-composite, 20% SiC reinforced Al-Cu alloy (AMC1),30% SiC reinforced Al-Cu alloy (AMC2) and Aluminium of 35%, copper of 40% and silicon carbide of 25%(AMC3) are subjected to various tests to analyze the mechanical and thermal properties. It was proven that AMC 3 has the highest wear resistance, high thermal conductivity, and low thermal expansion due to the presence of copper in its composition. In the research paper titled "Material characterisation of lightweight disc brake rotors" by Abdulwahab A.Alnaqi, Shahriar Kosarieh, David C.Barton, Peter C.Brooks, and Suman Shrestha(Abdulwahab A.Alnaqi et al,2018), the researchers have analyzed the impact of Keronite PEO coating on the Aluminium Alloy Brake Rotor and Al-MMC brake rotor(6061/40SiC) on the mechanical properties like hardness and coefficient of friction. It was found that the Keronite PEO coating on the Al-MMC brake rotor(6061/40SiC) has increased the maximum operating temperature up to 500 degrees Celsius while the maximum operating temperature of the aluminum alloy disc was increased to 550 degrees Celsius due to the Keronite PEO coating. The PEO Coating has increased the hardness of the Al-MMC and Al alloy. In the research paper titled "Material Selection Method in Design of Automotive Brake Disc" by M.A. Maleque, S.Dyuti and M.M. Rahman(M.A. Maleque et al,2010), the digital logic method has been used to select suitable material for a brake rotor by comparing the mechanical and thermal properties of Gray cast iron (GCI), Ti-alloy (Ti-6Al-4V), 7.5 wt% WC and 7.5 wt% TiC reinforced Ti-composite (TMC),20% SiC reinforced Al-composite (AMC 1) and 20% SiC reinforced Al-Cu alloy (AMC 2). It was found that the AMC 2 was the best suitable material for manufacturing the brake rotor because of its high coefficient of friction and low density. In the research paper titled "Performance Analysis And Material Optimization Of Disc Brake Using MMC" by Yathish K.O, Arun L.R, Kuldeep B and Muthanna K.P(Yathish K.O et al,2013), displacement, stress, contact pressure, contact status, contact sliding distance of disc and pad assembly of the rotors made up of Cast iron & Aluminium6061-SiC-red mud composite are analyzed using ANSYS (14.5) and hypermesh.It was found that lesser stress was developed in the Aluminium6061-SiC-red mud composite brake rotor as compared to the cast iron rotor. The displacement was less in the Aluminium6061-SiC-red mud composite brake rotor as compared to the cast iron rotor. In the research paper titled "Transient Thermal and Structural Analysis of the Rotor-Disc of Disc Brake" by V.M.M.Thilak, R.Krishnaraj, Dr.M.Sakthivel, K.Kanthavel, Deepan Marudachalam M.G and R.Palani(VMM Thilak et al,2013), transient thermal and structural analysis of the rotor-disc made up of cast iron, aluminum metal matrix composites, E Glass Fiber and S2 Glass Fiber using ANSYS 11.0. It was found that the composite material had a higher friction coefficient as compared with the conventional cast iron.

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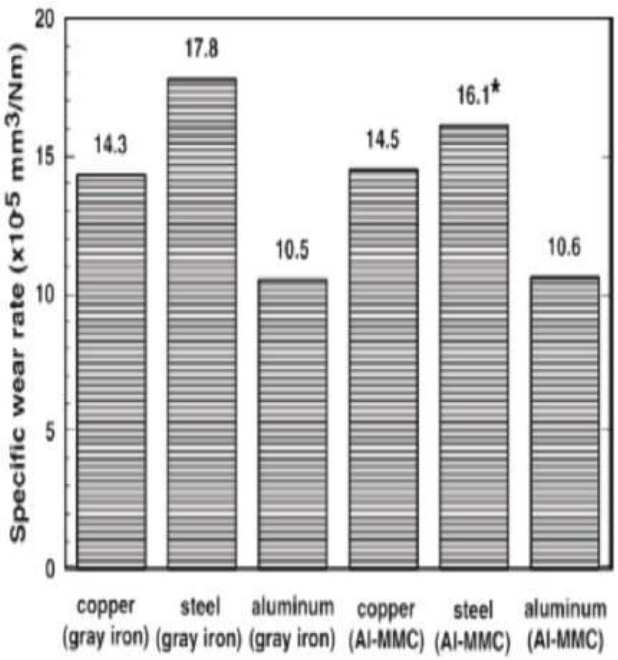

Fig 6:Specific Wear Rate Obtained From Wear Tests(Viswanatha B. M. et al,2016)

In the research paper titled "A Study On Metal Matrix Composites For Disc Brake Systems" by Viswanatha B. M., Prasanna Kumar M., Basavarajappa S., and Kiran T.S (Viswanatha B. M. et al,2016), the Al-MMC(A356+30% SiC) rotor was found to be light in weight and has a low coefficient of thermal expansion as compared with grey cast iron. In the research paper titled "Temperature Effects on the Friction and Wear Behaviors of SiCp/A356 Composite against Semimetallic Materials" (Like Pan,2017), the friction and wear behavior of the SiCp/A356 composites have been analyzed. It was found that third body films (TBFs) play a vital role in stabilizing the friction coefficient below 200°C and Massive Hard Mechanically Mixed Particles (MMPs) can generate deep grooves and severe adhesive pit on the surface of the rotor above 200°C.In the research paper titled ", Aluminum metal matrix composites a review of reinforcement; mechanical and tribological behavior."(Pranav Dev Srivyas et al,2018), it has been found that aluminum reinforced with SiC, Al_2O_3, CNT, and In-Situ Ceramics has high strength, increased stiffness, fatigue resistance and creep resistance making it suitable to produce brake rotors. In the research paper titled "SiCParticulate Reinforced Aluminium Metal Matrix Composite"(Patel M et al,2019), up to 10wt. % SiC reinforcement with aluminium can linearly increase the hardness, tensile strength, and wear resistance. In the research paper titled "Mechanical, Tribological And Corrosion Behaviour Of Aluminium Alloys And Particulate Reinforced Aluminium Or Aluminium Alloy Metal Matrix Composites - A Review" (Murlidhar Patel et al,2020), B_4C particulate reinforced AMMCs have a better hardness, tensile strength, and sliding wear resistance than the conventional Aluminium metal but lower corrosion resistance. Increasing the percentage of fly ash in the Aluminium-MMC will increase hardness, compressive strength, tensile strength, impact strength, damping capacity, slurry erosive wear resistance, abrasive wear resistance, and dry sliding wear resistance but reduce the coefficient of friction. Up to 10% of addition of Basalt by wt to the Aluminium-MMC will increase the hardness, tensile strength, compressive strength, COF, wear-resistance, and corrosion resistance but it reduces the ductility of the composite. An increase in the percentage of SiC up to 10% in the Al-MMC will reduce the coefficient of friction. In the research paper titled "Studies on 3 and 9 wt.% of B_4C particulates reinforced Al7025 alloy composites"(Nagaral, M et al,2017), it was found that increasing the % of B_4C in the Aluminium MMC will increase the tensile strength but the percentage of elongation decreases. In the research paper titled "Reinforcement size effects on the abrasive wear of boron carbide reinforced aluminum composites" (Nieto et al,2017), the nano-size of the B_4C particle reinforced in the Aluminium Metal Matrix Composite(Al-MMC) has hardness by 56% and abrasive wear resistance by 7% as compared to the micro and sub-micro size B_4C reinforced Al-MMC.In the research paper titled "Mechanical properties and corrosion behaviour of fly ash particles reinforced AA 2024 composites"(Rao et al,2012), AA2024-fly ash (2-10 weight %) particulate reinforced MMCs was manufactured using the stir-die casting method. It was found by increasing the fly ash percentage the hardness and compressive strength tends to increase but decrease the density and pitting corrosion resistance. In the research paper titled "Synthesis of fly ash particle reinforced A356 Al composites and their characterization" (Surappa,2008), A356-fly ash particulate reinforced MMC was synthesized. It was found that by increasing the fly ash volume %, the damping capacity of the fly-ash reinforced Al-MMC increases. In the research paper titled "Characterization of fly ash and its reinforcement effect on metal matrix composites: A review"(Dey and Pandey,2016), it was proven that if the fly ash percentage in the fly ash aluminium metal matrix increases beyond 15% then the tensile strength begins to decrease. The researchers have worked towards understanding the correlation between the fly ash content in Al-MMCs and the scratching abrasion resistance of the composite. In the research by (Bharathi et al,2017) and (Sharma et al, 2017), both the research teams concluded that the increase in weight percentage of the fly ash in the Al-MMC will increase the wear resistance of the composite. In the research paper titled "Effect of reinforcement of flyash on sliding wear, slurry erosive wear and corrosive behavior of aluminium matrix composite"(Ramachandra and Radhakrishna,2007), the researchers have attempted to analyze the sliding wear, slurry erosive wear and corrosive behavior of the fly ash reinforced Al-MMC. It was found that the increase in fly ash content in the Al-MMC tends to increase the sliding wear resistance and reduce the coefficient of friction. It was also found out that n slurry erosive wear resistance has been increased due to the formation of a protective layer to counter the impact of the slurry. In the research paper titled "Fabrication and characterisation of Al_2O_3 /aluminium alloy 6061 composites fabricated by Stir casting."(Kandpal and Singh,2017), 5, 10,15 and 20 weight % alumina was reinforced into the aluminium alloy 6061 and manufactured stir casting method. It was found that the ductility tends to decrease with the increase in the alumina percentage whereas an increase in microhardness & tensile strength was reported.

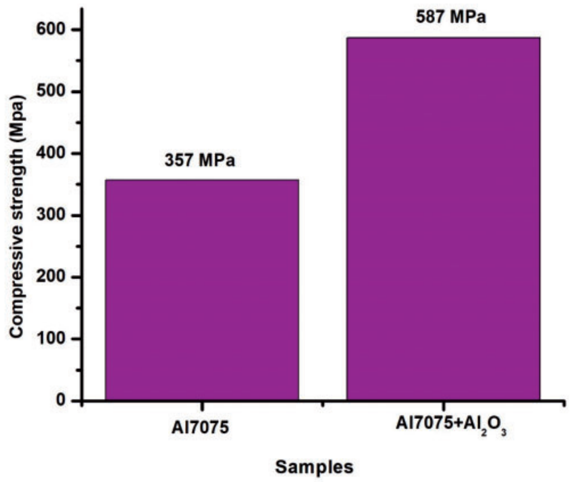

Fig 7: Compressive strength of the test materials(Muraliraja, R et al,2019)

In the research paper titled "Development of alumina reinforced aluminum metal matrix composite with enhanced compressive strength through squeeze casting process"(Muraliraja, R et al,2019), the Aluminium Metal Matrix Composite(Al-MMC) with 2.5 weight % alumina as reinforcement and AA7075 as the matrix material was manufactured using the squeeze casting process. The presence of alumina in the Al-MMC increased the hardness and compressive strength as compared to the properties of AA7075.In the research paper titled " Tribological properties of aluminum-clay composites for brake disc rotor applications." (Agbeleye et al,2020), it was found that the presence of aluminium clay improves the coefficient of friction and wear resistance of the composite. In the research paper titled "Wear resistance of basalt particulate-reinforced stir-cast Al7075 metal matrix composites."(Raja et al,2018), basalt particulate (0, 2.5, 5, 7.5, and 10 weight %) reinforced AA7075 composites was produced using stir casting methods. The increase in the percentage of Basalt in the Al-MMC will tend to increase the hardness,wear-resistance, and coefficient of friction but the coefficient of friction decreases & volumetric loss increases due to the application of the load. In the research paper titled "Investigation of mechanical and machinability properties of SiC particle reinforced Al-MMC"(Ozben et al,2008), the researchers worked towards understanding the impact of SiC reinforced in an Aluminium matrix. It was found that up to 10% by weight of SiC reinforced with Aluminium will tend to increase the tensile strength and tensile strength tends to decrease in the case 15 weight % of SiC reinforcement. In the research paper titled "An experimental investigation on mechanical and wear properties of Al7075/SiCp composites: effect of SiC content and particle size"(Rao,2018), it was found that by increasing the percentage and particle size of SiCp reinforced with aluminum the tensile strength and hardness of the composite increases but the ductility of the composite decreases.

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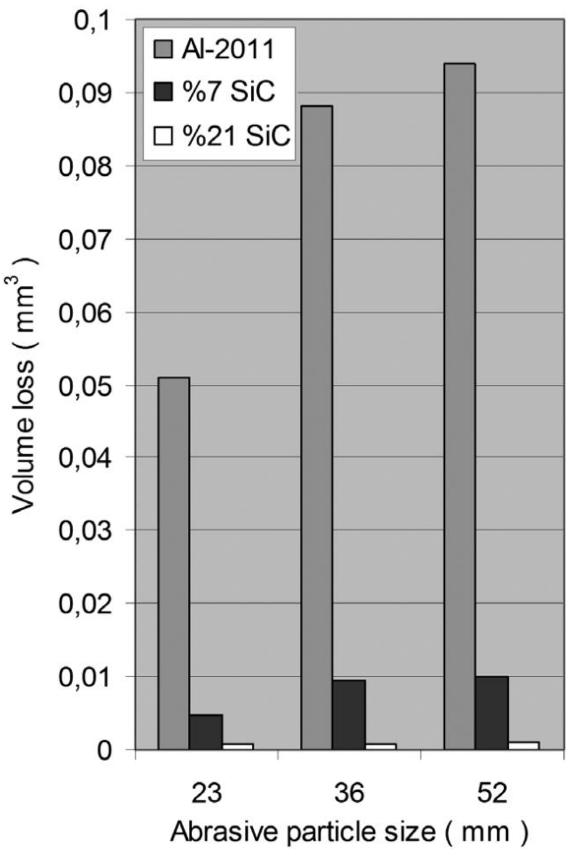

Fig 8:Wear Volume Loss v/s Abrasive Particle Size(Uzkut,2013)

The research paper titled "Abrasive wear behavior of SiCp reinforced 2011 Al-alloy composites"(Uzkut,2013), proved that the wear resistance of SiCp reinforced 2011 Al-alloy composites is higher than the conventional AA20211 alloy. The research paper titled "Characterization of functionally graded Al-SiCp metal matrix composites manufactured by centrifugal casting"(El-Galy et al,2017) proved that maximum wear resistance was achieved with 7.5-10 weight % SiC-p reinforcement with Aluminium. The research paper titled "Study of silicon carbide-reinforced aluminum matrix composite brake rotor for motorcycle application"(Sadagopan et al,2018), conducted the wear test to compare the performance of 20 weight % SiC-p reinforced AMMC and cast iron. The SiC-p reinforced AMMC had a better braking distance and heat dissipation as compared to that of grey cast iron. The problem arising due to fade in the brake rotor has been reduced in the cased of SiC-p reinforced AMMC because of the high heat dissipation.

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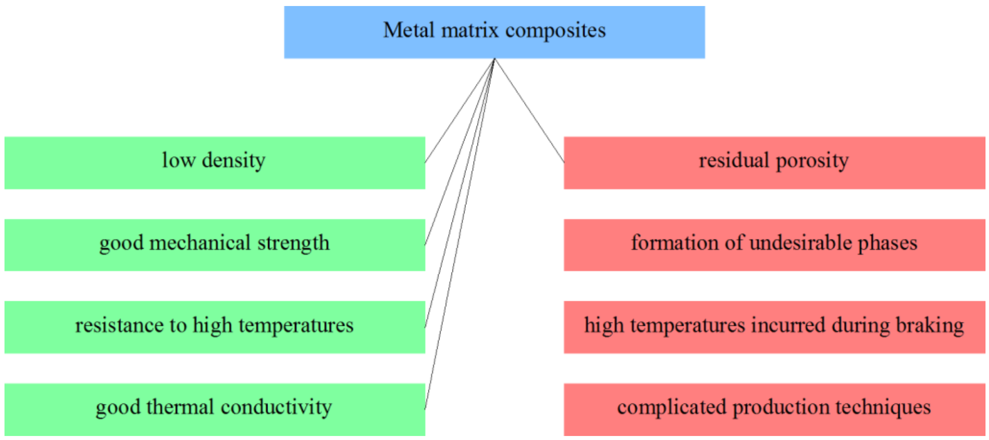

Fig 9: Properties of Metal Matrix Composites(Borawski, Andrzej,2020)

2.3 Titanium Alloys

In the research paper titled ``Design And Analysis Of Disc Brake With Titanium Alloy"(C.Radhakrishnan,2015) brake rotors made up of titanium 550 alloy and grey cast Iron are designed and thermal analysis was done on ANSYS software. It was found that the titanium alloy rotor has a lesser heat dissipation than the grey cast iron rotor. Brake rotors made up of titanium(AndreiCRĂCIUN,2015) are 37% lighter than the rotors made from grey cast iron. In the research paper titled "Force And Friction On Disc Brake Analysis"(Saran Jintanon,2009), it was found that the titanium alloy rotor has a better wear resistance than the grey cast iron rotor. Titanium Alloy Grade 5 is best suited for the use of a heat barrier that prevents the flow of heat to other parts(forcebeyond.com).

Properties	Cast iron (ALLOY)	Titanium (ALLOY)	AL-NI-CO (ALLOY)	Structural Steel(ALLOY)
TOTAL (mm) DEFORMATION	0.0144	0.023	0.014	0.018
EQUIVALENT STRESS (mpa)	73.56	71.32	70.02	75.1
EQUIVALENT ELASTIC STRAIN	0.00044	0.00069	0.00029	0.0023
FACTOR OF SAFETY	3.71	6.613	5.5	2.21
TEMPERATURE (TF) $^{\circ}$c	89	77.24	89.31	79.27
HEAT FLUX (w/mm^2)	0.523	0.2	0.163	0.483
WEIGHT (kg)	3.10	1.523	2.72	3.21

Fig 10:Final Results After The FEM Analysis(Durgesh Kaiwart and Prof. Yogesh Kumar Tembhurne,2019)

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In the research paper titled "Comparison Of Structural And Thermal Analysis Of Disc Brake Using Various Materials"(Durgesh Kaiwart and Prof. Yogesh Kumar Tembhurne,2019), the transient and thermal analysis of brake rotors made up of Structural steel alloy, Cast iron alloy, Ti–6Al–4V titanium alloy and Al-ni-co alloy. It was concluded that Ti–6Al–4V titanium alloy rotor was the lightest amongst all the test rotors. In the research paper titled "Tribological investigation of titanium-based materials for brakes"(Blau PJ et al,2007), the friction and wear rate of Ti64 alloy and Ti642 alloy were analyzed. It was found that the COF started to decrease with the increasing sliding speed and temperature. The mechanical and tribological properties of laser surface nitride Ti–6Al–4V material of disc brake rotor have been analyzed. It was found that the laser nitrided titanium alloy has a wear rate lesser than cast iron and untreated titanium alloy. The variation of the COF of the nitrided titanium alloy is very much constant during the test duration on the other hand the COF of the untreated titanium alloy showed a lot of variation during the testing(Muthukannan Duraiselvam et al, 2014).

Temperature(In Celsius)	**Velocity(m/s)**		**Volume Loss(mm^3)**	
		CGI	**Ti**	**Ti-LSN**
Room Temperature	2	0.29	163	0.22
Room Temperature	3	0.50	172	0.44
200	2	0.46	190	0.40
200	3	0.55	232	0.51
Avg. volume loss (mm^3)		0.45	189	0.39
Wear rate (mm^3/N-m x 10^6)		3.46	1453	3.00

Table 1:Volume Loss and Wear Rate(Muthukannan Duraiselvam et al, 2014)

In the research paper titled "Thermo-mechanical analysis of disk brake using finite element analysis"(Ahmad F et al,2021), four brake rotors are made up of aluminium, carbon-carbon, stainless steel, and titanium alloy were designed in Catia. The FEM analysis was conducted on ANSYS. Maximum temperature variation was recorded with the titanium alloy rotor. It was concluded that the titanium alloy rotor has a better heat dissipation as compared to the aluminium rotor. In the research paper titled "Titanium and/or Titanium Alloy Sintered Friction Material"(K. Takahashi et al,1999), the titanium alloy exhibits high strength at high temperatures. It is also found that the

Titanium alloys have good wear resistance and good capacity to retain high friction coefficient. Titanium alloy has good stiffness, relatively high-strength, and good resistance to corrosion(J. Sweet,2004).

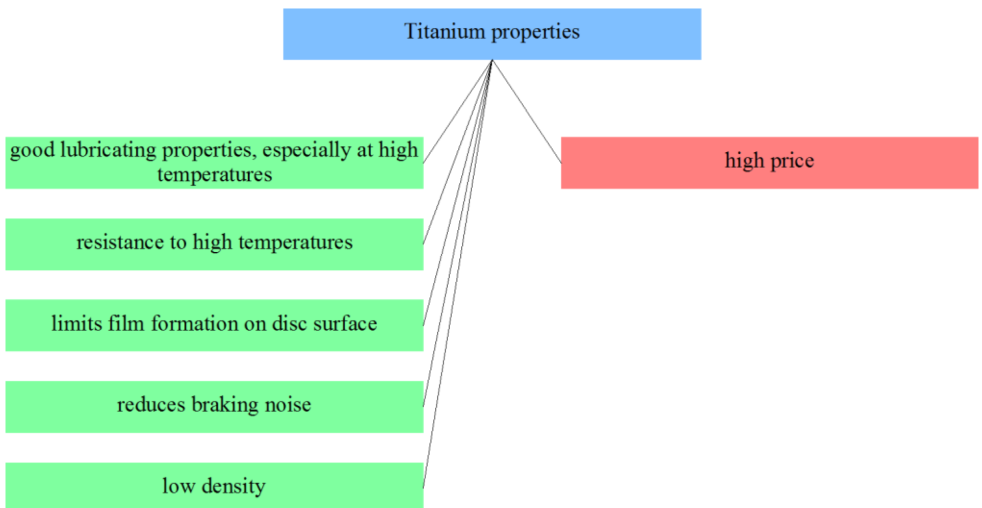

Fig 11: Properties of Titanium Alloy(Borawski, Andrzej,2020)

The lubricating nature of titanium arises at high temperatures. The titanium alloy has a special ability to balance the change of coefficient of friction due to the increasing temperature. This property of titanium allows a reduction in the noise due to the braking (Inada K et al,2005).In the research paper titled "Tribological performance of Ti6Al4V at elevated temperatures fabricated by electron beam powder bed fusion"(Sajid Alvi, et al 2021), the high temperature sliding friction, wear behavior, and mechanisms of the Ti6Al4V built using the EBPBF method have been analyzed in detail. It was found that high-temperature sliding wear against alumina counter ball was lowest at 200 ◦C followed by 400 ◦C and 500 ◦C. The Ti6Al4V showed the highest wear rate against a steel counter ball at 400 degrees celsius because of the TiO_2 layer formation.

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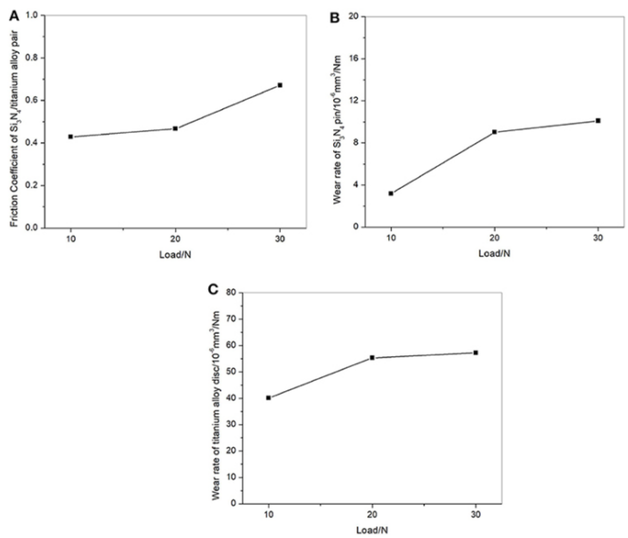

Fig 12:Titanium alloy in sliding contact against Si_3N_4 in seawater, (A) Friction coefficient, (B) wear rate of pin specimen, (C) wear rate of disc specimen. (Zhang et al,2019)

In the research paper titled "Wear in silicon nitride sliding against titanium alloy pairs at different loads under artificial seawater lubrication."(Zhang et al,2019), the tribological properties of Si_3N_4 sliding against the titanium alloy under artificial seawater lubrication conditions were analyzed using a pin-on-disc tester. It was found that the coefficient of friction of the Si_3N_4/titanium alloy pair tends to increase in normal load. In the research paper titled "Comparing and Analysing the Static and Thermal Characteristics of Brake Disc for Three Different Materials." (K, K., R, S., Richter R, A., K, S. et al,2021), three brake rotors made up of grey cast iron, EN31 alloy, and Ti-6Al-4V(Ti alloy) have been analyzed. It was found that Ti-6Al-4V and EN31 had a lesser deformation than the Grey Cast Iron.Ti-6Al-4V(Ti alloy) had a lower heat flux as compared to other materials.

2.4 Ceramic Matrix Composites (CMC)

Ceramic Matrix Composites (CMC) are manufactured by mixing carbon fiber with an epoxy binder and silicon(Marta Danylenko,2018). Ceramic Matrix Composites (CMC) are also called C/SiC or C/C-SiC composites. Ceramic matrix composites are known for their high strength, excellent wear resistance, and superior corrosion resistance(Miloradović D et al,2021).In the research paper titled "Thermo-Mechanical Analysis of Automotive Disc Brake Composite Rotor"(Ahmad Islahi et al, 2017), two brake rotors made up of S-2 Glass Fiber and Carbon Ceramic were analyzed using ANSYS. The deformation and von-mises stress due to the friction between the Carbon

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Ceramic brake rotor and the brake pad are less at high speeds as compared to the brake rotor made up of S-2 Glass Fiber. The ceramic matrix composite has a high thermal resistance and melting point as high as 1850 to 3000 °C.(R.Warren,1992).

	Dynamic Dry Water	Coefficient of Fresh Water	Friction Sea Water	Static Coefficient of Friction	Linear wear rate(mm.side^{-1} cycle^{-1})
C/C	0.26~0.45	0.13~0.16	0.10~0.16	0.16~0.21	0.8~1.0
C/SiC	0.27~0.35	0.29~0.35	0.24~0.29	0.46~0.58	0.6~1.4

Table 2: Friction and wear properties of 3D Needled C/C and C/SiC(G. Tian et al,2008)

Grain-abrasion, oxidation-abrasion, fatigue wear, and adhesive wear are the main reasons behind the wear of Carbon-Ceramic. The presence of Silicon in C/SiC has been attributed to the adhesive wear. Adhesive wear in the C/SiC may lead to extremely high wear rates and fluctuating COF. Adhesive wear can prove catastrophic. Therefore, there is a need to control the Silicon content in the C/SiC material used to manufacture brake roots. (Fan S et al,2016). Carbon-Ceramic has quasi ductile properties. These materials have 0.1-0.3% deformation at the breaking point (carbonceramicbrakes.com). The tribological tests were conducted on carbon-ceramic material to improve the efficiency of the emergency brakes. The tribological tests proved that low wear rates and high coefficients of friction even under high energy input conditions where conventional materials would tend to fail(R. Renz et al,2000 & B. Heidenreich et al,2001).

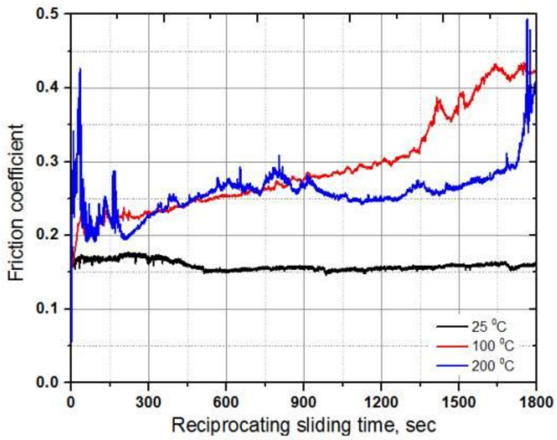

Fig 13:The variation of COF concerningConcerning time at 25, 100, and 200 °C(Byeong-Choon G et al,2017)

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The friction and wear behavior of the C/C-SiC composite was tested on a ball-on-disk friction tester under dry reciprocating conditions at three different temperatures(25, 100, and 200 °C). The COF of the C/C-SiC composite was quite stable at 25°C. The COF of the composite was unstable at 100, and 200 °C. The wear resistance was found to be decreasing with increasing temperature. The abrasive mode is found to be the main cause of wear of C/C-SiC composite against SAE52100 steel(Byeong-Choon G et al,2017). Brake rotors have been designed on CATIA V5 software. The thermal and transient analysis was conducted on these rotors made up of Ceramic Matrix Composites (CMC) and Stainless Steel using the ANSYS software. The rotors made up of Ceramic Matrix Composites (CMC) have a lower stress accumulation & higher wear resistance than the stainless steel rotor(Vishal Asokan et al,2015). The rotors made up of Ceramic Matrix Composites (CMC) weigh 50% less than the rotors made up of grey cast iron. The COF of the Ceramic Matrix Composites (CMC) is generally high and stable even under low temperatures and high humidity conditions(R. J. Koehler,2001).

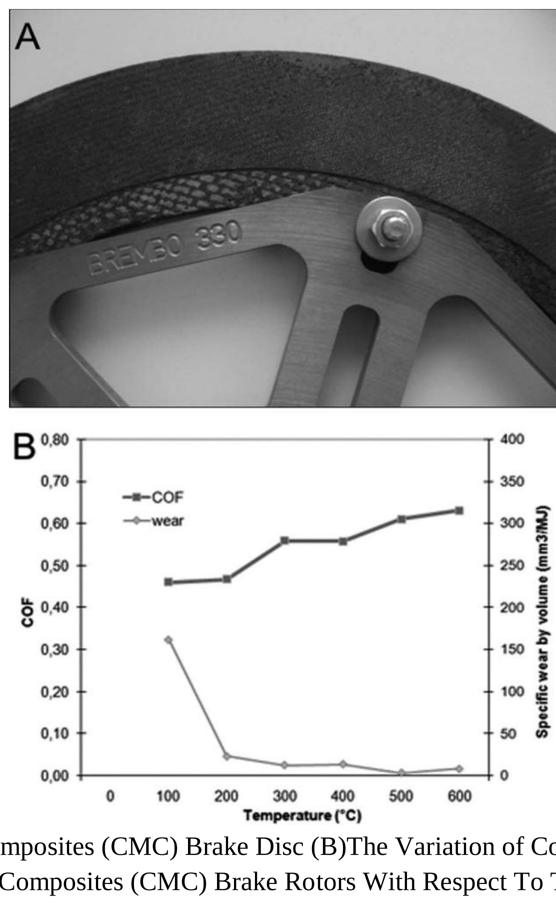

Fig 14:(A)Ceramic Matrix Composites (CMC) Brake Disc (B)The Variation of Coefficient of Friction(COF) and Wear of the Ceramic Matrix Composites (CMC) Brake Rotors With Respect To Temperature(Krnel et al,2008)

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The wear and COF of a Ceramic Matrix Composites (CMC) Brake Rotor have been assessed using a dynamometer test bench at a constant speed of 660 min^{-1}. It was found that the COF of the Ceramic Matrix Composites (CMC) Brake Rotor was increasing with the increase in temperature while the wear rate was constantly decreasing. The COF of conventional materials would tend to decrease at high temperatures(Krnel et al,2008).In the book titled “Material Science and Metallurgy”(V.D. Kodgire And S.V. Kodgire,2018), the ceramic matrix composites manufactured using the Liquid Silicon Infiltration (LSI) process possess the highest thermal conductivity due to its low porosity. The manufacturing method used to synthesize the ceramic matrix composites tends to affect their mechanical and thermal properties. The high young’s modulus and low elongation capability of a conventional ceramic make it susceptible to thermal stresses. Different elongations are generated at various points on a conventional ceramic due to their low elongation capability, temperature differences, and high young’s modulus tends to generate high stresses that further lead to rupturing, cracks, and brittle failure. The presence of fibers in a Ceramic Matrix Composites(CMC) can bridge the cracks and show no damage at the macroscopic level even if the matrix has experienced a failure or a crack at a particular point. (V.D. Kodgire And S.V. Kodgire,2018). Carbon Matrix Composites(CMC) are known for their resistance to wear, high durability, resistance to high and rapidly fluctuating temperatures, low coefficient of thermal expansion, and lightweight(Szpica D et al,2015).

Materials	**CVI-C/SiC**	**LPI-C/SiC**	**LSI-C/SiC**	**CVI-SiC/SiC**	**SiSiC**
Thermal Conductivity (p)[W/mK]	15	11	21	18	>100
Thermal Conductivity (v)[W/mK]	7	5	15	10	>100
Linear Expansion (p)[$10^{-6}.K^{-1}$]	1.3	1.2	0	2.3	4
Linear Expansion (v)[$10^{-6}.K^{-1}$]	3	4	3	4	3

Table 3: The thermal properties of Ceramic Matrix Composites(Note: LPI stands for Liquid Polymer Infiltration. LSI stands for Liquid Silicon Infiltration (LSI) and CVI stands for Chemical Vapor Infiltration. The (p) and (v) represent the parallel and vertical fiber orientation in the 2D-fiber structure, respectively.)(V.D. Kodgire And S.V. Kodgire,2018)

Researchers have found that the COF of the Ceramic Matrix Composites depends on the friction conditions. It can fluctuate from a value as low as 0.2 to a value as high as 0.8(Langhofa N et al,2016). Despite the brittle nature of the constituents of the Ceramic Matrix Composites, they are known for their toughness. The Ceramic Matrix Composites are tailorable concerning fiber type, interphase, matrix, and coatings(Nalsain R,2004).

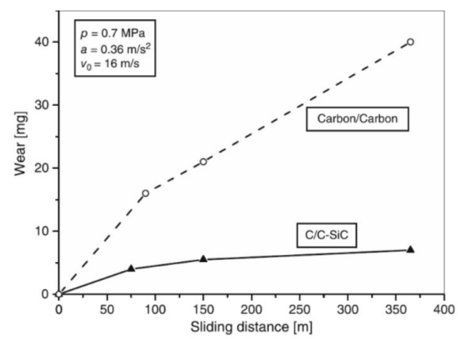

Fig 15:The wear rate of C/C and C/SiC couples tested in disc-on-disc configuration(J. Föhl et al 2000)(J. Föhl et al,2001)

From Figure 15(J. Föhl et al 2000)(J. Föhl et al,2001), it is quite clear that the wear rate of C/C is higher than C/SiC when being tested using a disc-on-disc configuration. The low wear rate makes the C/SiC suitable for making the brake rotors. The fading tests were conducted on C/SiC discs and phenolic resin-bonded LowMet pads while decelerating from a speed of 134 kmph to 44 kmph. The temperature of the C/SiC discs went up higher than 600 degrees Celsius. Despite the temperature rise, the COF was constant ranging from 0.35 to 0.45.

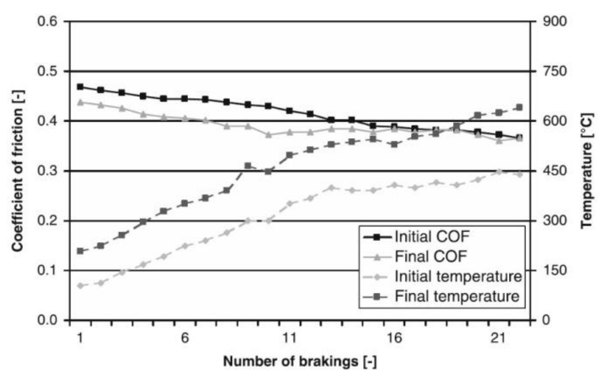

Fig 16:Fading tests were conducted on C/SiC discs and phenolic resin-bonded LowMet pads while decelerating from a speed of 134 kmph to 44 kmph

In the research paper "Manufacture and Tribological Properties of C/C-SiC Brake Composites Fabricated by Warm Compacted In Situ Reaction", C/C-SiC brake composites were manufactured by warm compacted in-situ reaction method. The microstructure, tribological properties, and wear mechanisms of the C/C-SiC composite were assessed. The friction and wear properties were assessed using a friction testing machine (QDM150, China) with the C/C-SiC Brake Composite as a static plate & steel discs were used as moving plates. The COF increased to a maximum of 0.67 at 16m/s and then began to decrease. While the wear rate tends to increase until a speed of 20m/s to a maximum value of f 2.02 cm^3 MJ^{-1}. On SEM analysis of the C/C-SiC Brake Composite after the friction test, it was found that the micro-peaks on the surface meshed with each other causing deformation, shearing, and breaking that in turn lead to the initial increase of the COF(Peng X et al,2010).

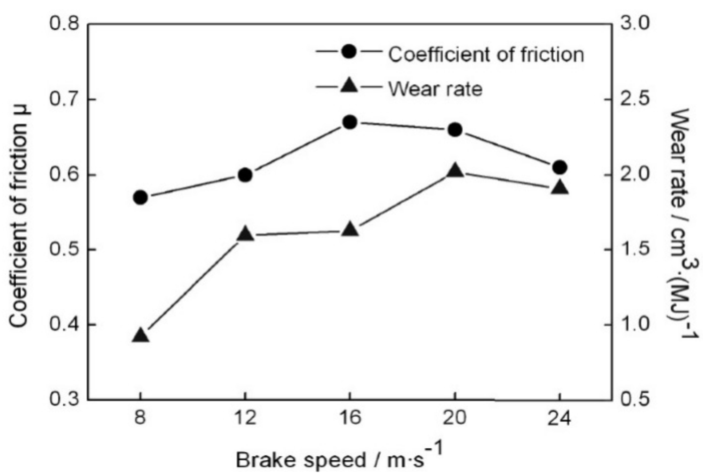

Fig 17:The graphical representation of the relationship between COF, Wear Rate, and Brake Speed (Peng X et al,2010)

In the research paper titled "Tribological Properties of C/C-SiC Composites for Brake Discs"(Jang GH et al,2010), two Ceramic Matrix Composites (CMC) discs namely Disc A and Disc B are manufactured using the LSI process. The area fraction of the phases on the surface of the two CMC discs is shown in table 4. The tribological properties of the two discs have been assessed. From Fig 18, we can say that Disc B has a higher average COF than Disc A because the surface of the disc has been changed due to several instances of applying the brakes due to the removal of the friction films initially.

	SiC(%)	Si(%)	C(%)
Disc A	32.8 (±0.9)	11.0 (±3.1)	56.2 (±3.8)
Disc B	32.7 (±0.7)	51.3 (±1.6)	16.0 (±1.2)

Table 4:The area fraction of the phases on the surface of the two CMC discs(Jang GH et al,2010)

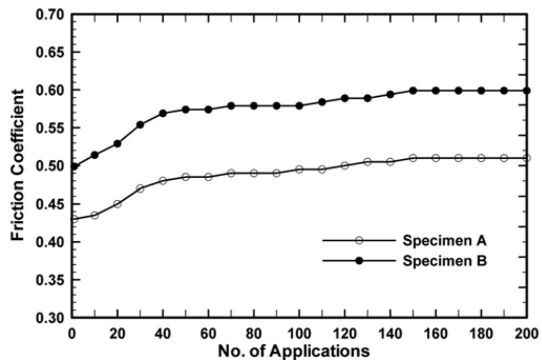

Fig 18:The variation in friction coefficient during burnish(Jang GH et al,2010)

The wear of friction material in Disc A is greater than Disc B.Disc B has an improved wear resistance because of the uniform friction films on the disc as these films prevent the direct contact of the surface asperities of the discs with the friction material(Jang GH et al,2010).

	Disc A	Disc B	Grey Iron Disc
Disc (g)	0.015	0.012	1.206
Friction material ($\times 10^{-5} mm^3/Nm$)	129.1	85.7	131.4

Table 5:Wear Rate of Disc A and Disc B after 1000 stops against the same friction material(Jang GH et al,2010)

The presence of silicon carbide in the ceramic matrix composite is considered to be the main reason behind the increase of the COF of the ceramic matrix composite. On the other hand, the abrasive action of the silicon carbide tends to increase the wear rate of the ceramic matrix composite. The presence of free silicon in the ceramic matrix composite is considered to be the main reason behind the adhesive wear of the composite. The presence of free silicon can increase the COF and decrease the wear of the composite. Plastic deformation of silicon causes adhesion. Free silicon is less hard than silicon carbide(Fouquet S et al,2008).To prevent the overheating of the friction surface,

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there must be a flow of heat from the outer region to the center of the composites. Therefore the ceramic matrix composites must possess a high transverse thermal conductivity. Certain modifications in the composition and microstructure of the ceramic matrix composites are required to make sure that the composite has a high transverse thermal conductivity(Kumar P et al,2016). By increasing the percentage of SiC in the ceramic matrix composites will tend to increase the transverse thermal conductivity of the composite(Krenkel W et al,2002). By keeping the carbon content low and increasing the silicon carbide content, the damage tolerance of the composite will decrease & will in turn impact the mechanical properties of the ceramic matrix composites. The silicon carbide content must be higher on the outside surface as compared to the inner surface of the composite.

The silicon content on the outer surface of the composite can be increased either by gradually increasing the silicon carbide content from the center to the friction surface or by coating homogeneous C/C–SiC composites with Si–SiC(Krenkel W et al,2005). The main wear mechanisms in the ceramic matrix composites are grain-abrasion, oxidation-abrasion, fatigue wear, and adhesive wear. These wear mechanisms tend to occur simultaneously. The hard SiC grain action is the main reason behind grain-abrasion wear(Fan S et al,2011).

Braking Conditions	**Friction Factor**	**Stability coefficient**	**Braking energy/ ($J{\cdot}cm^{-2}$)**	**Dimension (loss/µm)**	**Counterpart dimension (loss/µm)**
Dry	0.38	0.69	1245.36	1.10	0.97
Wet	0.35	0.64	1242.78	0.70	0.63

Table 6:Tribological properties of Ceramic Matrix Composites on Wet and Dry Conditions(Zhuan L et al,2009)

From Table 6(Zhuan L et al,2009), there is a very minimal difference in the COF of Ceramic Matrix Composites under wet and dry conditions. The dimension loss in wet conditions ⅔ times under dry conditions. The ceramic matrix composites can withstand high temperatures as high as 1000 degrees celsius. Therefore they are suited for high-performance emergency braking systems(Renz et al,2000).

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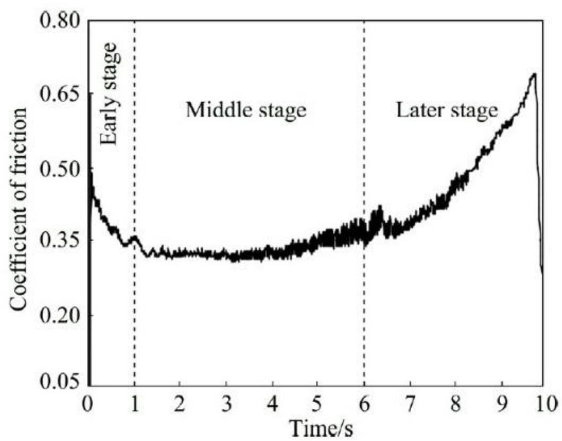

Fig 19:The Braking Curve (Chen GY et al,2019)

The braking process lasts only for 10 seconds. The graph between COF and Time is a saddle-type graph. It has three sections namely the Early Stage, the Middle Stage, and the Later Stage. The COF is maximum in the early stage. In the middle stage, the COF decreases and increases steadily. In the later stage, the COF increases to a maximum value. The highest COF was found to be 0.68 and the average COF was found to be 0.36 (Chen GY et al,2019). Factors like matrix type, fiber type,fiber-volume fraction, fiber shape, fiber orientation, and porosity distribution influence the thermal and mechanical properties of Ceramic Matrix Composites(Michael May et al,2020).

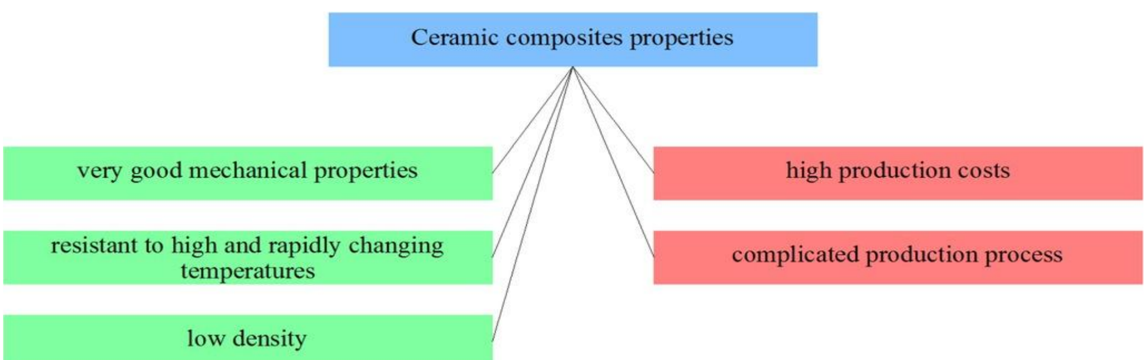

Fig 20:Properties of Ceramic Matrix Composites((Borawski, Andrzej,2020)

3. Conclusion

In my review article, I have analyzed 100 research papers that have been published on the mechanical and thermal properties of various brake rotor materials from 1992 to 2021. I have covered the thermal and mechanical properties of six brake rotor materials namely cast iron, steel, aluminium, aluminium metal matrix composite, titanium alloys, and ceramic matrix composites. The desirable properties of good thermal conductivity, low wear rate, long durability, high vibration resistance, heat resistance, and fast cooling rate. As a conclusion, I will be summarizing the mechanical and thermal properties of the six materials that were analyzed in the review article.

I. **Cast Iron**: Cast Iron has a fast cooling rate. It has good damping properties. It has poor corrosion resistance. The density of cast iron ranges from 6800 to 7800 Kg/m^3. The thermal conductivity of cast iron is 52 W/m K.

II. **Steel:** Steel has a density ranging between 7750 and 8050 kg/m^3. It is lighter than cast iron. It is more resistant to corrosion than cast iron. The thermal conductivity of steel varies from 10 W/m K to 66 W/mK depending upon the alloying material.

III. **Aluminium:** Aluminium has a very high strength to density ratio. It has a very high coefficient of thermal expansion. It has a very low operating temperature i.e as low as 400 degrees celsius.

IV. **Aluminium Metal Matrix Composites:** The presence of various particulates like B_4C, SiC, Al_2O_3, and basalt in suitable percentages by weight in the aluminium matrix composite has increased the operating temperature of the composite. It has a low density, high wear resistance, high compressive strength, and a stable coefficient of friction at high temperatures. It has a high rate of heat dissipation as compared to aluminum, steel, and cast iron.

V. **Titanium Alloys:** Titanium alloys are 37% lighter than grey cast iron. The majority of the titanium alloys have a stable COF at high temperatures. The COF of certain titanium alloys without any surface treatment is fluctuating with the increase in temperature. Suitable surface treatment of these titanium alloys is required to make sure that the COF is stable at high temperatures.

VI. **Ceramic Matrix Composites(CMC):** Ceramic Matrix Composites are light in weight. They have a low coefficient of thermal expansion. They can operate at temperatures as high as 1850 to 3000 °C. The COF of the CMCs increases with the increase in temperature while the wear rate of the CMCs decreases with the increase in temperature. They have very good mechanical properties.

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A Brief Author Biography

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