Effect of Material Selection on the Structural and Thermal Performance of a Disc Brake

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Abstract - *Brakes play a crucial role in vehicle safety by enabling controlled deceleration. Improper geometry and material selection can lead to disc rotor damage or failure, compromising braking efficiency and vehicle control. This research work centers on analyzing both structural and thermal behavior of braking parts (e.g., rotor, caliper) using various materials under differing conditions. Finite Element Analysis (FEA) is used to assess von Mises stress, overall deformation, and strain in structural tests, while thermal simulations evaluate temperature distribution and heat dissipation during abrupt braking.*

The selected materials for this investigation include Grey Cast Iron, Stainless Steel, Magnesium Alloy, 1060 Aluminum Alloy, and Vanadium Alloy. The modeling and simulations are conducted using SolidWorks 2023 and Solid Edge. The results indicate that no single material excels in all conditions, with each material demonstrating strengths and limitations based on specific performance criteria. This study provides valuable insights into material selection strategies for optimizing disc brake efficiency and durability.

Key Words: *Mechanical properties, CAD Modelling, Finite Element Analysis, Heat dissipation, Braking efficiency.*

1. INTRODUCTION

Braking systems are essential for vehicle safety, ensuring controlled deceleration and stability.. Among braking components, the disc brake rotor significantly influences braking efficiency, thermal performance, and structural integrity. During braking, friction between the brake pad and rotor converts kinetic energy into heat, which, if not dissipated effectively, can cause thermal stress, material degradation, and reduced performance.

Traditionally, Grey Cast Iron has long been favored for brake rotors owing to its wear resistance, thermal conductivity, and affordability.. However, the demand for lightweight, high-performance braking systems has led to the exploration of alternative materials such as Stainless Steel, Magnesium, and Aluminum alloys. While cast iron offers superior heat dissipation, its high weight increases un-sprung mass and affects fuel efficiency. Lightweight alloys reduce weight but may exhibit lower thermal resistance and durability under extreme braking conditions.

This study employs Finite Element Analysis (FEA) to evaluate the effect of material selection on disc brake rotor performance. Structural and thermal simulations determine von Mises stress, deformation, strain, heat dissipation, and temperature distribution under sudden braking conditions. The modeling is conducted using SolidWorks 2023 and Solid Edge to ensure accurate representation of real-world scenarios.

The findings provide a comparative analysis of different materials, highlighting trade-offs between structural integrity, thermal efficiency, and weight reduction. By identifying the optimal material for disc brake rotors, this study aims to contribute to advanced braking systems that enhance vehicle safety, performance, and energy efficiency in conventional and electric vehicles.

2. OBJECTIVES

This research work focuses on assessing the structural and thermal performance of selected disc brake materials. The main objectives are listed below:

1). To analyze the impact of different materials on the structural integrity of a disc brake rotor by evaluating von Mises stress, total deformation, and strain elongation under braking conditions.

2). To examine the thermal characteristics of each material by measuring heat dissipation ability and temperature variation during emergency braking situations.

3). To compare and evaluate the suitability of different materials—Grey Cast Iron, Stainless Steel, Magnesium Alloy, 1060 Aluminum Alloy, and Vanadium Alloy—based on their mechanical and thermal properties.

4). To identify an optimal material that balances strength, thermal efficiency, durability, and weight reduction for improved braking performance and vehicle efficiency.

5). To utilize Finite Element Analysis (FEA) for simulating real-world braking scenarios using SolidWorks 2023 for modeling and Solid Edge for structural and thermal analysis..

3. LITERATURE REVIEW

1) **Ali Belhocine and Oday Ibrahim Abdullah et. al. (2021) -** This investigation utilized numerical modeling to study the performance of three different disc brake materials. A three-dimensional thermal analysis was applied to understand how heat is distributed across the disc, and a comparative evaluation was conducted to determine the most effective material for braking. Results were illustrated through a thermomechanical modeling approach. [1]

2) **Srushti Newase, Pradnya Kosbe et. al. (2021) -** The research is centered on thermal analysis of vented brake rotors specifically for the Mahindra Bolero. It aimed to determine appropriate rotor and pad materials that can efficiently manage heat while maintaining mechanical strength. [2]

3) **Adarsh Bhat et. al. (2021) -** This study presents a comparison between disc and drum brakes, assessing stopping distances, heat management, and overall braking performance. While drum brakes are more economical, the focus was on enhancing disc brake systems to reduce deformation and improve heat handling. [3]

4) **Aakash Jawla, Rahul Anand, Shobhit Agarwal et. al. (2020) -** Thermal simulation techniques were applied in this study to investigate how stainless steel performs in disc brake applications, particularly under conditions of heat buildup and thermal stress. SolidWorks and ANSYS Workbench tools were used to conduct the analysis, offering guidance for better material choices. [4]

5) **Sanket Darekar, Ajinkya Dhage et. al. (2020) -** In this design-based project, a disc brake for the Bajaj Pulsar 220F was developed using CATIA. The team analyzed how temperature changes during braking, employing ANSYS Workbench for simulation. Various rotor designs were compared to achieve an optimized configuration. [5]

6) **S.A.M Da Silva, DVV Kallon et. al. (2019) -** This research contrasts the structural performance of grooved and drilled-grooved disc rotors under several linear load conditions. Using Brembo rotor designs for a Renault vehicle, the team analyzed load paths, stress zones, and displacements through simulation. [6]

4. MATERIALS & METHODS

This study examines the influence of material selection on the structural and thermal performance of a disc brake rotor using Finite Element Analysis (FEA). The selected materials—Grey Cast Iron, Stainless Steel, Magnesium Alloy, 1060 Aluminum Alloy, and Vanadium Alloy—were chosen for their distinct mechanical and thermal properties. Grey Cast Iron is widely used for its high thermal conductivity and wear resistance, while Stainless Steel offers superior corrosion resistance. Magnesium and Aluminum alloys are considered for their lightweight characteristics, reducing overall vehicle mass.

Structural analysis determined von Mises stress, deformation, and strain elongation under braking forces, while thermal analysis assessed heat dissipation and temperature distribution during sudden braking. By comparing material performance, this study identifies an optimal rotor material that balances structural strength, thermal efficiency, and weight reduction, contributing to high-performance braking systems for conventional and electric vehicles.

4.1. Factors

Choosing the right material for a component involves evaluating several critical factors, which can be grouped into the following key categories :

- **Material attributes** – Mechanical, thermal, and chemical characteristics that influence performance.
- **Material Cost and Availability** – Economic feasibility and accessibility of the material.
- **Manufacturing Process** – Suitability of the material for fabrication and machining.
- **Environmental Factors** – Impact of the material on sustainability, recyclability, and resistance to external conditions.

5. METHODOLOGY

This study analyzes the structural, thermal and fatigue performance of a disc rotor using Finite Element Analysis (FEA). The rotor is modeled in SolidWorks 2023 software. Structural analysis determines von Mises stress and deformation, while thermal analysis evaluates heat dissipation and temperature distribution under braking.

Five materials—Grey Cast Iron, Stainless Steel, Magnesium Alloy, 1060 Aluminum Alloy, and Vanadium Alloy—are selected for their mechanical strength, thermal conductivity, and weight efficiency. Realistic boundary conditions, including rotational velocity, braking force, and convective heat transfer, replicate actual braking conditions.

The analysis highlights trade-offs between strength, heat resistance, and weight reduction, aiding in material selection for high-performance disc brake rotors in modern and electric vehicles.

6. CAD MODEL

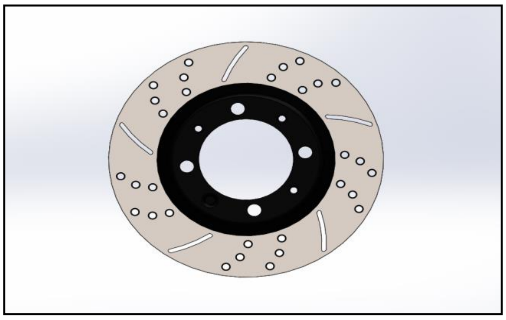

Fig 01 : 3D CAD Model of Disc Brake Rotor

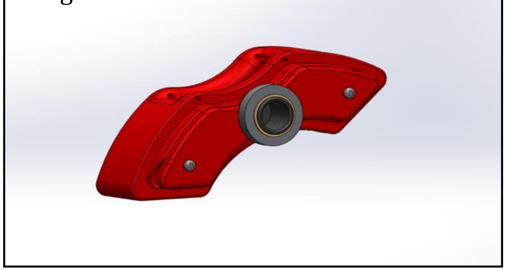

Fig 02 : 3D CAD Model of Disc Brake Calliper

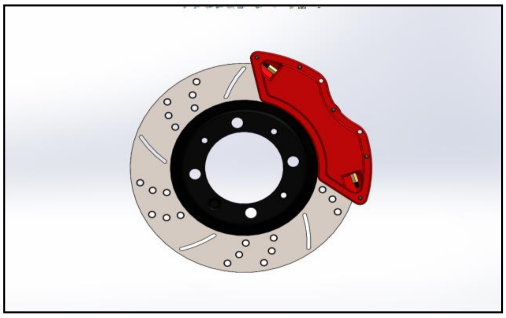

Fig 03 : 3D CAD Model of Disc Brake

7. PROPERTIES OF MATERIALS

Properties	Grey C.I.	Stainless Steel	1060 Aluminium Alloy	Titanium	Magnesium Alloy
Density (Kg/m³)	7200	8000	2700	4500	1740
Young's Modulus (MPa)	120	190	70	120	45
Yield Strength	250	400	85	375	220
Thermal Conductivity (W/m-k)	45	25	237	20	160
Poisson's Ratio	0.28	0.29	0.33	0.34	0.35
Specific Heat	460	495	930	560	1050
Coefficient of Friction	0.40	0.3	0.25	0.3	0.25

Table 01 : Represents properties of different

- Grey Cast Iron has a higher COF due to its surface roughness, making it an excellent material for brake rotors.
- Stainless Steel has a moderate COF, but its corrosion resistance makes it ideal for high-performance applications.1060
- Aluminum Alloy & Magnesium Alloy have a lower COF, reducing frictional braking performance, but their lightweight properties are advantageous.
- Titanium (Annealed) provides moderate friction while maintaining high strength and heat resistance.

8. RESULTS

Structural Analysis :-

Grey Cast Iron

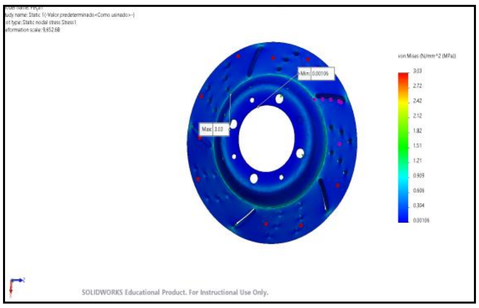

Fig 04 : Result of Equivalent Stress

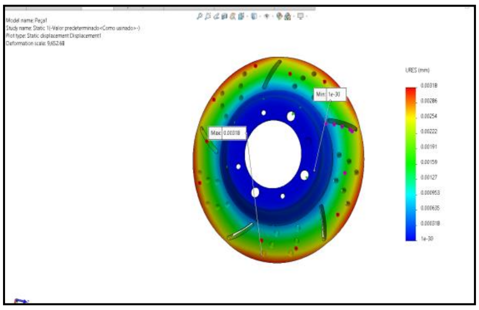

Fig 05 : Result of Total Deformation

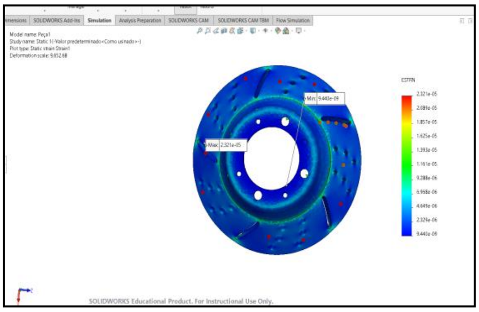

Fig 06 : Result of Maximum Principal Strain

Grey Cast Iron :

- The structural analysis of the disc brake made of grey cast iron shows good performance in terms of strength and durability.
- The material's excellent damping properties help in reducing vibrations, while its high wear resistance ensures longevity.
- Stress distribution is even, with localized high stresses near the rotor's center.

Stainless Steel

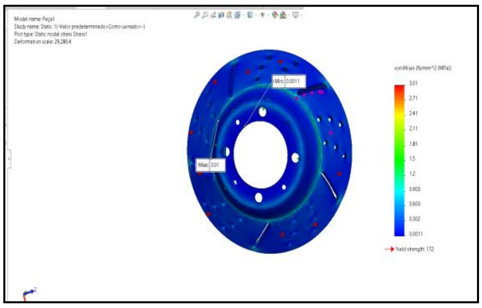

Fig 07 : Result of Equivalent Stress

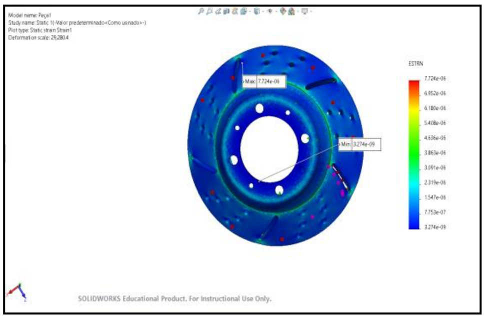

Fig 08 : Result of Total Deformation

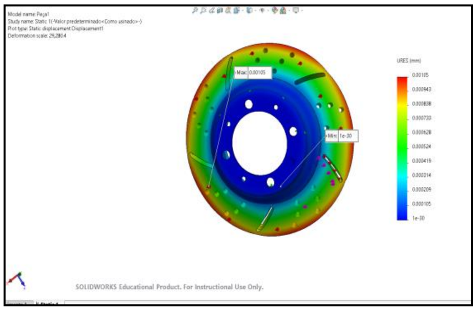

Fig 09 : Result of Maximum Principal Strain

Stainless Steel :

- In the structural analysis of a disc brake made from stainless steel, the material's strength, stiffness.
- The analysis highlighted the brake's ability to withstand high mechanical stresses and thermal expansion during braking.
- Stainless steel's durability provides effective heat dissipation, reducing wear and ensuring longevity, while maintaining structural integrity during cyclic loading conditions typical in automotive applications.

1060 Aluminium Alloy

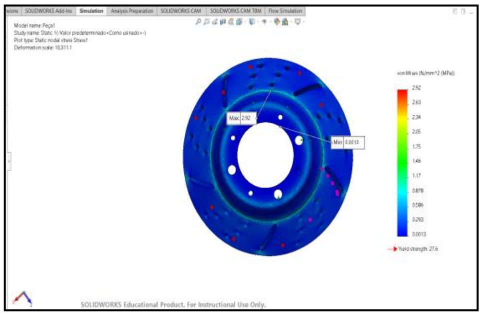

Fig 10 : Result of Equivalent Stress

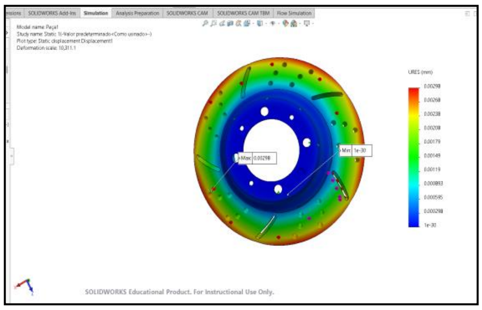

Fig 11 : Result of Total Deformation

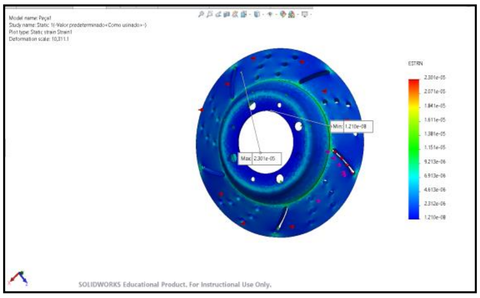

Fig 12 : Result of Maximum Principal Strain

1060 Aluminium Alloy :

- In the structural analysis of a disc brake made from 1060 Aluminum alloy, the material's low strength and high ductility were considered.
- Results indicated that while the brake disc can handle moderate thermal stresses, it may not perform well under extreme conditions due to the material's relatively low tensile strength.
- The analysis highlights the importance of optimizing design parameters and considering alternative materials for high-performance braking systems.

Titanium (Annealed)

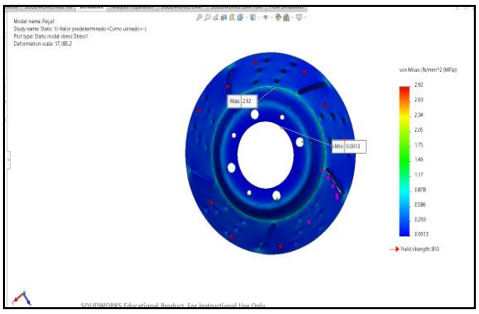

Fig 13 : Result of Equivalent Stress

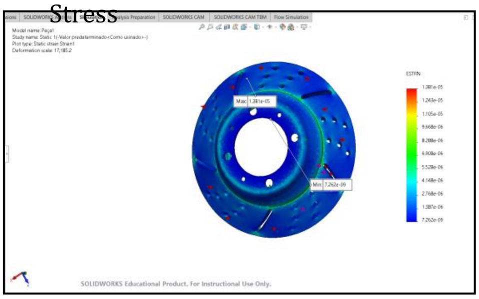

Fig 14 : Result of Total Deformation

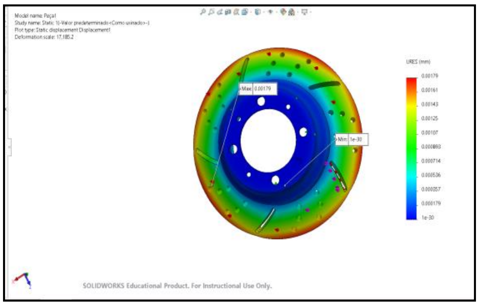

Fig 15 : Result of Maximum Principal Strain

Titanium (Annealed) :

- The Structural evaluation of an annealed titanium disc brake shows a high strength-to-weight ratio along with superior fatigue and corrosion resistance.
- The titanium's ability to ithstand thermal cycling and extreme temperatures is beneficial for brake performance.
- The analysis shows that the material maintains structural integrity under stress, offering improved durability and lightweight characteristics compared to traditional materials like cast iron, enhancing overall braking efficiency and vehicle performance.

Magnesium Alloy

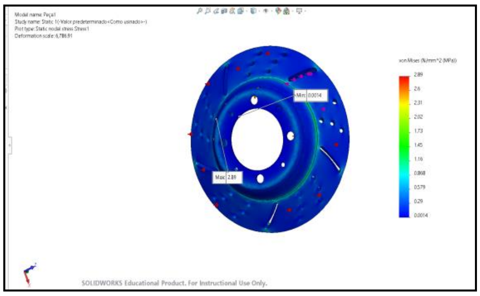

Fig 16 : Result of Equivalent Stress

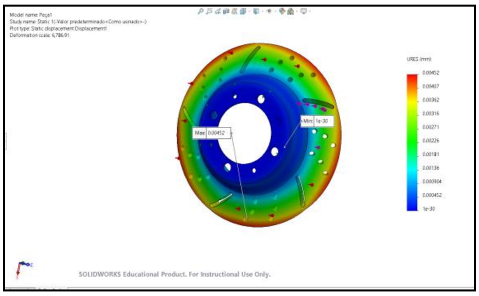

Fig 17 : Result of Total Deformation

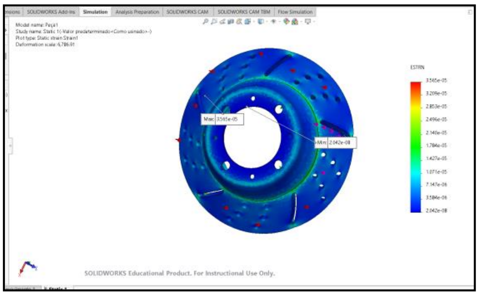

Fig 18 : Result of Maximum Principal Strain

Magnesium Alloy :

- The Structural evaluation of a magnesium alloy disc brake shows a favorable strength-to-weight ratio, making it suitable for lowering vehicle mass.
- Stress distribution analysis shows that the magnesium alloy handles braking forces effectively, though it exhibits higher deformation compared to steel.
- The material's lower density contributes to better performance in high-speed applications, but it requires careful consideration for durability and thermal management due to its lower thermal conductivity.

Thermal Analysis :-

Grey Cast Iron

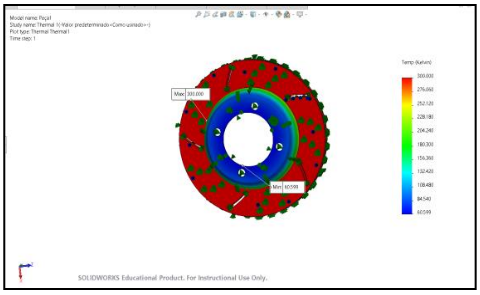

Fig 19 : Result of Temperature

Stainless Steel

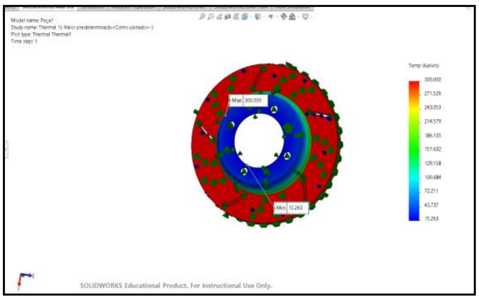

Fig 20 : Result of Temperature Dispersion

1060 Aluminium Alloy

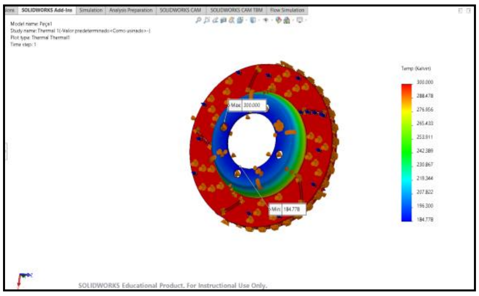

Fig 21 : Result of Temperature Dispersion

Titanium (Annealed)

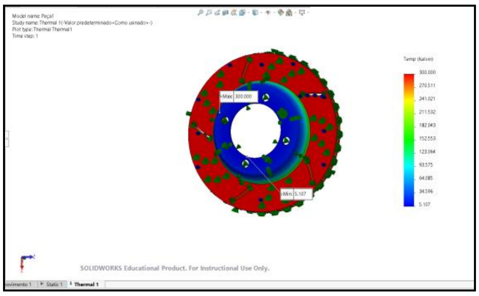

Fig 22 : Result of Temperature Dispersion

Magnesium Alloy

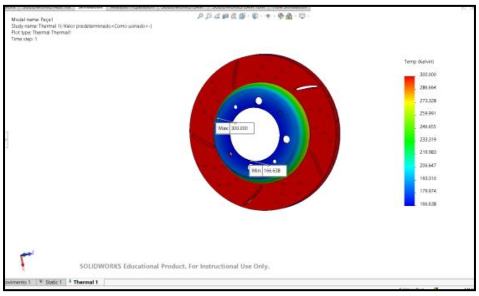

Fig 23 : Result of Temperature Dispersion

Magnesium Alloy :

- In the thermal analysis of a disc brake made from magnesium alloy, results show that the material's low thermal conductivity limits heat dissipation, leading to higher temperatures during braking.
- This can cause thermal stresses, reducing performance and lifespan.
- However, magnesium's lightweight nature offers benefits in reducing overall vehicle weight.
- Proper cooling mechanisms and heat-resistant coatings are crucial to managing thermal loads and improving the brake system's efficiency.

9. GRAPH VARIATION FOR DIFFERENT CONDITIONS

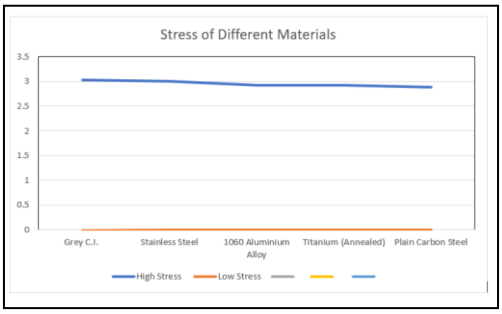

Fig 24 : Graphical Representation of Stress Distribution

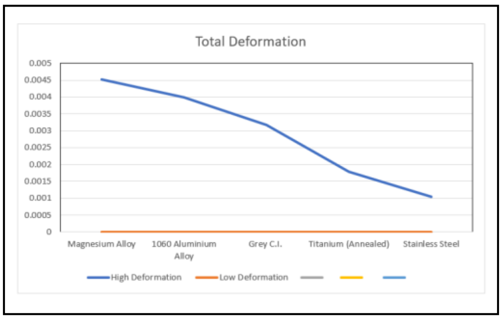

Fig 25 : Graphical Representation of Deformation

10. Discussion

The structural analysis of the disc brake revealed key insights into material performance under braking loads. Von Mises stress distribution highlighted high-stress concentrations at the brake pad-rotor interface, especially at the outer edges. Grey Cast Iron showed superior structural integrity, withstanding high stress without exceeding yield strength. Stainless Steel exhibited moderate deformation but maintained strength due to higher elasticity. 1060 Aluminum and Magnesium Alloys displayed increased deformation, suggesting potential failure under extreme braking.

Titanium Alloy provided a balanced response with moderate deformation and superior fatigue resistance. Total deformation analysis showed that lighter materials experienced greater elongation, making them unsuitable for high-load applications. Thermal analysis indicated that 1060 Aluminum and Magnesium Alloys had excellent thermal conductivity, leading to rapid heat dissipation but higher temperature gradients and potential thermal fatigue.

11. CONCLUSION

The analysis highlights the importance of material selection for optimal braking efficiency and durability. Grey Cast Iron showed superior structural integrity and moderate thermal resistance, making it ideal for disc brakes. Titanium Alloy offered an excellent strength-to-weight ratio and fatigue resistance, suitable for high-performance applications. 1060 Aluminum and Magnesium Alloys provided efficient heat dissipation but suffered from excessive deformation. Stainless Steel, while corrosion-resistant, had higher thermal stress concentrations. The study confirms that the best material choice depends on balancing mechanical strength, thermal performance, and fatigue resistance for specific braking requirements.

FUTURE SCOPE OF WORK

Future research on the effect of material selection on disc brake performance may focus on advanced materials such as ceramic matrix composites, carbon-carbon composites, and nano-reinforced alloys to enhance thermal and structural properties. Exploration of hybrid and functionally graded materials tailored for electric and high-performance vehicles is also promising. Multi-physics simulations combined with experimental validation using embedded sensors can offer deeper insights into real-time performance.

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BIOGRAPHIES

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