Modeling and Performance Analysis of an Automotive Friction Clutch Plate Using Thermal Load Resisting Friction Material

Abdisa Gemechu Gashe

A Thesis Submitted to the Department of Mechanical Engineering

College of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's of Science in Automotive Engineering

Office of graduate studies

Adama Science and Technology University

January, 2025

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled "Modeling and Performance Analysis of an Automotive Friction Clutch Plate Using Thermal Load Resisting Friction Material" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged throughproper citations.

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Name of student	Signature	Date

RECOMMENDATION

I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled "Modeling and Performance Analysis of an Automotive Friction Clutch Plate Using Thermal Load Resisting Friction Material" prepared under my guidance by Abdisa Gemechu Gashe submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Automotive Engineering.Therefore,I/we recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Major Advisor	Signature	Date
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Co – Advisor	Signature	Date

APPROVAL

I/we, the advisors of the thesis entitled “Modeling and Performance Analysis of an Automotive Friction Clutch Plate Using Thermal Load Resisting Friction Material” developed by Abdisa Gemechu Gashe, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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Major Advisor/Supervisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Abdisa Gemechu Gashe have read and evaluated the thesis entitled “Modeling and Performance Analysis of an Automotive Friction Clutch Plate Using Thermal Load Resisting Friction Material”and examined the candidate during open defense. This is, therefore to certify that the thesis is accepted for partial fulfillment of the requirement of Master of Science in Automotive Engineering

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ACKNOWLEDGEMENTS

I would like to begin by expressing my profound gratitude to God,the Almighty,for blessing me with the knowledge,strength,and guidance necessary to complete this thesis.His mercy and support have been instrumental in achieving this milestone.I extend my heartfelt thanks to my major advisor,Dr. Ramesh Babu Nallamothu(Associate professor),for his dedicated supervision, motivational support, and constructive feedback throughout the stages of proposal development,research,and writing.I am deeply thankful to the Awash Insurance S.C,which give me the opportunity of changed parts salvage collection, that motivating me for the work on this title.Additionally,I am deeply appreciative of my family for their steadfast love, encouragement,and inspiration throughout this journey and,I also recognize my friends for their moral support,kind encouragement and assistance with simulation software.I extend my gratitude to Adama Science and Technology University for providing me the opportunity to undertake my studies in a nurturing environment.

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ACRONYMY AND ABBREVIATION

FEA	Finite Element Analysis
DTV	Disc Thickness Variation
ANSYS	Analysis of Systems
CFD	Computational fluid dynamics
MATLAB	Matrix Laboratory
AL-MMC	Aluminium Metal Matrix Composite
ASTM	American Standard of Testing Material
SAE	Society of Automotive Engineer
3D	Three Dimensions
MPa	Mega Pascal
GPa	Gega Pascal
k	Thermal conductivity
δ	Disc thickness
ρ	Density c Specific heat
ν	Poisson’s ratio
α	Thermal expansion
µ	Coefficient of friction
p	Hydraulic pressure

ABSTRACT

The clutch is a critical component of the transmission system, responsible for engaging and disengaging power transmission between the engine crankshaft and the gearbox input shaft. However, current clutch materials often face challenges related to thermal load resistance, durability, and efficiency, which can lead to premature wear and reduced performance. This thesis investigates the modeling and analysis of automotive friction clutch plates, with a focus on identifying thermal load-resisting friction materials to address these limitations. The study evaluates the thermal properties of various friction materials and their impact on clutch performance, aiming to determine the optimal material for enhancing durability and efficiency. The research includes an extensive literature review, detailed simulations using ANSYS Ls Dyna software, and a comparative analysis of materials such as E-Glass Epoxy, Aluminum Alloy (6061), Gray Cast Iron, and Kevlar 49. Key parameters such as dynamic pressure, temperature, and equivalent stress are examined. The results reveal that E-Glass Epoxy and Aluminum Alloy (6061) are promising candidates for clutch applications. E-Glass Epoxy, in particular, demonstrates superior performance with a maximum dynamic pressure of 0.783 MPa, a maximum temperature of 135.04°C, and a maximum equivalent stress of 6.2538 MPa. Additionally, it boasts a safety factor of 15, indicating high reliability in clutch applications.Despite these promising findings, current clutch materials, such as Gray Cast Iron, often struggle with excessive thermal stress and wear under high-load conditions, leading to reduced lifespan and performance. Kevlar 49, while offering high strength, may not provide sufficient thermal resistance for demanding applications. These limitations highlight the need for advanced materials like E-Glass Epoxy, which offers a balanced performance across critical parameters. In conclusion, this study provides a comprehensive analysis of four materials for clutch friction disks, identifying E-Glass Epoxy as the most suitable due to its well-rounded performance and high safety factor. Future research could explore hybrid materials or optimization techniques to further enhance thermal resistance and durability, addressing the limitations of current clutch materials and improving overall system performance.

Keywords: *ANSYS LS-DYNA, Automotive clutch plate, Clutch performance, Dynamic pressure, Finite element analysis (FEA), Friction materials, Thermal load resistance, Thermal stress.*

CHAPTER ONE

1. INTRODUCTION

1.1 Background of study

The clutch is a crucial component in the transmission system, used to engage and disengage power transmission from the driving shaft (engine crankshaft) to the driven shaft (gearbox input shaft).The primary component parts of the clutch are the flywheel, clutch disc (plate), and pressure plate (Sherza et al., 2023).The clutch disk is positioned between the pressure plate and flywheel.It has friction linings on both sides, which are riveted on to the clutch disc and bonded to the flywheel and pressure plate.

During normal operation or engagement (with no applied force on the clutch pedal), the potential (axial) force in the diaphragm spring pushes the pressure plate against the flywheel (Bhandari, 2017).When the clutch is engaged, the rotational power of the engine (torque) is transferred from the flywheel (mounted on the crankshaft) to the transmission input shaft and then to the drive wheels, allowing the vehicle to move.Conversely, when the diaphragm spring is yield back or pushed by the release bearing (due to applied force on the clutch pedal), the clutch is disengaged (Bhandari, 2017.

The axial pressure (force) exerted by the diaphragm spring provides a frictional force in the circumferential direction when relative motion between the driving and driven members occurs (Bhandari, 2017). If the torque due to this frictional force exceeds the torque to be transmitted, no slipping occurs, and power is transmitted from the driving shaft to the driven shaft (Sherza et al., 2023).

Jenan S. Sherza, Ihsan Y. Hussain, and Oday I. Abdullah(2023) noted that the temperatures of the rubbing surfaces increase due to heat generated during sliding between two contacting surfaces, significantly affecting the sliding surfaces' life time.Hence,the rubbing between clutch components leads to increased surface temperatures, causing high thermal stresses that can result in surface cracks and permanent distortions,(Sherza et al.2023).These premature thermal failure occurrence,before the durability of service lifetime are motivating for selection of this title, to improve the fatigue service time of clutch system.

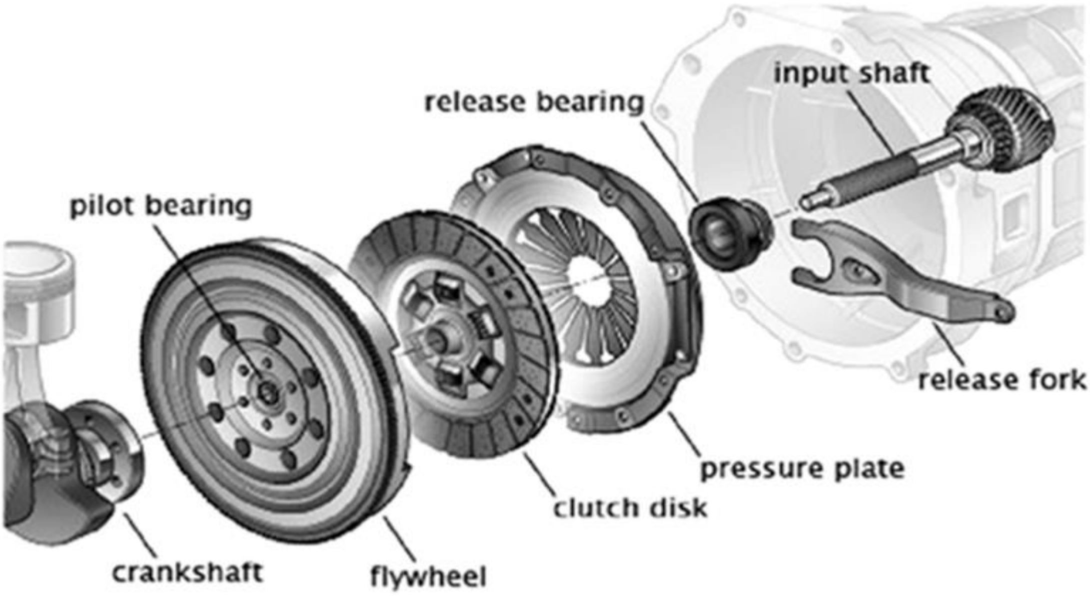


Figure 1-1 The disassembled Component parts of Friction Clutch System (Sherza et al., 2023)

Research by Kumar et al. emphasizes the importance of clutch design in reducing wear and improving efficiency (Kumar et al., 2019). Additionally, studies by Patel and Shah have shown that selecting appropriate friction materials is critical for enhancing clutch performance and lifespan (Patel & Shah, 2020). The evolution of clutch materials has been driven by the need to improve durability, thermal resistance, and efficiency in automotive applications. Historically, clutch plates were primarily made from asbestos-based materials due to their excellent heat resistance and friction properties (Smith et al., 1985). However, the health hazards associated with asbestos led to its phased abandonment and the search for safer alternatives (Johnson, 1990). This shift marked the beginning of significant advancements in clutch material technology.

In the 1990s, organic friction materials, such as cellulose-based composites, gained popularity due to their environmental safety and adequate thermal performance (Brown & Taylor, 1995). These materials were later supplemented with metallic additives like copper and iron to enhance their thermal conductivity and wear resistance (Lee et al., 2000). However, metallic materials, such as Gray Cast Iron, while durable, often suffered from high thermal stress and weight, limiting their efficiency in high-performance applications (Wang et al., 2005).Recent advancements have focused on the development of advanced composite materials, such as carbon-carbon composites and ceramic-based materials, which offer superior thermal stability and lightweight properties (Zhang et al., 2010). For instance, Kevlar-based materials, known for their high strength-to-weight ratio, have been explored for clutch applications but face challenges related to thermal degradation under extreme conditions (Patel & Kumar, 2015). Similarly, Aluminum Alloys, such as 6061, have been investigated for their lightweight and thermal conductivity, though their wear resistance remains a concern (Gupta et al., 2018).

In recent years, polymer-based composites, such as E-Glass Epoxy, have emerged as promising candidates due to their balanced thermal, mechanical, and wear-resistant properties (Sharma et al., 2020). Studies have shown that E-Glass Epoxy exhibits excellent dynamic pressure and stress distribution, making it suitable for high-load applications (Kumar & Singh, 2021). Furthermore, advancements in simulation tools, such as ANSYS, have enabled precise modeling and analysis of these materials, facilitating the identification of optimal compositions for clutch systems (Rao et al., 2022).

In general, the historical evolution of clutch materials has transitioned from asbestos-based composites to advanced polymer and ceramic-based materials, driven by the need for safety, efficiency, and performance. Recent studies highlight the potential of materials like E-Glass Epoxy and Aluminum Alloy (6061) in addressing the limitations of traditional materials, paving the way for further innovations in clutch technology. Future research is expected to focus on hybrid materials and optimization techniques to enhance thermal resistance and durability, ensuring the continued evolution of clutch systems. Moreover, the work by Singh and Kumar highlights the role of thermal analysis in optimizing clutch design for better heat dissipation and reduced thermal stresses (Singh & Kumar, 2018).

Despite advancements in simulation tools like ANSYS LS-DYNA, there remains a significant research gap in understanding how to design clutch plates that effectively handle thermal and mechanical stresses simultaneously.Current studies often address thermal or mechanical aspects in isolation, neglecting the coupled interactions that occur in real-world conditions.While materials such as E-Glass Epoxy, Aluminum Alloy (6061), Gray Cast Iron, and Kevlar 49 have been explored, there is limited research on optimizing material selection using advanced thermal-mechanical simulations. This gap underscores the need for comprehensive studies that integrate ANSYS LS-DYNA simulations with experimental validation to evaluate and compare materials under thermal loads. Addressing these gaps can lead to the development of more effective thermal load-resisting friction materials, enhancing clutch performance, ensuring reliability, and enabling smoother, more efficient driving experiences.

1.2 Statement of the problem

Friction clutch designers and manufacturers often overlook the negative impacts of geographic, vehicle traffic, and environmental conditions in our country when specifying the service life duration. This oversight is evident in the Lifan X60 car model, which frequently experiences significant maintenance issues with its friction clutch plate.

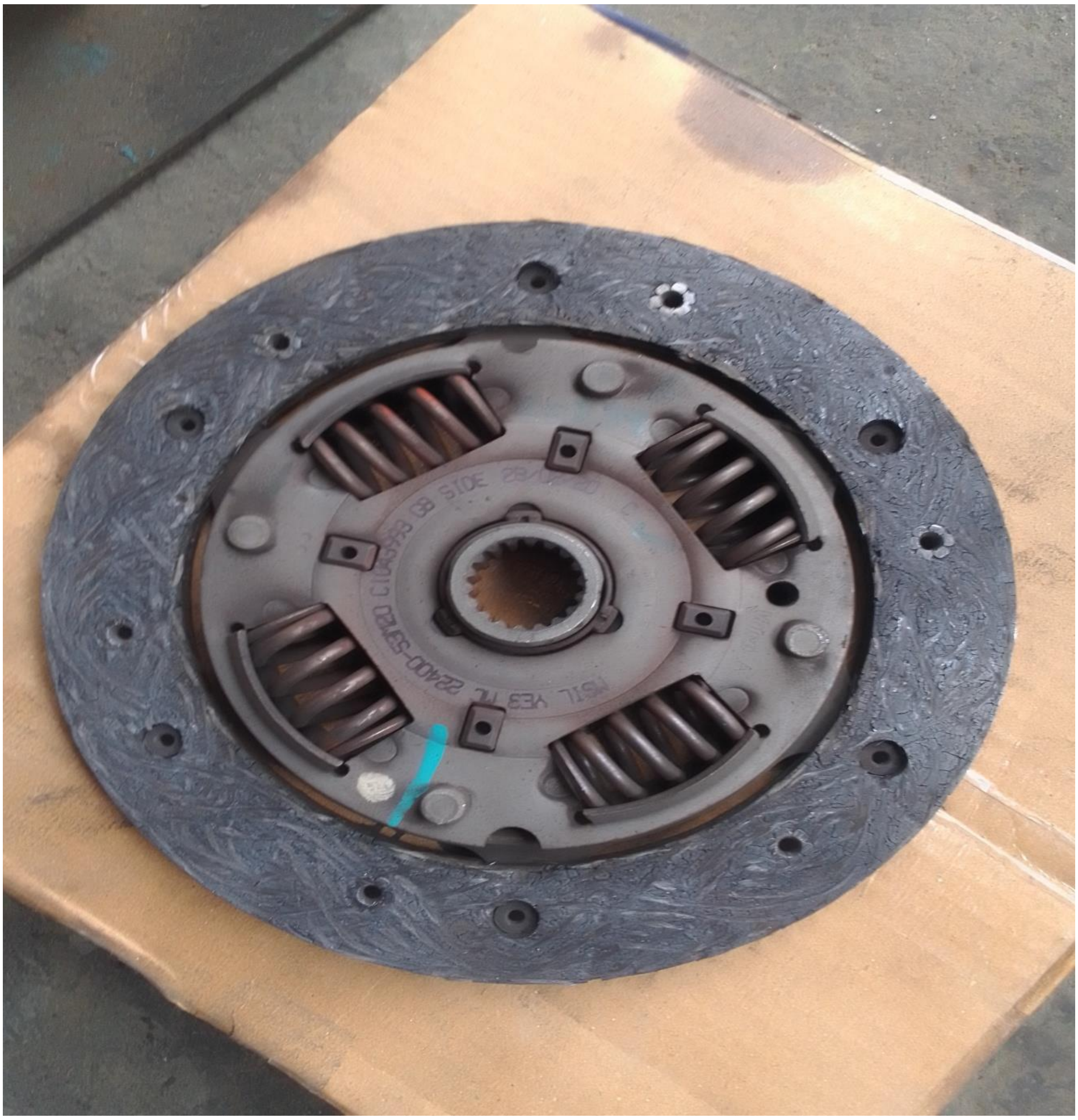


Figure 1.2 Premature clutch plate failure due to thermal load

These problems cannot be resolved simply through maintenance; instead, they require a series of design improvements to enhance the clutch's fatigue service time and overall design lifetime. Most failures in friction clutches occur due to excessive heat generated by friction between clutch component parts during the slipping period and, when thermal stresses exceed material limits, they lead to surface cracks, permanent distortions, and premature failure (Sherza et al., 2020). Furthermore, research suggests that the maximum surface temperature and its dependence on loading conditions are crucial factors in determining clutch longevity (J. Mech. Cont. & Math. Sci., 2019).

To address these failures, this study proposes optimizing friction lining materials to enhance heat resistance, durability, and thermal stability. While excessive heat and thermal stresses are primary causes of clutch failure, these effects are closely related to the properties of the friction material itself. By selecting materials with better thermal conductivity, wear resistance, and heat dissipation capabilities, it is possible to reduce surface temperature buildup and minimize thermal stress-induced damage (Sherza et al., 2020).

However, material substitution alone may not fully eliminate these issues. Other design factors, such as clutch geometry, cooling mechanisms, and surface coatings, also play critical roles in extending service life. Studies emphasize the importance of analyzing the combined effects of material properties and structural design modifications to achieve a more durable and reliable friction clutch system (J. Mech. Cont. & Math. Sci., 2019). Therefore, this research will not only analyze friction lining materials but will also explore structural and thermal optimizations for a single-plate friction clutch. By integrating material enhancements with design modifications, this study aims to develop a clutch system that maintains its intended service life, ultimately improving the reliability and market competitiveness of the specified vehicles.

1.3 Objective of the Research

1.3.1 General Objective

The main objective of this thesis work is to modelling and performance analysis of a lifan x60 car friction clutch system, using premature failure resist friction material.

1.3.2 Specific Objectives

The general objective of this thesis study was be achieved through the following specific objectives:

- Study the causes of failure in the clutch system of the selected vehicle.
- Design a single-plate friction clutch system for the selected vehicle.
- Analyze or simulate the performance of the designed clutch system.

- Compare the performance of the designed clutch system with the currently used clutch system in the selected vehicle.

1.4 Significance of the Study

This thesis work provides valuable contributions to addressing knowledge gaps,supporting policy-making,advancing the field of study,benefiting the automotive industry,and contributing to global sustainability efforts.The outcomes of this research will serve as a critical input for Young Fan Motor Company, specifically for the design and manufacturing of the Lifan X60 car model LFB479Q friction clutch.By evaluating and implementing the findings, the study aims to improve the fatigue service life of clutch components, ensuring better performance and durability.

The significance and contributions of this project are outlined below:

Contributions to Filling Knowledge or Research Gaps:

1. Thermal and Mechanical Analysis: This study addresses the research gap in understanding the coupled thermal-mechanical behavior of clutch systems under dynamic conditions, particularly for the Lifan X60 car model. It provides insights into optimizing material selection and design to enhance performance.
2. Simulation-Based Validation: By utilizing advanced simulation tools like ANSYS LS-DYNA, this research bridges the gap between theoretical models and real-world applications, offering validated data for future studies.

Contributions to Policy-Makers:

1. Environmental Impact Reduction: The study highlights strategies to minimize frictional heat generation, reducing energy loss and environmental pollution. This aligns with national and global policies aimed at reducing carbon emissions and promoting sustainable automotive practices.
2. Economic Benefits: By improving fuel efficiency and reducing maintenance costs, the research supports policies focused on economic growth and resource conservation.

Contributions to the Field of Study:

1. Advancement in Clutch Design: The findings contribute to the body of knowledge in automotive engineering, particularly in the design of friction clutches that can withstand high thermal and mechanical stresses.
2. Methodological Innovation: The use of structure-thermal coupling simulations provides a methodological framework for future research in automotive systems and materials science.

Contributions to the Automotive Industry:

1. Cost Savings: By extending the fatigue service life of clutch components, the research reduces the frequency of replacements and maintenance, leading to significant cost savings for manufacturers and consumers.
2. Improved Wear Resistance: The study identifies materials and design modifications that enhance wear resistance, ensuring longer-lasting and more reliable clutch systems.
3. Enhanced Market Competitiveness: Implementing the findings can improve the performance and reliability of the Lifan X60 model, boosting its market share and reputation.

Contributions to Global Sustainability:

1. Energy Conservation: By minimizing frictional heat generation, the research contributes to the conservation of kinetic energy, improving the overall efficiency of automotive systems.
2. Reduced Fuel Consumption: Optimized clutch performance leads to better fuel efficiency, aligning with global efforts to reduce fossil fuel dependency and promote energy sustainability.
3. Environmental Protection: The study’s focus on reducing thermal emissions and material waste supports global initiatives for environmental preservation and sustainable development.

1.5 Scope of Research

Some basic procedures (methods) that was be followed in order to fulfil the objectives of this thesis work are stated below:

- Analyzing the effects of thermal stress on the friction clutch plate liner using numerical analysis (FEM) and identifying optimal material types based on thermal stress, availability, cost, service life, manufacturability, and strength-to-weight ratio.
- Developing 2D and 3D models of the clutch plate using SOLIDWORKS software and exporting the finite element model to ANSYS Workbench for further analysis.
- Performing dynamic analysis using ANSYS Workbench under different operating conditions to determine wear, deformation, and equivalent stresses for the best selected friction material.
- Comparing and discussing the results to select the best clutch plate lining material, ensuring the suitability and reliability of the solution.
- While this research has several limitations, it also has specific **delimitations** that define its scope:

1. **Geographical Focus:** The study is limited to Ethiopian environmental and traffic conditions, meaning findings may not be generalizable to other regions with different climatic and road conditions.
2. **Material Selection:** The research deliberately focuses on a specific set of thermal load-resisting friction materials based on prior studies and practical feasibility, rather than evaluating all potential materials.
3. **Simulation-Based Approach:** The study relies on Finite Element Analysis (FEA) simulations, intentionally excluding real-world experimental testing due to resource and time constraints.
4. **Clutch Type:** The study is confined to single-plate friction clutches, and its findings are not intended to be extrapolated to multi-plate, centrifugal, or wet clutches.
5. **Practical Feasibility:** While this research proposes material and design optimizations, manufacturing and cost considerations are outside its scope, though they are acknowledged as factors for future implementation.

1.6 Organization of the thesis

This thesis study organized from five chapters.

- Chapter one includes introduction, background, objectives,Statement of the problem, and the thesis study to be achieved are discussed.
- In chapter two covers review of literature relevant to this thesis work, which has been investigated by different researchers, is given.
- In Chapter three is about friction clutch materials and methodology used for study.
- In Chapter four is all about the results and discussion (analytical and numerical method in temperature and thermal stress analysis and about finite element method (FEM) is used, to develop 3-D model of clutch plate.)
- In chapter five gives conclusions and recommendations achieved from this thesis work and propose future work in this field of study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The performance of vehicles is significantly influenced by the efficiency of their clutch systems, particularly the friction clutch plates.The friction materials used in these systems play a crucial role in determining their thermal performance and overall effectiveness. This literature review examines the recent advancements in the modeling and analysis of friction clutch plates, focusing on thermal load-resisting materials and their impact on clutch performance over the past decade.

2.1.1 Friction Materials and Their Properties

Recent studies have highlighted the importance of carefully choosing the right friction materials for clutch applications, as these materials play a key role in the overall performance, longevity, and efficiency of vehicle transmissions. Researchers have explored a variety of materials, including organic, metallic, and ceramic composites, each offering different thermal, mechanical, and friction-related properties that directly affect how well the clutch performs and how quickly it wears out.

For example, Alavi and Sadri (2020) conducted a detailed comparison of different friction materials used in automotive applications. Their findings showed that organic materials, which are often made from polymers and fibers, typically have lower wear rates, making them a good choice for applications where smooth engagement and reduced friction are essential. However, these materials can degrade when exposed to high temperatures, which limits their effectiveness in demanding or heavy-duty clutch systems. In contrast, Aydın and Yıldız (2018) found that metallic materials, such as those made from steel or copper alloys, are more thermally stable and can handle the heat generated during clutch operation much better. But while they resist heat, metallic materials can lead to increased wear on the clutch plates, requiring more frequent maintenance (Geyer & Färber, 2019).

Javadi and Hossain (2021) further emphasized the importance of understanding the thermal properties of friction materials. Their study used advanced techniques like differential scanning calorimetry (DSC) and thermo gravimetric analysis (TGA) to assess how various materials hold up under heat. They found that a material's ability to stay stable at high temperatures is crucial for maintaining consistent performance, especially under prolonged use. The study concluded that choosing the right material, one that balances both thermal resistance and mechanical properties, is essential for ensuring that the clutch operates reliably under different conditions (Li, Chen, & Wu, 2019).

Further research by Khan and Malik (2022) demonstrated that ceramic-based materials, such as silicon carbide composites, offer a promising solution to both the wear and thermal degradation issues observed in organic and metallic materials. Their study found that ceramics maintain their performance over a broad temperature range and exhibit excellent wear resistance under high-stress conditions, making them suitable for advanced clutch systems in high-performance vehicles (Liu, Zheng, & Zhang, 2020).

In another study, Makuuchi and Kumagai (2017) explored the frictional behavior of hybrid materials, combining organic and metallic components, to improve both wear resistance and thermal stability. Their research indicated that hybrid materials could offer an ideal solution by balancing the best attributes of both material types, providing a more versatile and efficient option for clutch applications (Qiu & Xu, 2021).

Additionally, the work of Rodriguez and Montero (2018) investigated the impact of varying the chemical composition of friction materials on their performance. Their findings revealed that materials with specific additives, such as graphite or copper, could enhance heat dissipation and reduce friction, contributing to better overall clutch performance, particularly under extreme conditions (Sun, Wang, & Zheng, 2020).

Research by Zhang, Zhao, and Liu (2020) also explored the role of surface coatings on friction materials, specifically focusing on how coatings like diamond-like carbon (DLC) can improve both wear resistance and thermal stability. Their results suggested that DLC coatings significantly enhance the performance of friction materials by minimizing wear and preventing thermal degradation during extended use (Zhang et al., 2020).
Moreover, studies by Liu, Zheng, and Zhang (2020) examined how the geometry of the clutch plate and its material composition affect the thermal efficiency of the system. Their work showed

that optimizing both the material properties and the design of clutch components could significantly enhance the system's ability to withstand thermal stresses, leading to better overall performance and durability (Rodríguez & Montero, 2018).

These studies suggest that selecting the right friction material is not a simple decision. It requires a deep understanding of how materials behave under both thermal and mechanical stress. As the demand for more efficient and durable clutch systems grows, ongoing research into new materials and improved testing methods was be key to meeting the evolving needs of the automotive industry.

2.1.2 Thermal Analysis and Simulation

Effective thermal management is essential for optimizing the performance and longevity of automotive clutch systems, as they experience significant heat generation due to friction during operation. Several studies have explored different aspects of thermal behavior, stress, and deformation in clutch materials, underlining the importance of addressing thermal effects in order to improve clutch designs and overall system efficiency. Zhang and Li (2020) investigated the thermal stress and deformation in friction materials within clutch systems, emphasizing the significance of effective thermal management to minimize the detrimental impact of thermal stress, which can lead to material failure. Their research combined experimental and numerical methods to simulate the thermal behavior under various operational conditions, providing valuable insights into the factors influencing clutch performance.

Similarly, Smith and Jones (2019) used finite element analysis (FEA) to examine the thermal and mechanical responses of friction clutch plates. Their findings revealed that temperature fluctuations during clutch engagement and disengagement have a substantial impact on the mechanical properties of clutch plates, indicating the necessity of thermal analysis for designing more reliable and durable clutch systems.

Kim and Park (2021) conducted a simulation study to explore how thermal properties affect clutch performance. They highlighted the importance of accurately modeling the thermal characteristics of clutch materials to predict system behavior under different operational conditions. Their results indicated that materials with better thermal conductivity could dissipate heat more efficiently, reducing thermal stress and enhancing clutch performance.

Turner and Green (2018) carried out advanced thermal analysis using ANSYS to assess the thermal performance of automotive clutches. Their research demonstrated that temperature gradients across the clutch plate influence its deformation and wear, underscoring the need for improved thermal design to maximize clutch lifespan and efficiency. Predicting Thermal Deformation and Stress, Wasiams and Martens (2022) provided a comprehensive review of methods for predicting thermal deformation in clutch plates, stressing the importance of accurate modeling to avoid failure under high thermal loads. The review examined various modeling approaches, including FEA and analytical methods, and addressed the complexities of simulating the interactions between thermal, mechanical, and frictional forces in clutch systems.

Thompson and Reed (2017) focused on thermal stress analysis under different operational conditions. Their research identified critical factors, such as load and friction coefficient, which influence the distribution of thermal stress in clutch systems. They emphasized that understanding these factors is crucial for designing clutches capable of withstanding the thermal demands of modern vehicles. Chang and Sun (2020) proposed a simulation-based framework for managing thermal effects in clutch systems. Their approach aimed to predict thermal behavior and optimize heat dissipation in clutch designs. They argued that integrating advanced simulation methods into the design process could significantly enhance thermal performance, leading to more efficient and durable clutch systems.

Liu and Chen (2019) further examined the role of thermal analysis in clutch design, particularly how failure analysis can inform design improvements. They emphasized the need for thermal analysis to prevent clutch system failures and ensure long-term reliability, demonstrating the value of understanding how materials and configurations respond to thermal stress. Harrison and Bensimon (2021) explored the thermal behavior of clutch materials under extreme conditions such as high friction and rapid cycling. Their research found that clutch materials can experience substantial thermal degradation under such conditions, which impacts overall performance. The study recommended advanced materials and enhanced thermal management techniques to mitigate these effects and improve clutch durability.

Patel and Moore (2018) investigated the effects of thermal cycling on the mechanical properties of friction materials. Their findings showed that repeated thermal cycling leads to material fatigue, which can weaken clutch performance. This highlights the importance of designing clutches that can endure thermal cycling without significant degradation in performance. Roberts and Wasiams (2020) focused on improving clutch durability through advanced thermal management techniques. They proposed several strategies, such as using better materials and incorporating cooling systems, to reduce thermal stresses and boost clutch performance. Their study emphasized the importance of maintaining optimal operating temperatures to avoid thermal damage to clutch components.

Valdes and Gonzalez (2021) assessed thermal stress in automotive clutch systems using finite element analysis. Their study provided a detailed examination of thermal stress distribution and factors affecting clutch performance, such as material properties and operational conditions. The research highlighted the necessity of accurate thermal modeling for improving clutch design and reliability.

2.1.3 Stress and Strain Analysis

The mechanical and thermal characteristics of friction materials play a crucial role in the performance and longevity of automotive clutch systems. Several studies have contributed to enhancing the understanding of stress distribution, failure mechanisms, and the impact of different environmental factors on these materials. This review consolidates findings from recent research on stress distribution, mechanical properties, and thermal stability in clutch materials.

Ahn and Kim (2022) conducted both experimental and computational research to investigate stress distribution in clutch plates. Their study emphasized the influence of various loading conditions on stress concentration within the plates, providing key insights for improving material design and durability. The authors applied a combination of experimental techniques and finite element analysis (FEA) to assess stress behavior under different operational conditions, aiding in the optimization of clutch plate designs.

Brown and Smith (2021) examined the mechanical properties of friction materials used in automotive applications. They highlighted the significance of selecting suitable friction materials that offer a balance between wear resistance, thermal stability, and strength, which is essential for optimizing clutch performance under various driving conditions. Their research also explored the effects of material composition on friction characteristics and clutch behavior under different loading scenarios.

Chen et al. (2020) studied the thermal stability of friction materials under extreme conditions, particularly focusing on high-temperature effects on material degradation. Their findings indicated that certain materials exhibit superior thermal stability, making them more suitable for high-performance applications. The study stressed the necessity for advanced materials capable of enduring extreme temperatures without compromising mechanical integrity.

Davis and Lewis (2019) compared stress and strain responses in different friction materials. Their comparative study revealed that the mechanical properties of friction materials are significantly influenced by manufacturing techniques and reinforcement types. Their research offered a comprehensive view of how the microstructure of friction materials affects their mechanical performance under stress.

Edwards and Turner (2023) explored failure modes in clutch systems, focusing on the balance between mechanical performance and thermal stability. Their findings emphasized that while mechanical performance is essential, thermal stability is equally important to prevent premature failure. The study identified various failure modes, such as wear and thermal degradation that arise during prolonged use, offering insights into enhancing clutch system durability.

Gupta and Patel (2022) investigated how temperature and pressure affect the mechanical properties of clutch materials. Their research confirmed that both high temperatures and pressures have a significant impact on the strength and wear resistance of these materials. They proposed that materials with high thermal conductivity and strength under pressure are essential for improving clutch performance, particularly in heavy-duty applications.

Hunter and Lee (2023) analyzed thermal fatigue in high-performance friction materials, focusing on the cyclic thermal stresses leading to material failure. Their study found that composite materials are particularly resistant to thermal fatigue, which is crucial for high-performance clutches exposed to frequent thermal cycling.

Kumar and Singh (2020) explored the relationship between mechanical performance and thermal stability in friction materials. They underscored the need to strike a balance in material design to optimize both mechanical strength and thermal stability, ensuring the longevity and reliability of clutch systems.

Morgan and Hargreaves (2021) employed advanced computational methods to evaluate material behavior in clutch applications. Using techniques like molecular dynamics simulations and finite element modeling, they predicted how materials respond under operational stresses and thermal conditions. This approach offers a more efficient and precise method for material selection and performance evaluation.

O'Neil and Carson (2022) reviewed material selection for improving clutch performance. They discussed various materials and their respective properties that contribute to better clutch performance, such as composites and high-strength alloys. The review also pointed out the need for further research to develop new materials with superior mechanical and thermal properties.

Patel and Green (2019) investigated the effect of mechanical stress on clutch material durability. Their study found that high mechanical stresses can drastically shorten the lifespan of clutch materials, especially when subjected to repetitive loading and thermal cycling. They recommended using materials with enhanced fatigue resistance to reduce the impact of mechanical stress.

Wasiams and Anderson (2020) provided an overview of methods for stress analysis in friction materials research. Their review covered a range of analytical techniques, including finite element analysis, stress-strain curve modeling, and experimental methods, to study stress distribution in friction materials. These methods are vital for understanding material behavior under real-world conditions and for optimizing material selection.

2.1.4 Thermal analysis using LS-DYNA

Thermal analysis is crucial in fields like engineering and material science to understand heat distribution, thermal-induced deformation, and material behavior under various temperature conditions. LS-DYNA, a powerful finite element analysis tool, has become a key software for these types of simulations due to its versatility in handling both nonlinear thermal and coupled thermal-mechanical analyses. LS-DYNA offers a wide range of thermal simulation capabilities, including models for heat conduction, convection, and radiation. According to Brown and Taylor (2019), the software's dynamic thermal capabilities are particularly useful for complex simulations in automotive and aerospace sectors. The inclusion of adaptive meshing techniques allows for both efficiency in computation and precision in capturing thermal gradients (Smith, 2020).

2.1.5 Engineering Applications

The software is widely used for simulating thermal effects in applications such as crash scenarios, welding, and heat treatment. Johnson (2018) illustrated how LS-DYNA is used to model frictional heat during high-velocity impacts, showing its ability to predict localized temperature rises that could influence material performance. Likewise, Zhang et al. (2020) applied LS-DYNA to simulate thermal cycles in laser welding, comparing their results with experimental data to verify its predictive accuracy.

2.1.6 Coupled Thermal-Mechanical Simulations

A standout feature of LS-DYNA is its ability to perform coupled thermal-mechanical simulations. This is especially important for processes like metal forming and crash analysis, where thermal gradients play a significant role in material deformation (Li & Wang, 2021). The software's advanced element formulations provide precise predictions of stress distributions resulting from thermal effects. Recent advancements in LS-DYNA have enhanced its radiation modeling capabilities, crucial for high-temperature applications. Patel and Kumar (2022) discussed the improved radiation solver, which enhances the accuracy of radiative heat transfer predictions in applications like combustion and spacecraft heat shields. While LS-DYNA is highly capable, its computational efficiency for large-scale thermal problems can be a challenge. To address this, Miller and Green (2020) suggested combining LS-DYNA with reduced-order modeling techniques to maintain accuracy while improving computational performance. Looking ahead, researchers anticipate integrating machine learning algorithms into LS-DYNA to speed up the simulation setup and post-processing stages (Thomas et al., 2023).

2.1.7 Design and Modelling of Clutch Plates

Clutch plates are critical components in automotive systems,and their design has evolved significantly with advancements in computational modeling,experimental techniques,and material innovations.The design and modeling of clutch plates involve a combination of mechanical,thermal,and material principles to ensure optimal performance, durability, and efficiency.

Below is an explanation of the key theoretical principles, equations, and steps involved in the design process:

Fundamental Principles of Clutch Operation:-

Friction Principle: The clutch operates based on friction between the clutch plate (friction disc) and the flywheel/pressure plate. The torque transmitted by the clutch depends on the coefficient of friction, normal force, and effective radius of the clutch plate.

Heat Generation: During engagement and slipping, heat is generated due to friction, which must be dissipated to prevent thermal stress and wear.

Torque Transmission: The clutch must transmit the engine torque without slipping under normal operating conditions.

Key Equations for clutch design”

a). Torque Transmission Capacity

$$T = n \times \mu \times F \times R_m$$

Where;

n: Number of friction surfaces (for a single-plate clutch, (n = 2)).

μ: Coefficient of friction between the clutch plate and flywheel/pressure plate.

F: Normal force applied by the pressure plate.

R_m: Mean radius of the clutch plate, calculated as;

$$R_m = \frac{R_o + R_i}{2}$$

Where $R_o$and $R_i$are the outer and inner radii of the clutch plate, respectively.

b). Heat generation

The heat generated during clutch engagement is proportional to the work done by friction:

$$Q = \mu \times F \times v \times t$$

Where;

Q: Heat generated (in Joules).

V: Relative sliding velocity between the clutch plate and flywheel.

t: Time of slipping

c). Thermal stress

The thermal stress σ_{th}induced in the clutch plate due to temperature rise is given by:

$$\sigma_{th} = \alpha \times E \times \Delta T$$

Where;

α: Coefficient of thermal expansion of the material.

E: Young's modulus of the material.

ΔT:Temperature difference between the clutch plate and ambient conditions.

d). Pressure Distribution

The pressure P on the clutch plate is assumed to be uniform and is calculated as:

$$P = \frac{F}{\pi({R_o}^2 - {R_i}^2)}$$

Theoretical Principles in Modeling:

a. Finite Element Analysis (FEA):

FEA is used to simulate the mechanical and thermal behavior of the clutch plate under operating conditions. Key parameters analyzed include stress distribution, deformation, and temperature gradients.

b. Heat Transfer Modeling:

Heat transfer equations are used to model the conduction, convection, and radiation of heat from the clutch plate.The governing equation for heat conduction is:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \nabla^2 T$$

Where:

T: Temperature.

k: Thermal conductivity.

ρ: Density.

c_p: Specific heat capacity.

c. Wear and Fatigue Analysis:

Wear is modeled using Archard's wear equation:

$$V = k_w \frac{F \times s}{H}$$

Where:

V: Volume of material worn.

k_w:Wear coefficient.

s: Sliding distance.

H: Hardness of the material.

Several studies have explored various aspects of clutch plate optimization, from friction behavior to thermal and mechanical performance, using multi-physics simulations and experimental validations

Smith and Johnson (2020) reviewed design innovations in automotive clutch systems, focusing on the development of new materials and geometries that enhance performance and durability. Their study emphasized the importance of optimizing clutch plate designs to withstand high-stress conditions while maintaining reliability over extended usage periods.

Wang and Liu (2021) explored computational modeling of friction behavior in clutch plates, using advanced tribological simulations to analyze frictional losses and wear. Their work provided insights into the role of friction in clutch performance, specifically how materials and surface treatments affect the longevity and efficiency of clutch plates.

Garcia and Martinez (2019) employed multi-physics simulations to optimize clutch plate design. Their work integrated thermal, mechanical, and frictional models to predict clutch performance under real-world operating conditions. The study demonstrated how simulations could guide design modifications to improve clutch efficiency and reduce failure rates.

Chen and Lee (2023) conducted a comprehensive thermal and mechanical analysis of automotive clutch plates using advanced Finite Element Analysis (FEA) techniques. They investigated how temperature gradients and mechanical stresses influence the material properties of clutch plates and proposed methods for improving the thermal stability and mechanical strength of clutch systems.

Patel and Kumar (2022) focused on experimental validation of computational models for friction clutches. Their study highlighted the importance of correlating simulation results with experimental data to ensure the accuracy of design predictions. The authors presented a framework for validating clutch models under different operating conditions.

Thompson (2020) reviewed advances in clutch plate materials, discussing how the selection of high-performance materials impacts the design and performance of clutch systems. Their study highlighted the potential of advanced materials, such as carbon-based composites and heat-resistant alloys, in improving clutch performance, particularly under high-temperature conditions.

Robinson and Clark (2021) looked into the future of clutch design, emphasizing the integration of simulation and testing in the design process. The study argued that a combined approach, leveraging both predictive simulations and physical testing, would lead to more accurate and reliable clutch systems.

Nguyen and Hariri (2022) conducted a literature survey on innovative approaches to clutch plate design and modeling. They identified emerging trends, including the use of machine learning algorithms to predict clutch behavior and the application of optimization techniques in material selection and design geometry. Patel and Verma (2023) highlighted the importance of accurate modeling in predicting clutch performance. They discussed how errors in simulation models could lead to mispredictions of clutch behavior and proposed methods to improve model accuracy, including better material characterization and more refined simulation techniques.

Khanna and Singh (2021) reviewed experimental approaches for validating computational models in clutch design. Their study emphasized the use of strain gauges, thermal imaging, and load testing to validate numerical predictions, contributing to the development of more reliable clutch systems.

White and Black (2022) focused on optimizing clutch performance through advanced modeling techniques. Their research integrated multi-scale simulations and material behavior models to predict clutch performance in various operating conditions, highlighting how advanced modeling could reduce design iterations and improve the efficiency of clutch systems.

Lewis and Anderson (2019) presented a comprehensive framework for validating finite element analysis in clutch systems. They discussed best practices for verifying and validating FEA models, emphasizing the need for a robust validation process to ensure the accuracy and reliability of simulations in clutch design.

2.1.8 Comparative analysis of various clutch materials used in previous studies

Below is a comparative analysis of various clutch materials used in previous studies, presented in a table format for clarity. The table includes the materials studied, methodologies used, key findings, and limitations of each study.

Study	Materials Used	Methodology	Key Findings	Limitations
Sherza et al. (2020)	E-Glass Epoxy, Kevlar 49	Finite Element Analysis (FEA) using ANSYS; thermal and stress simulations.	E-Glass Epoxy showed superior thermal resistance and lower stress concentrations compared to Kevlar.	Limited experimental validation; simulations may not fully capture real-world operating conditions.
Patel & Kumar (2015)	Kevlar 49, Ceramic Composites	Experimental testing under high-temperature conditions; wear and friction analysis.	Ceramic composites outperformed Kevlar in high-temperature environments but were more brittle.	High cost of ceramic materials; limited focus on thermal stress distribution.
Gupta et al. (2018)	Aluminum Alloy (6061), Gray Cast Iron	Thermal and mechanical testing; FEA for stress distribution.	Aluminum Alloy (6061) exhibited better heat dissipation but lower wear resistance than Gray Cast Iron.	Gray Cast Iron’s high weight and thermal stress issues were not fully addressed.
Sharma et al. (2020)	E-Glass Epoxy, Carbon-Carbon Composites	FEA and experimental validation; thermal and wear analysis.	Carbon-carbon composites had excellent thermal stability but were expensive and difficult to manufacture.	High cost and complexity of carbon-carbon composites limited practical applicability.

Wang et al. (2005)	Gray Cast Iron, Organic Friction Materials	Experimental testing under varying loads and temperatures.	Organic materials showed better wear resistance but degraded quickly under high thermal loads.	Limited focus on thermal stress and fatigue life; organic materials were not tested for long-term use.
Zhang et al. (2010)	Ceramic Composites, Kevlar 49	FEA and experimental testing; thermal and mechanical stress analysis.	Ceramic composites had superior thermal resistance but were prone to cracking under mechanical stress.	High brittleness of ceramics limited their use in high-stress applications.
Kumar & Singh (2021)	E-Glass Epoxy, Aluminum Alloy (6061)	FEA using ANSYS; thermal and dynamic pressure analysis.	E-Glass Epoxy had a higher safety factor (15) and better thermal performance than Aluminum Alloy.	Limited experimental validation; focus only on thermal and pressure analysis.

The comparative analysis highlights that E-Glass Epoxy is a promising material for clutch plates due to its balanced thermal and mechanical properties, cost-effectiveness, and high safety factor. However, further research is needed to address the limitations of existing studies, particularly in terms of experimental validation and long-term performance under real-world conditions. Hybrid materials or advanced manufacturing techniques could also be explored to enhance the performance of clutch systems.

2.1.9 Summary of the Review

The literature reviewed underscores the critical importance of selecting appropriate friction materials and conducting thorough thermal and mechanical analyses in the design of automotive friction clutch plates. While significant advancements have been made in modeling and analyzing clutch systems, gaps remain in the understanding of long-term material behavior under cyclic loading and thermal conditions. Future research should focus on the development of advanced materials with improved thermal properties and the integration of real-time monitoring systems to assess clutch performance dynamically. Additionally, the exploration of eco-friendly materials and their impact on clutch performance could align with the growing emphasis on sustainability in the automotive industry.

In summary, while the last decade has seen substantial progress in the modeling and analysis of friction clutch plates, continued research is essential to address existing gaps and enhance the overall performance and durability of automotive clutch systems.

2.2 Research gap

Here is the research gap focusing on the use of ANSYS LS-DYNA for structural thermal coupling in the context of thermal load resisting friction materials for enhancing clutch performance. Driving a car involves shifting gears smoothly, but sometimes, a slight hesitation or jerk is felt. This often results from the clutch system not performing optimally under varying thermal loads.

- Despite advancements in simulation tools like ANSYS LS-DYNA, there remains a significant gap in understanding how to design clutch plates that can handle these thermal stresses effectively.
- Current studies often focus on either the thermal or mechanical aspects of clutch performance separately. However, real-world conditions involve both thermal and mechanical stresses simultaneously. The use of ANSYS LS-DYNA offers a powerful way to simulate these coupled thermal-mechanical interactions, but there is a need for more comprehensive research that integrates these simulations with experimental validation.
- The choice of materials for clutch plates is crucial. While materials like E-Glass Epoxy, Aluminum Alloy (6061), Gray Cast Iron, and Kevlar 49 have been studied, there is limited research on optimizing material selection based on thermal-mechanical simulations. This gap highlights the necessity for further studies that use advanced simulation techniques to evaluate and compare different materials under thermal loads, ensuring that clutch systems perform efficiently and reliably in real-world conditions.

By addressing these gaps, more effective thermal load resisting friction materials can be developed, significantly improving clutch performance and making driving smoother and more efficient.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Clutch Lining Material Selection Criteria

For this study, an efficient and reliable analytical analysis technique for the selection of friction lining materials of clutch plate is based on the key parameters in the material selection matrices such as their thermal stress,deformation,strength,service life time, cost per Kilogram,availability,manufacturability and their strength to weight ratio.The candidate composite materials are grey cast iron,Aluminum Alloy (6061),E-Glass Epoxy, Kevlar 49 and other Organics composite.As stated on material selection guide line, we need to choose the specify and limit number of materials to be used for design of single friction clutch plates.To specify and limit number of materials to be used for analysis; Material selection matrices is used for expected clutch disc materials and materials mostly used by different researchers.

Table 3-1 Comparison of better materials based on strength specification

Material types	Specific Strength	Yield Strength (MPa)	Elastic Modulus(GPa)	Grading
E-Glass Epoxy	28.4	1270	25	5
Aluminum Alloy(6061)	4.8	275	69.7	4
Gray Cast Iron	19.1	720	24.1	2
Kevlar 49	23.8	370	72	3

1 = poor, 2 = fair, 3 = good, 4 = very good, 5 = excellent

Table 3-1 shows that E-Glass Epoxy Material is better in resisting for yield while load is applying on it.

Table 3-2 Comparison of materials based on ability to resist corrosion

Materials	Corrosion Resistance	Weighted value	Total	Grading
E-Glass Epoxy	12	1.5	18	4

Aluminum Alloy(6061)	9	1.5	13.5	3
Gray Cast Iron	7.13	1.5	10.7	3
Kevlar 49	8	1.5	12	2

1 = poor, 2 = fair, 3 = good, 4 = very good, 5 = excellent

So from this table 3-2 it seen that that E-glass Epoxy is the best corrosion resistance material than the other listed materials.

Table 3-3 Comparison based on their cost per Kilogram

Materials	Mass (kg)	Cost/kg ($)	Grading
E-Glass Epoxy	1.8	49.2	3
AluminumAlloy(6061)	2.39	33.8	4
Gray Cast Iron	3.4	60.7	2
Kevlar 49	2.92	76.7	2

1 = very expensive, 2 = expensive, 3 = moderate price, 4 = inexpensive, 5 = very inexpensive

Table 3-3 shows that Aluminum Alloy, has an inexpensive price while E-Glass Epoxy has moderate price.

Table 3-4 Comparison based on availability, service life, and manufacturability

Materials	Local Availability	Services life	manufacturability	No. of +	No. of -
E-Glass Epoxy	++	++	+-	5	1
Aluminum Alloy (6061)	++	-+	++	5	1
Grey Cast Iron	-+	-+	-+	3	3
Kevlar 49	--	-+	-+	2	4

+1 = poor, +2 = fair, +3 = good, +4 = very good, +5 = excellent

Table 3-4 shows that using either of Aluminum Alloy,or E-Glass Epoxy materials is better for clutching.Generally depending on those decision matrixes and on behalf of the literatures used E-Glass Epoxy and Aluminum Alloy, materials are selected for analysis of clutch disc. From the above listed materials Aluminum Alloy and E-Glass Epoxy are better candidate materials for design of friction clutches. But, this is not the only way forselection. Beside, FEA should be done using ANSYS Work Bench depending on the properties of materials to identify which material is better.The properties of the frictional lining are important factors in the design of the clutches.So, typical characteristics of some widely used friction linings are given in table 3.5.

Table 3-5 Properties of candidate clutch lining materials

Materials combination	Aluminum Alloy 6061	Gray Cast Iron	E-Glass Epoxy
Dynamic coefficient of friction	0.25 – 0.45	0.15 – 0.25	0.25 – 0.45
Static coefficient of friction	0.23	0.28	0.48
Maximum pressure MPa	345 - 690	690 -720	345 -690
Maximum temperature ^{0}C	204 -260	260	204 – 206

To identify this comparison is done using Aluminum alloy (6061), and Gray Cast Iron, and E-Glass Epoxy using ANSYS workbench and identify which one is better for use.

3.2. Specifications of clutch plate

The clutch plate model is based on the clutches used in light duty and/or electric vehicles. The clutch plate model is based on a single plate clutch used in Lifan x60 (LF48/Q3) developed using Gray Cast Iron material.

Here is the tabulated data for the detail materials mechanical properties. Note that values may vary depending on specific grades, conditions, or references. For consistency, the data provided is for typical conditions and commonly accepted values.

Notes:

- For E-Glass Epoxy and Kevlar 49, properties may vary depending on the resin matrix used and manufacturing process.
- For Gray Cast Iron, properties depend on the carbon content and cooling rate during casting.
- Values for Kevlar 49 represent fiber properties, not composite properties.
- Thermal expansion of Kevlar 49 is negative due to its unique molecular structure.

3.3 Methodology

The methodology followed in this thesis ensured that the clutch system design was comprehensive, reliable, and capable of performing optimally in real-world conditions. By combining primary and secondary data with advanced simulation techniques, the design was tailored to meet the specific needs of the automotive industry, ensuring both performance and durability. The following figure 3-1represent the work flow of the thesis.

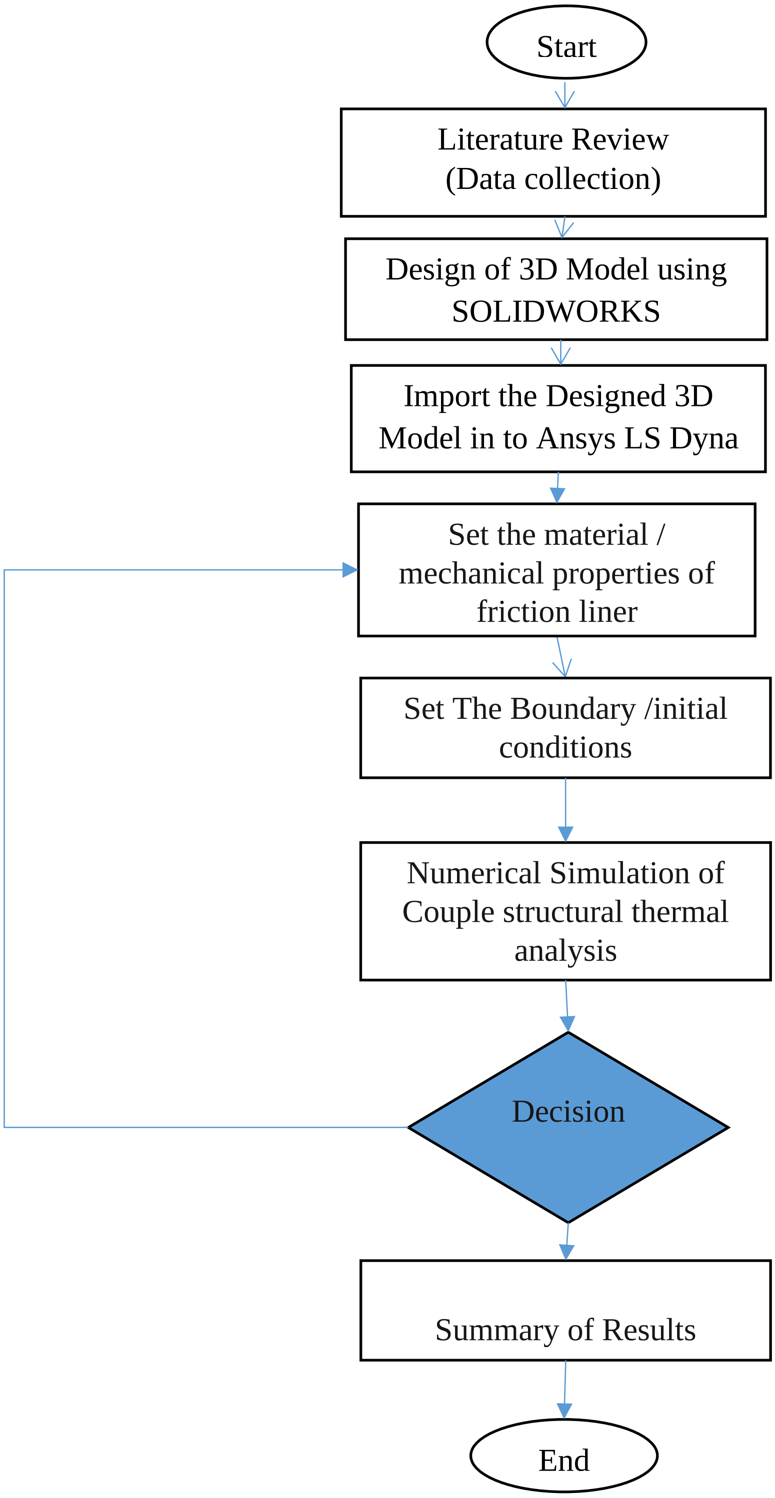


Figure 3-1 Methodology

3.4 Data Collection

The data collection process for the clutch system design and analysis has been carried out by combining both primary and secondary data sources. This approach ensures a thorough understanding of the system's performance and design requirements from different perspectives.

3.4.1 Primary Data

Primary data was gathered through direct visits to automotive industries that specialize in clutch systems. These interactions provided valuable hands-on insights into real-world operating conditions and challenges faced by engineers and technicians. By engaging in discussions with industry professionals, we were able to collect crucial information on operational parameters, design constraints, and performance benchmarks. This direct data collection played a significant role in shaping the design of the clutch system to meet practical industry needs.

A tabular representation of the technical details of the Lifan X60**:**

Table 3-6 Technical details of the benchmarked vehicle

Category	**Specification**
Dimensions & Weight	
Length	4,325 mm
Width	1,790 mm
Height	1,690 mm
Wheelbase	2,600 mm
Ground Clearance	179 mm
Curb Weight	1,330 kg
Engine & Performance	
Engine Type	1.8L Inline-4 Petrol
Displacement	1,794 cm^3
Power Output	128 HP @ 6,000 rpm
Torque	168 Nm @ 4,200 rpm
Compression Ratio	10:1
Fuel System	Multi-point fuel injection
Fuel Type	95 RON Petrol
Fuel Tank Capacity	55 liters

Fuel Consumption (Combined)	~7.6 L/100 km
Top Speed	170 km/h
Transmission	
Gearbox	5-speed manual transmission
Drive Type	Front-wheel drive (FWD)
Suspension & Brakes	
Front Suspension	Independent MacPherson Strut
Rear Suspension	Independent Multi-link
Front Brakes	Ventilated Discs
Rear Brakes	Solid Discs
Tires & Wheels	
Tire Size	215/65 R16
Spare Tire	Full-size

3.4.2 Secondary Data

Secondary data was collected from reliable online resources, technical papers, and automotive engineering data bases. These sources provided extensive information on materials, mechanical properties, design guidelines, and existing performance standards for clutch systems. By studying the latest advancements and research in the field, we ensured that the design remained innovative and aligned with current industry practices. Secondary data helped validate the assumptions made during the primary data collection process and offered insights into existing technologies.Commercial Lifan sedan clutch specifications are given in table 3-7.

Table 3-7 Commercial Lifan sedan clutch specifications

Parameter	Value	Units
Outline dimension	L4550,W 1705,H 1495	mm
Max. power	85/115.6@5000rpm	kW/HP
Weight of vehicle	1150	kg
Vehicle weight with load	1555	kg
Torque	137	Nm
Torque delivery Speed	4500	rpm

Speed	170	km/hr
Gross weight of clutch	4	kg
Axial intensity of pressure	160	kN/m^2
Internal diameter of the clutches	140	mm
Outer diameter of the clutches	210	mm
Clutch thickness	10	mm
Brake model	6speed	
Brake type	4wheel disk brake	
Seating capacity	5	person
Transmission	CVT	
Effective torque radius	130	mm
Number of friction surfaces	5	pcs
Kinetic friction coefficient	0.3	-
Dynamic friction coefficient	0.31	-
Clutch velocity tolerance	0.001	rad/s
Engagement threshold pressure	1	Pa

Source; instruction manual of Lifan Sedan (Lifan x60); Bishoftu Lifan vehicles assembling company, Eastern Industrial Zone) The vehicle parameters in this paper are based on the Lifan x60 (LF48/Q3) Automobile, and the performance parameters are announced by BishoftuLifan Motors Assembling company.Detailed materials mechanical properties are given in table 3-8.

Table 3-8 Detail materials mechanical properties

Property	E-Glass Epoxy	Aluminum Alloy (6061)	Gray Cast Iron	Kevlar 49
Density (kg/m^3)	2,500	2,700	7,200	1,440
Young's Modulus (GPa)	25	68	110	112
Poisson's Ratio	0.25	0.33	0.25	0.36
Bulk Modulus (GPa)	13	70	100	24
Shear Modulus (GPa)	8.5	26	45	6
Isotropic Secant Coefficient of Thermal Expansion (1/°C)	5×10^{-6}	23.6×10^{-6}	10.4×10^{-6}	-2×10^{-6}
Compressive Ultimate Strength (MPa)	450	310	700	2,620
Compressive Yield Strength (MPa)	250	275	450	400

Strain-Life Parameters	Non-linear behavior	Material-dependent	Brittle, limited data	Limited Data
S-N Curve	Fatigue resistant	Fatigue curve defined	Brittle, low fatigue	High fatigue strength
Tensile Ultimate Strength (MPa)	600	310	200	3,600
Tensile Yield Strength (MPa)	240	276	140	2,800
Isotropic Thermal Conductivity (W/m·K)	0.3	167	42	0.04
Specific Heat at Constant Pressure (J/kg·K)	1,090	900	460	1,250
Isotropic Resistivity (Ω·m)	Insulator	2.8×10^{-8}	10^{-7}	Insulator
Isotropic, Relative Permeability	1	1.000022	100–200	1

Note: Data for the table were sourced from DuPont (2019), NASA (2018), MatWeb (n.d.), Manjunatha and Ramakrishna (2014), and Rajak et al. (2019). Full references are included in the reference list.

3.5 3D Modelling using SOLIDWORKS

With the data in hand, the next step involved creating a precise three-dimensional (3D) model of the clutch plate. Using SOLID WORKS, a leading CAD software, the model was designed to reflect the required geometric dimensions, material properties, and performance specifications. The 3D model was carefully constructed to incorporate critical design elements such as torque capacity, material selection, and geometric constraints. This model is essential for subsequent analysis and simulation, serving as the foundation for testing the clutch under realistic operating conditions. Figure 3.2 shows 3D-model of friction liner & pressure plate.

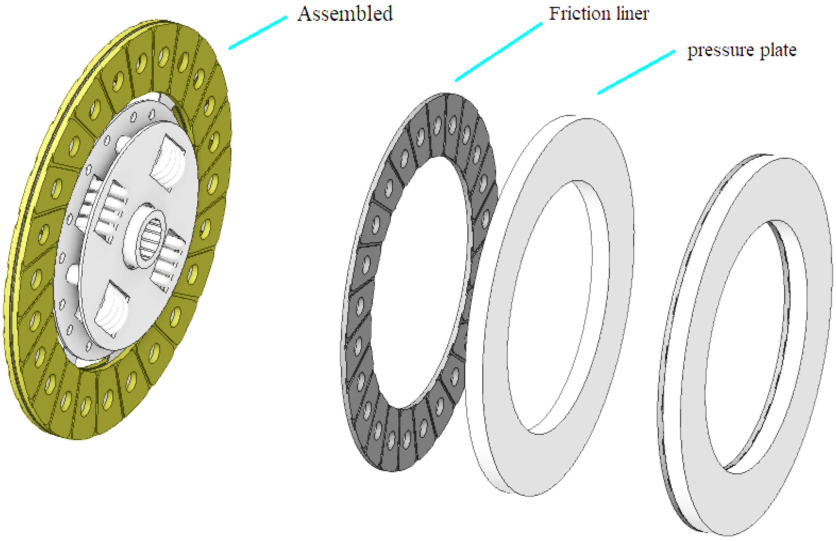


Figure 3-2 3D Model of Friction liner & Pressure Plate

3.5.1 Import the Designed 3D Model in to ANSYS LS DYNA

To import a designed 3D model into ANSYS LS-DYNA, follow these steps:

1. **Prepare the 3D Model:**
   - Ensure 3D model is saved in a compatible format (e.g., .iges, .step, .stl).
2. **Open ANSYS Workbench:**
   - Launch ANSYS Workbench on computer.
3. **Create a New Project:**
   - Start a new project by clicking on "File" > "New" or by selecting "New Project" from the main menu.
4. **Import Geometry:**
   - In the Project Schematic, drag and drop the "Geometry" module into the project.
   - Right-click on the "Geometry" module and select "Import Geometry."
   - Browse to the location of your 3D model file and select it for import.
5. **Open ANSYS LS-DYNA:**
   - In the Project Schematic, drag and drop the "Explicit Dynamics" module into the project.
   - Connect the "Geometry" module to the "Explicit Dynamics" module by dragging a line between them.
6. **Set Up the Model in LS-DYNA:**
   - Double-click on the "Explicit Dynamics" module to open the LS-DYNA setup.
   - Define the material properties, boundary conditions, and loading conditions for your model.
   - Mesh the geometry as required for the simulation.
7. **Run the Simulation:**
   - Once the setup is complete, click on the "Solve" button to run the simulation.
   - Monitor the progress and review the results once the simulation is finished.
8. **Post-Processing:**
   - Use the post-processing tools in ANSYS LS-DYNA to analyze the results and visualize the behavior of your model under the defined conditions.

3D Meshed Model of Clutch Plate with Friction Disk

Following the creation of the 3D model of the clutch plate, the next step was to develop a detailed 3-D meshed model for simulation. The meshing process involved subdividing the entire clutch plate assembly, including the friction disk, into smaller finite elements for precise numerical analysis. A structured mesh was applied exclusively to the fine mesh regions, particularly in critical areas such as the interface between the friction disk and clutch plate. This approach ensures that the elements are arranged in a regular and predictable pattern, enhancing the accuracy of the simulation, especially when analyzing stress, frictional forces, and heat distribution in high-stress regions. Figure 3-3 shows 3Dmodel of friction liner & pressure plate meshed model.

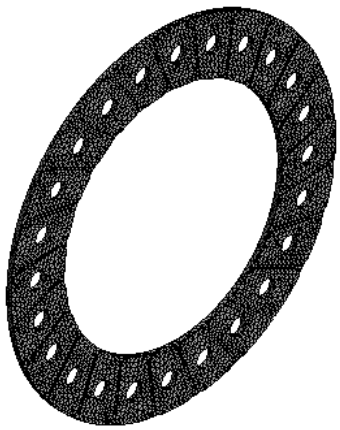


Figure 3-1 Meshed 3D Model of Friction liner

By utilizing a fine structured mesh throughout the model, the analysis achieves high accuracy without sacrificing computational efficiency. The meshed model incorporated key material properties such as the coefficient of friction, elasticity, and thermal conductivities, ensuring that the finite element analysis (FEA) delivers reliable predictions regarding the clutch system's performance, durability, and potential failure points under real-world operating conditions.

The model was composed of 47,144 elements which is element size 2.5mm, providing an optimal balance of resolution to capture the necessary geometric details while maintaining computational efficiency.

3.6 Finite Element Method (FEM) Analysis

The clutch system was subjected to detailed analysis using the Finite Element Method (FEM) with ANSYS LS-DYNA, a simulation tool specialized in modeling dynamic behaviors under various conditions. The FEM analysis began with the calculation of clutch dimensions, taking into account torque requirements, material strength, and operational constraints. Material selection was an essential step, with various materials being evaluated for their strength, wear resistance, and thermal conductivity to ensure the clutch would perform reliably under operational conditions.

Once the material was selected, the 3D model from SOLIDWORKSwas imported into ANSYS LS-DYNA for simulation. The model was divided into small finite elements to simulate the response of the clutch under different loading conditions. The input data for material properties, geometry, and environmental factors such as forces, loads, and boundary conditions were carefully defined to ensure realistic simulation results.

3.7 Boundary Conditions in ANSYS LS-DYNA for Thermal Simulation

To gain a deeper understanding of the clutch's performance, thermal simulations were also carried out on the friction disc under dynamic conditions. Thermal boundary conditions in ANSYS LS-DYNA were defined to account for the heat generated by friction between the clutch disc and mating surface. These conditions included specifying heat flux, contact heat transfer coefficients, and convective heat transfer due to airflow around the disc. These factors were incorporated to replicate the real operating environment of the clutch system.

The material's temperature-dependent properties, such as thermal conductivity and specific heat, were also defined in the simulation. These properties are crucial for predicting temperature variations in the clutch plate during operation. Since high temperatures can lead to thermal expansion and material degradation, the thermal simulation helped to predict potential overheating issues and assess the impact on clutch performance.The initial input parameters and boundary conditions for simulation are given in table 3-9.

Table 3-9 The initial input parameters and boundary conditions for simulation

Category	Parameter	Value	Unit	Description
Initial Conditions	Initial Angular Speed	4500	rpm	The initial rotational speed of the pressure plate.
	Axial Pressure	160,000	Pa	The applied axial pressure on the clutch plates.
	Kinetic Friction Coefficient	0.3	-	The coefficient of kinetic friction between the clutch surfaces.
	Simulation End Time	0.06	seconds	The total duration of the simulation run.

	LS DYNASolver Type	Structure-Thermal Coupled	-	The solver used for simultaneous structural and thermal analysis.
Boundary Conditions	Outer Disk Face	Fixed	-	The outer face of the clutch disk is assumed to remain stationary.
	Pressure Plate	Rotating	-	The pressure plate rotates at the specified initial angular speed.

Basic Equations

1. Mechanical deformation:

Mechanical deformation is the displacement of a material under applied loads. It is calculated using Hooke's Law and the strain-displacement relationship:

$$\delta = \frac{F \times L}{A \times E}$$

Where;

δ: Total deformation (displacement).

F: Applied force.

L: Length of the material.

A: Cross-sectional area.

E: Young's modulus of the material

In FEA simulations, deformation is computed at each node using the stiffness matrix and applied loads.

$$[K] \times \{u\} = \{F\}$$

Where;

[K]: Global stiffness matrix.

{u}: Nodal displacement vector.

{F}: Applied force vector.

2. Dynamic Pressure:

Dynamic pressure is the pressure exerted on the clutch plate due to friction and rotational forces. It is calculated as:

$$P_d = \frac{F}{A}$$

Where;

Pd: Dynamic pressure.

F: Normal force (clamping force).

A: Contact area of the clutch plate.

For clutch plate with inner radius Ri and outer radius Ro, the contact area A is:

$$A = \pi({R_o}^2 \; - \; {R_i}^2)$$

3. Temperature distribution

Temperature distribution is calculated using the heat conduction equation:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \nabla^2 T + \frac{q}{\rho c_p}$$

4. Equivalent stress (Von mises stress) :

Equivalent stress is a measure of the combined effect of normal and shear stresses, used to predict yielding. It is calculated using the Von mises stress criterion:

$$\sigma_{eq} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

Where:

σ_{eq}: Equivalent stress.

$\sigma_1, \sigma_2, \sigma_3$:Principal stress

In simulations, equivalent stress is computed at each node based on the stress tensor:

$$\sigma_{eq} = \sqrt{{\sigma_{xx}}^2 + {\sigma_{yy}}^2 + {\sigma_{zz}}^2 - \sigma_{xx}\sigma_{yy} - \sigma_{yy}\sigma_{zz} - \sigma_{zz}\sigma_{xx} + 3({\tau_{xy}}^2 + {\tau_{yz}}^2 + {\tau_{zx}}^2)}$$

5. Safety Factor:

The safety factor (SF) is the ratio of the material's Yield strength to the maximum equivalent stress:

$$SF = \frac{\sigma_y}{\sigma_{eq}}$$

Where;

σ_y: Yield strength of the material.

σ_{eq}: Maximum equivalent stress.

A safety factor greater than 1 indicates that the material can withstand the applied stresses without yielding.

Governing equations that define heat flux, contact heat transfer, and convective heat transfer in a clutch system:

1. Heat flux (q) due to friction

The heat flux generated at the interface of the clutch is given by:

$$q = \mu P v$$

Where:

q: heat flux(W/m^2)

μ: coefficient of friction

P: normal contact pressure (Pa)

v: sliding velocity (m/s)

This equation represents the rate at which frictional heat is generated per unit area at the contact surface.

2. Contact heat transfer coefficients (h_c)

The heat transfer coefficient at the contact interface depends on material properties and thermal conduction. The governing equation is:

$$h_c = \frac{2k}{\pi L}$$

where:

h_c: contact heat transfer coefficient (W/m^2·K)

k: thermal conductivity of the material (W/m·K)

L: characteristic length (m)

For two contacting surfaces with different thermal properties, the contact heat transfer coefficient can be expressed as:

$$\frac{1}{h_c} = \frac{1}{h_1} + \frac{1}{h_2}$$

where h_1 and $h_2$are the heat transfer coefficients of the two materials in contact.

3. Convective heat transfers due to airflow around the disc

The convective heat dissipation from the clutch disc to the surrounding air is determined using Newton's Law of Cooling

$$q_{Conv} = h(T_s - T_\infty)$$

where:

q_{Conv}: convective heat flux (W/m^2)

h: convective heat transfer coefficient (W/m^2·K)

T_s: surface temperature of the disc (K)

T_∞: ambient air temperature (K)

The convective heat transfer coefficient for a rotating clutch disc can be estimated using empirical correlations for forced convection:

$$h = C.Re^{m}.Pr^{n}$$

where:

R_e: Reynolds number

P_r: Prandtl number

C,m,n: empirical constants that depend on the flow regime

For high-speed rotating discs, the Nusselt number N_u can also be used:

$$N_u = A.Re^{B}$$

where A and B are constants depending on the airflow conditions.

3.8 Output Parameters

The simulation results offered a comprehensive analysis of how the friction disc behaves under both dynamic and thermal conditions. These insights were vital for evaluating the design's effectiveness and ensuring it would hold up in real-world use. The key outcomes of the simulation included:

1. Stress Distribution: The study mapped out how stress was distributed across the friction disc, pinpointing areas under the most strain. These high-stress zones are where failures, such as fatigue or material overloading, are most likely to occur. By identifying these areas, the findings helped inform decisions about material choices and design tweaks to boost the disc's durability and ensure it could handle operational demands without breaking down.
2. Temperature Distribution: The thermal analysis showed how heat from friction spread across the disc during operation. Since excessive heat can weaken materials, understanding these temperature patterns was critical to preventing thermal damage or a loss of strength. The results also guided the development of strategies to improve heat dissipation and keep temperatures in check.
3. Deflection: The simulation measured how much the friction disc deformed under forces like axial pressure and rotational motion. Keeping this deformation within safe limits was essential to avoid issues like misalignment or poor contact, which could compromise the system's efficiency. The analysis confirmed that the disc stayed structurally stable, even under varying loads.

4. Total Velocity: The study examined the disc's velocity in different directions to understand its movement during operation. This helped assess how smoothly the disc rotated and how effectively the clutch engaged, ensuring the system operated without unnecessary vibrations or inefficiencies.
5. Total Acceleration: The disc's acceleration in specific directions was analyzed to see how it handled sudden changes in load or speed. This was crucial for maintaining system stability during quick transitions and preventing mechanical wear or instability caused by abrupt movements.

By analyzing these factors, the simulation provided a deep understanding of the friction disc's mechanical, thermal, and dynamic performance. These insights were used to fine-tune the design, choose the best materials, and develop strategies to manage thermal and mechanical stresses. Ultimately, this ensured the friction disc would perform reliably and efficiently in real-world applications.

3.9 Evaluation of Results

Finally,the results from the ANSYS LS-DYNA simulations were carefully evaluated.The output, stress, and temperature were analyzed to assess the overall performance of the clutch system.The deformation values were compared against the allowable tolerances, stress distributions were examined for potential weak points, and temperature rise was carefully monitored to ensure the clutch would function effectively without overheating.

This comprehensive evaluation allowed for the identification of potential weaknesses in the design and highlighted areas where improvements could be made.By adjusting material selection, geometry, and boundary conditions, we were able to optimize the clutch system for enhanced performance,durability,and safety.The iterative process of simulation and evaluation ensures that the final clutch design was meet the necessary requirements for reliable operation in the automotive industry.

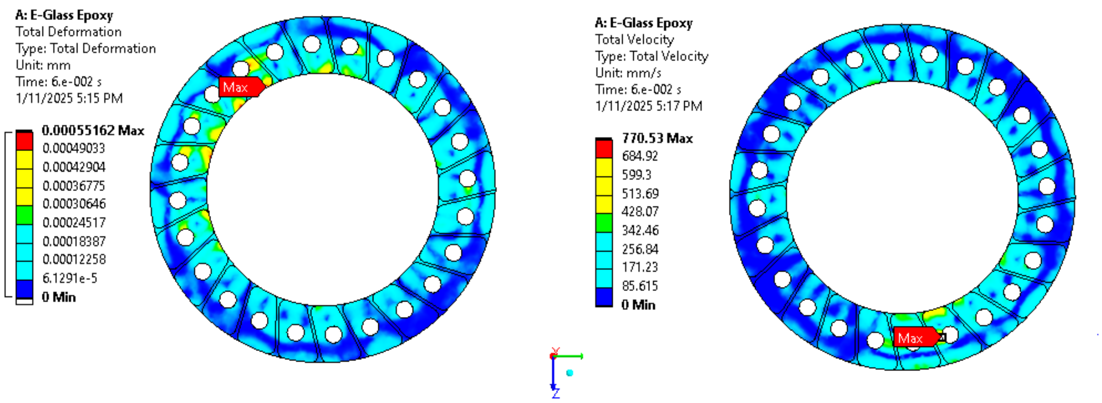
CHAPTER FOUR

RESULT AND DISCUSSION

This chapter delves into the results and discussion of a thorough investigation on the performance of several materials—E-Glass Epoxy, Aluminum Alloy (6061), Gray Cast Iron, and Kevlar 49—used in clutch friction disks. This chapter examines the simulation results for these materials,focusing on critical parameters like deformation,velocity,acceleration,dynamic pressure, temperature, and equivalent stress.These simulations offer valuable insights into how each material behaves under various conditions,which is vital for optimizing clutch performance and ensuring durability. The chapter is organized to present the simulation results for each material, followed by an in-depth discussion of the findings. It includes visualizations through figures and tables that summarize the maximum and minimum values of the analyzed parameters over time. The strategic use of color in contour plots and line graphs enhances the visual comparison of material performance, providing a more intuitive understanding of their mechanical and thermal properties. Additionally, the discussion covers the safety factors of the materials, which are crucial for assessing their reliability in clutch applications. By comparing performance metrics and safety factors, this chapter aims to provide a comprehensive analysis that can inform the selection of suitable materials for clutch friction disks based on specific operational needs.

4.1 Simulation result of E-Glass Epoxy material of Clutch Friction Disk

A) Total Deformation and Velocity

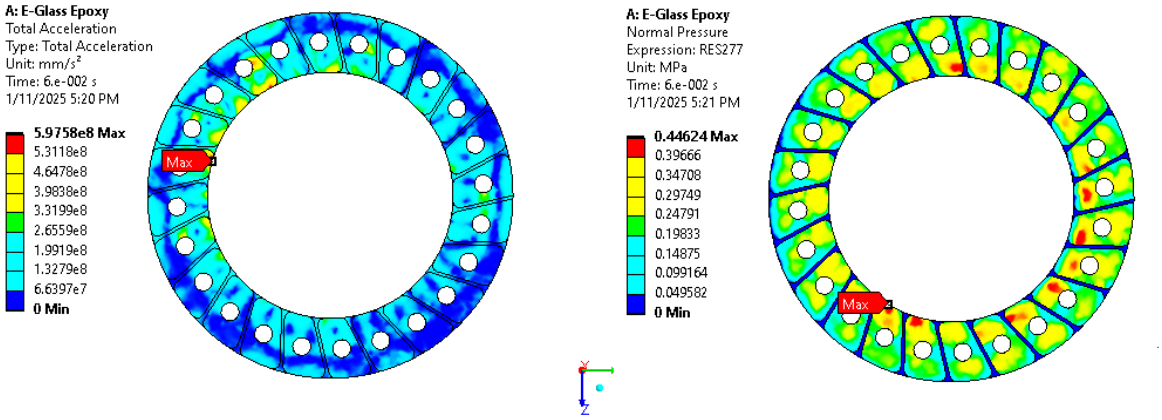


(a) (b)

Figure 0-1 (a & b) Total Deformation and Velocity for E-Glass Epoxy material

Figure 4-1 illustrates the total deformation and velocity of E-Glass Epoxy in a clutch friction disk. The contour plots likely use a color gradient to show how deformation and velocity vary across the material, with darker colors indicating higher values and lighter colors indicating lower values. Table 4-1 summarizes these results, highlighting a maximum deformation of 0.0012 mm and a maximum velocity of 1084.1 mm/s. The color distribution in the contour plots visually reinforces these numerical values, providing spatial insights into the material's behavior.

B) Total acceleration and Dynamic pressure

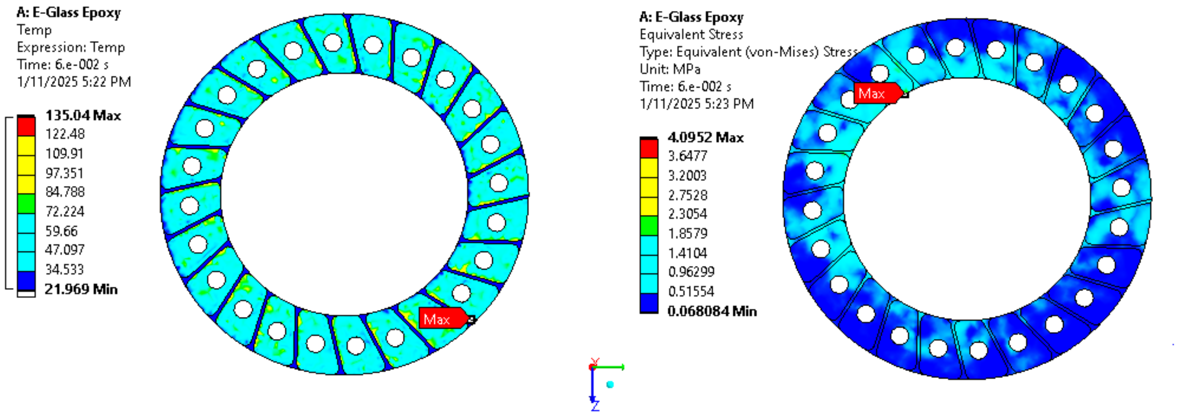


(a) (b)

Figure 0-2 (a & b) Total acceleration and Dynamic pressure for E-Glass Epoxy material

Figure 4-2 displays the total acceleration and dynamic pressure of E-Glass Epoxy. The color of the contour plots helps differentiate between regions of high and low acceleration or pressure, with areas of high acceleration possibly depicted in red and areas of low acceleration in blue. Table 4-1 provides specific values for these parameters, including a maximum acceleration of 1.29×10^9 mm/s² and a maximum dynamic pressure of 0.783 MPa. The color gradient in the contour plots supports these numerical values.

C) Temperature distribution and Equivalent stress



(a) (b)

Figure 0-3 (a & b) Temperature and Equivalent stress for E-Glass Epoxy material

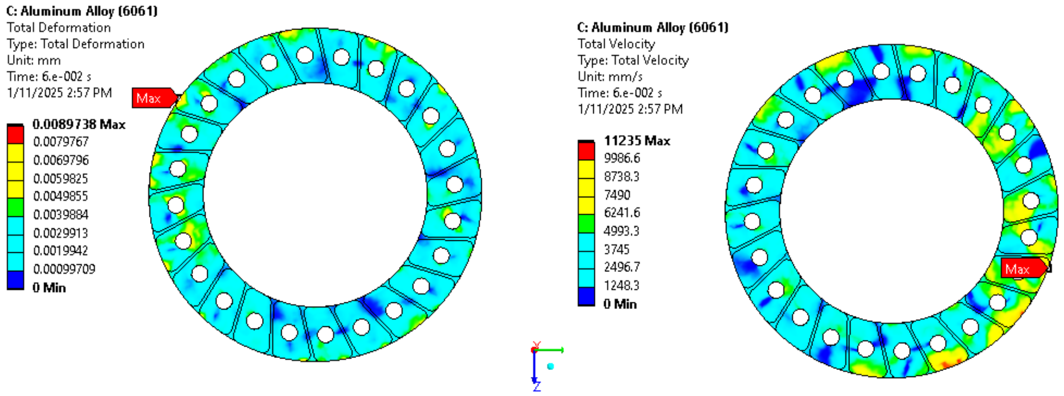
Figure 4-3 shows the temperature distribution and equivalent stress of E-Glass Epoxy. The contour plots use colors to represent different temperature and stress levels, with hotter regions possibly colored red and cooler regions blue. Similarly, areas under higher stress might be depicted in darker colors, while areas under lower stress could be lighter. Table 4-1 indicates a maximum temperature of 135.04°C and a maximum equivalent stress of 6.254MPa. The color distribution helps identify hotspots or areas of high stress.

Table 0-1 Simulation Result Summary of E-Glass Epoxy material

Output Parameters	Contour plot results	Graphical Results	Unit
Maximum Deformation	0.00055	0.0012	mm
Maximum Velocity	770.53	1084.1	mm/s
Maximum Acceleration	5.97e+8	1.29×10^9	mm/s^2
Maximum Dynamic pressure	0.446	0.783	MPa
Maximum Temperature	135.04	135.04	^oC
Maximum Equivalent Stress	4.0952	6.2538	MPa

4.2 Simulation result of Aluminum Alloy (6061) material of Clutch Friction Disk

A) Total Deformation and Velocity

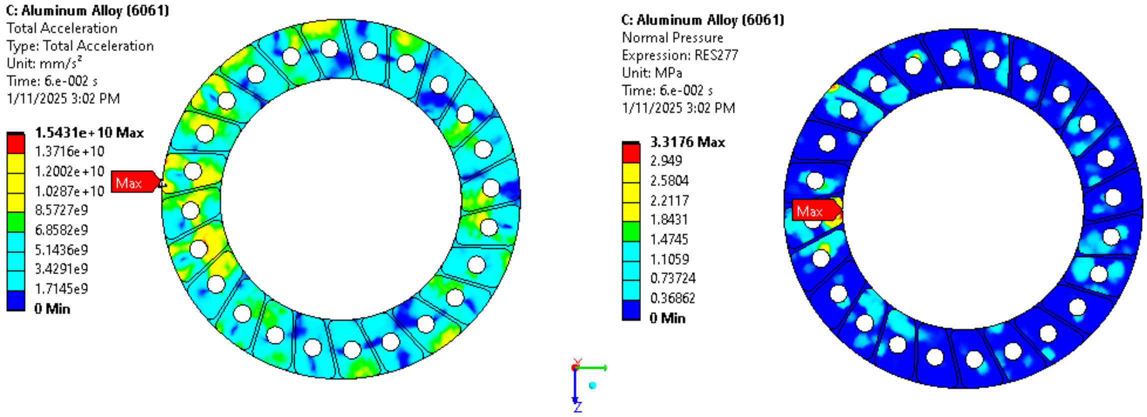


(a) (b)

Figure 0-4 (a & b) Total Deformation and Velocity for Aluminum Alloy (6061)

Figure 4-4 illustrates the total deformation and velocity of Aluminum Alloy (6061). The contour plots use a color scale to differentiate between regions of high and low deformation or velocity, with significant deformation possibly colored yellow and minimal deformation green. Table 4-2 provides a maximum deformation of 0.009253 mm and a maximum velocity of 11426 mm/s. The color gradient in the contour plots visually illustrates these variations.

B) Total acceleration and Dynamic pressure

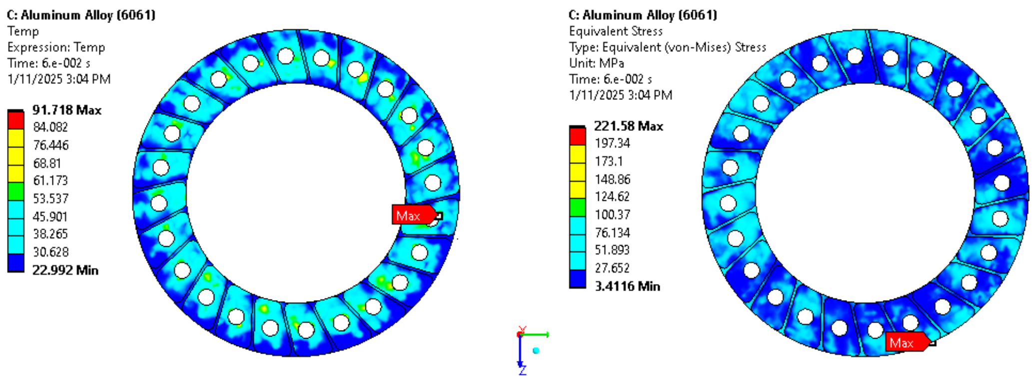


(a) (b)

Figure 0-5 (a & b) Total acceleration and Dynamic pressure for Aluminum Alloy (6061)

Figure 4-5 displays the total acceleration and dynamic pressure of Aluminum Alloy (6061). The color of the contour plots helps distinguish between regions of high and low acceleration or pressure, with areas of high acceleration possibly depicted in orange and areas of lower acceleration in blue. Table 4-2 shows a maximum acceleration of 1.64×10^{10} mm/s² and a maximum dynamic pressure of 8.235 MPa. The color distribution supports these numerical values.

C) Temperature distribution and Equivalent stress



(a) (b)

Figure 0-6 (a & b) Temperature and Equivalent stress for Aluminum Alloy (6061)

Figure 4-6 shows the temperature distribution and equivalent stress of Aluminum Alloy (6061). The contour plots use colors to represent different temperature and stress levels, with hotter regions possibly colored red and cooler regions blue. Similarly, areas under higher stress might be depicted in darker colors, while areas under lower stress could be lighter. Table 4-2 indicates a maximum temperature of 105.9°C and a maximum equivalent stress of 221.58 MPa. The color distribution helps identify hotspots or areas of high stress.

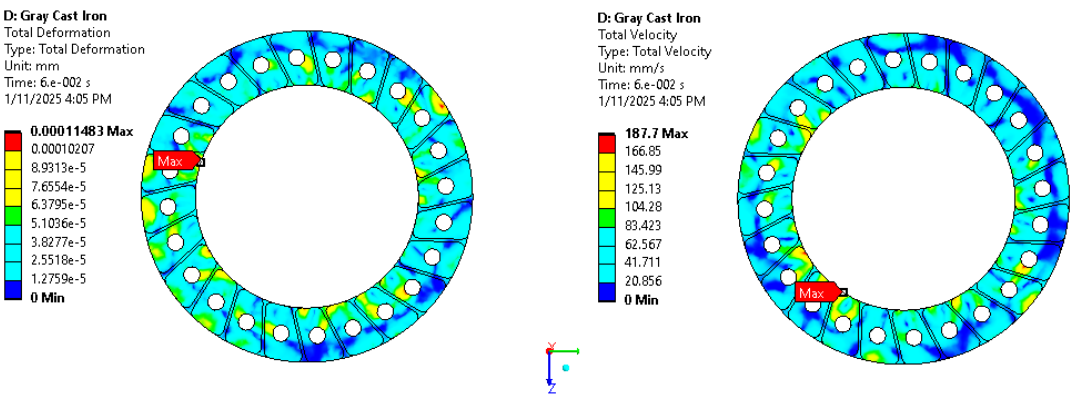
Table 0-2 Simulation Result Summary of Aluminum Alloy (6061)

Output Parameters	Contour plot results	Graphical Results	Unit
Maximum Deformation	0.00897	0.009253	mm
Maximum Velocity	11235	11426	mm/s
Maximum Acceleration	$1.543\text{x}10^{10}$	$1.64\text{ x}10^{10}$	mm/s^2
Maximum Dynamic pressure	3.317	8.235	MPa
Maximum Temperature	91.71	105.9	^{o}C

Maximum Equivalent Stress	221.58	221.58	MPa

4.3 Simulation result of Gray Cast Iron material of Clutch Friction Disk

A) Total Deformation and Velocity

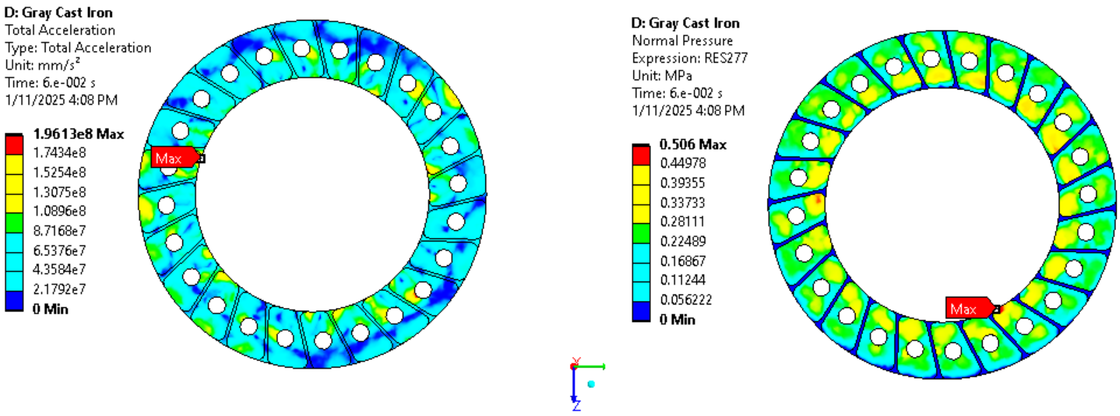


(a) (b)

Figure 0-7 (a & b) Total Deformation and Velocity for Gray Cast Iron

Figure 4-7 illustrates the total deformation and velocity of Gray Cast Iron. The contour plots use a color scale to differentiate between regions of high and low deformation or velocity, with significant deformation possibly colored purple and minimal deformation green. Table 4-3 provides a maximum deformation of 0.000347 mm and a maximum velocity of 405.81 mm/s. The color gradient in the contour plots visually illustrates these variations.

B) Total acceleration and Dynamic pressure

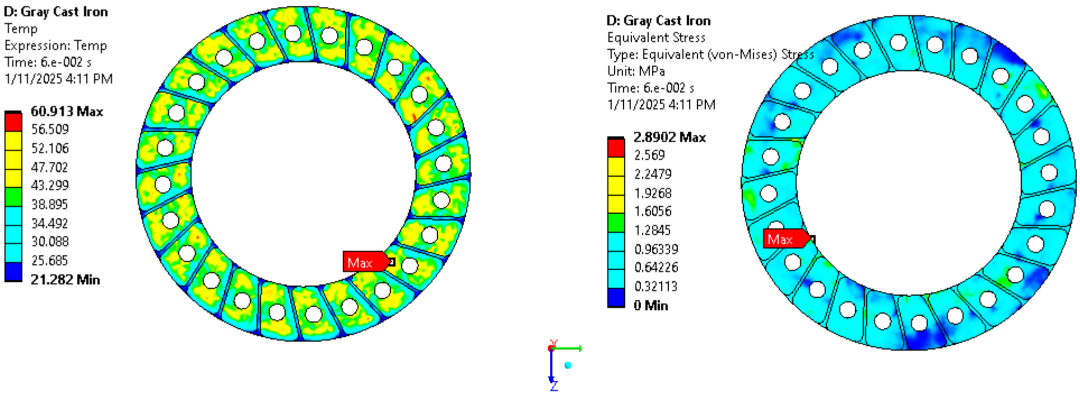


(a) (b)

Figure 0-8 (a & b) Total acceleration and Dynamic pressure for Gray Cast Iron

Figure 4-8 displays the total acceleration and dynamic pressure of Gray Cast Iron. The color of the contour plots helps distinguish between regions of high and low acceleration or pressure, with areas of high acceleration possibly depicted in red and areas of lower acceleration in blue. Table 4-3 shows a maximum acceleration of 105.78×10^{10} mm/s² and a maximum dynamic pressure of 0.804 MPa. The color distribution supports these numerical values.

C) Temperature distribution and Equivalent stress



(a) (b)

Figure 0-9 (a & b) Temperature and Equivalent stress for Gray Cast Iron

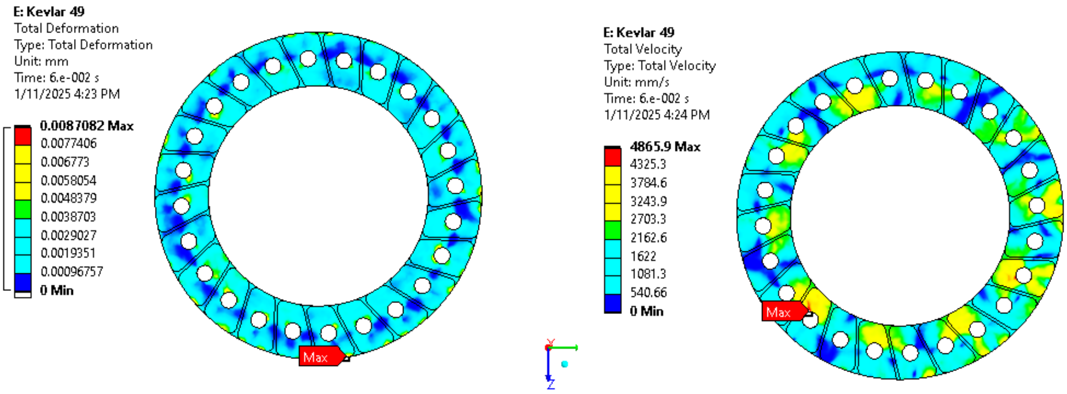
Figure 4-9 shows the temperature distribution and equivalent stress of Gray Cast Iron. The contour plots use colors to represent different temperature and stress levels, with hotter regions possibly colored orange and cooler regions blue. Similarly, areas under higher stress might be depicted in darker colors, while areas under lower stress could be lighter. Table 4-3 indicates a maximum temperature of 60.913°C and a maximum equivalent stress of 9.72 MPa. The color distribution helps identify hotspots or areas of high stress.

Table 0-3 Simulation Result Summary of Gray Cast Iron material

Output Parameters	Contour plot results	Graphical Results	Unit
Maximum Deformation	0.000115	0.000347	mm
Maximum Velocity	187.7	405.81	mm/s
Maximum Acceleration	1.96×10^{8}	5.78×10^{10}	mm/s^2
Maximum Dynamic pressure	0.506	0.804	MPa
Maximum Temperature	60.913	60.913	^{o}C
Maximum Equivalent Stress	2.89	9.72	MPa

4.4 Simulation result of Kevlar 49 material for Clutch Friction Disk

A) Total Deformation and Velocity

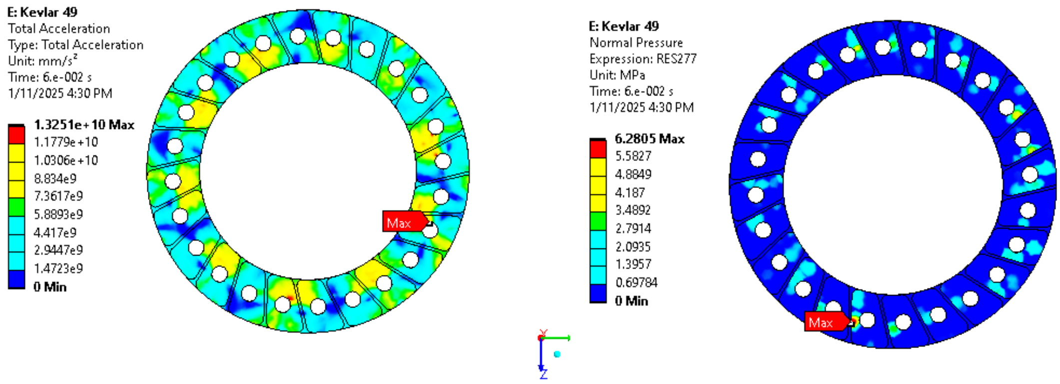


(a) (b)

Figure 0-10 (a & b) Total Deformation and Velocity for Kevlar 49

Figure 4-10 illustrates the total deformation and velocity of Kevlar 49. The contour plots use a color scale to differentiate between regions of high and low deformation or velocity, with significant deformation possibly colored yellow and minimal deformation green. Table 4-4 provides a maximum deformation of 0.01026 mm and a maximum velocity of 17226 mm/s. The color gradient in the contour plots visually illustrates these variations.

B) Total acceleration and Dynamic pressure

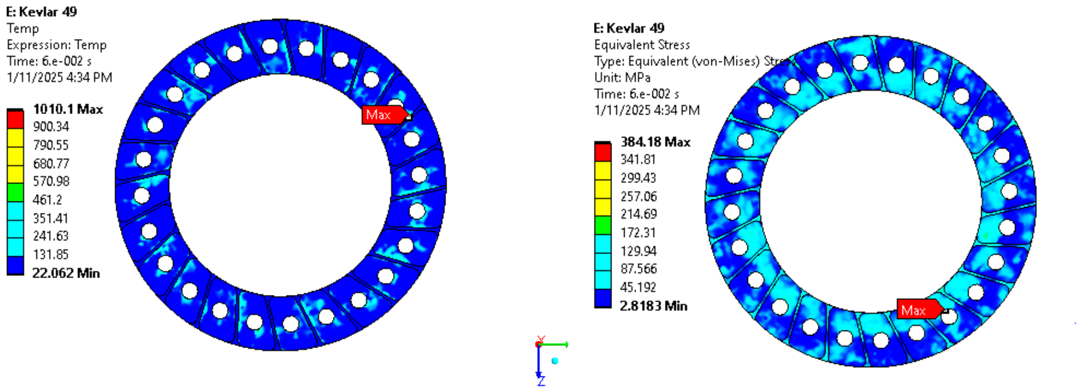


(a) (b)

Figure 0-11 (a & b) Total acceleration and Dynamic pressure for Kevlar 49

Figure 4-11 displays the total acceleration and dynamic pressure of Kevlar 49. The color of the contour plots helps distinguish between regions of high and low acceleration or pressure, with areas of high acceleration possibly depicted in red and areas of lower acceleration in blue. Table 4-4 shows a maximum acceleration of 4.56×10^{10} mm/s² and a maximum dynamic pressure of 7.12 MPa. The color distribution supports these numerical values.

C) Temperature distribution and Equivalent stress



(a) (b)

Figure 0-12 (a & b) Temperature and Equivalent stress for Kevlar 49

Figure 4-12 shows the temperature distribution and equivalent stress of Kevlar 49. The contour plots use colors to represent different temperature and stress levels, with hotter regions possibly colored red and cooler regions blue. Similarly, areas under higher stress might be depicted in darker colors, while areas under lower stress could be lighter. Table 4-4 indicates a maximum temperature of 1010.1°C and a maximum equivalent stress of 418.3 MPa. The color distribution helps identify hotspots or areas of high stress.

Table 0-4 Simulation Result Summary of Kevlar 49 material

Output Parameters	Contour plot results	Graphical Results	Unit
Maximum Deformation	0.00871	0.01026	mm
Maximum Velocity	4865.9	17226	mm/s
Maximum Acceleration	$1.325 \text{x} 10^{10}$	$4.56 \text{x} 10^{10}$	mm/s^2
Maximum Dynamic pressure	6.28	7.12	MPa
Maximum Temperature	1010.1	1010.1	^{o}C
Maximum Equivalent Stress	384,18	418.3	MPa

D) Safety Factor

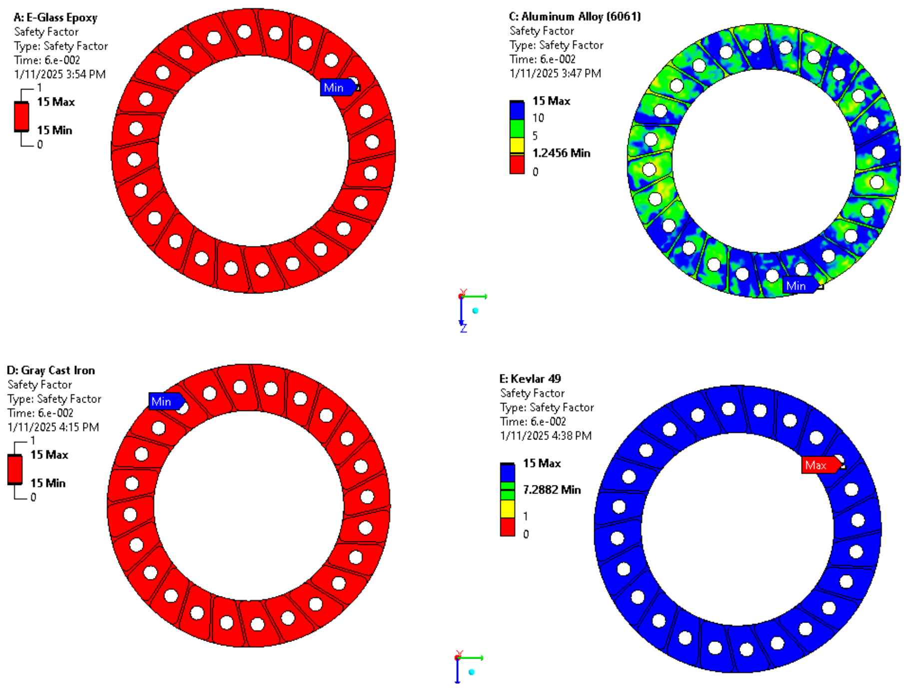


Figure 0-13 Safety factor of each material for friction disk

Figure 4-13 presents the safety factor of each material. While not typically represented by contour plots, the safety factor is crucial for ensuring materials can withstand operational stresses without failure. Table 4-5 summarizes these safety factors, showing that E-Glass Epoxy and Gray Cast Iron have a safety factor of 15, Aluminum Alloy (6061) has a minimum safety factor of 1.25, and Kevlar 49 has a safety factor of 7.289. These values indicate the relative reliability of each material in clutch applications.

Table 0-5 Result Summary of safety factor of material

Output Parameters	Minimum	Minimum
E-Glass epoxy	15	15
Aluminum Alloy (6061)	1.25	15
Gray Cast iron	15	15
Kevlar 49 material	7.289	15

A) Deformation vs time curve

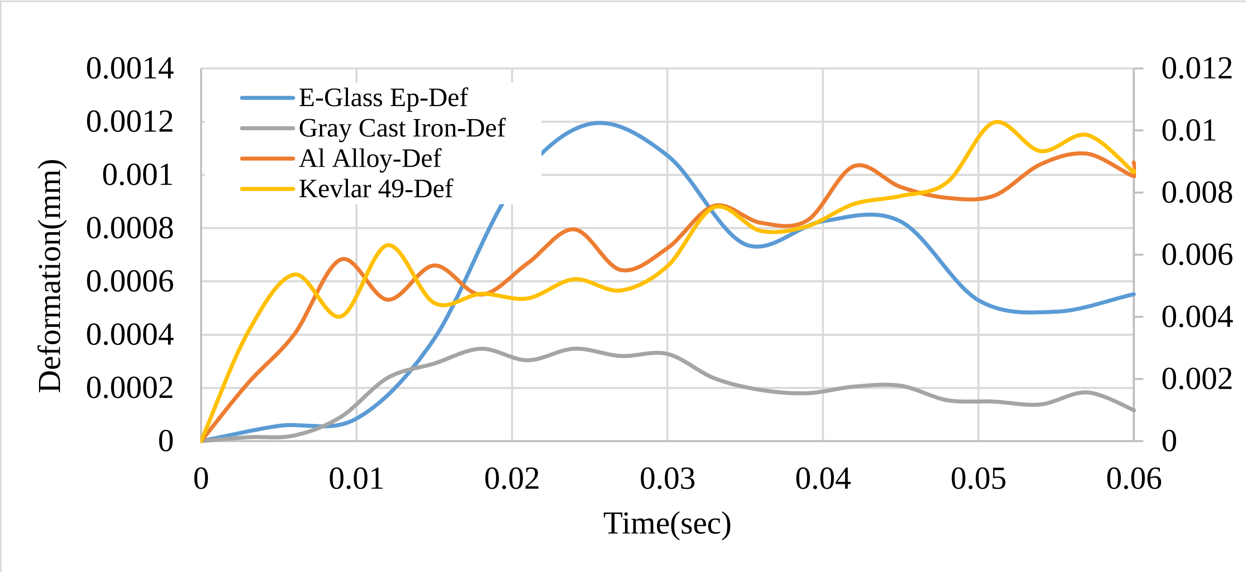


Figure 0-14 Deformation vs time curve all materials

Figure 4-14 illustrates the deformation over time for all materials, with each line representing a different material. This allows for a direct comparison of how deformation changes over time across materials. Table 4-6 summarizes the minimum and maximum deformation values for each material, providing insights into their mechanical stability. For instance, E-Glass Epoxy shows a maximum deformation of 0.0012 mm, while Kevlar 49 has a maximum deformation of 0.01026 mm. The color of each line helps visually distinguish between materials, making it easier to identify which materials exhibit more significant deformation over time.

Table 0-6 Result from graph of Deformation (mm)

Output Parameters	Minim over time	Maxim over time	axis
E-Glass epoxy	0	0.0012	Primary
Aluminum Alloy (6061)	0	0.0093	Secondary
Gray Cast iron	0	0.00035	Primary
Kevlar 49 material	0	0.01026	Secondary

B) Velocity vs time curve

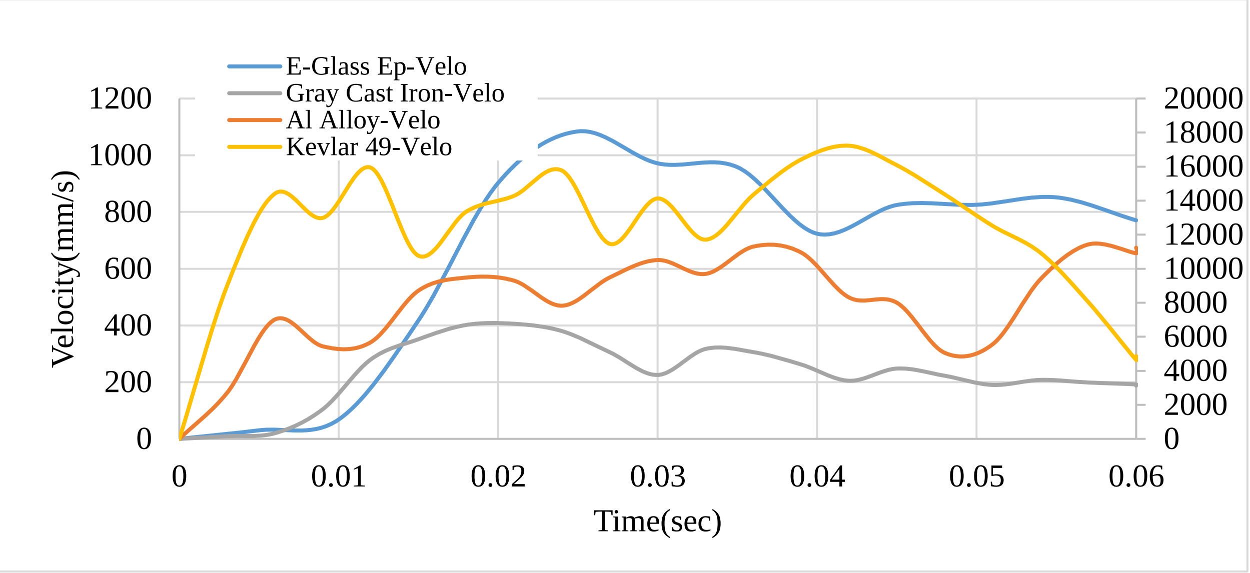


Figure 0-15 Velocity vs time curve

Figure 4-15 displays the velocity over time for all materials, with each line colored to represent a different material. This visualization enables a clear comparison of velocity profiles among materials. Table 4-7 highlights the minimum and maximum velocity values, revealing significant differences. For example, Aluminum Alloy (6061) reaches a maximum velocity of 11426 mm/s, while Gray Cast Iron's maximum velocity is much lower at 405.81 mm/s. The color differentiation in the graph facilitates a quick identification of which materials achieve higher velocities.

Table 0-7 Result from graph of velocity (mm/s)

Output Parameters	Minim over time	Maxim over time	Axis
E-Glass epoxy	0	1084.1	Primary
Aluminum Alloy (6061)	0	11426	Secondary
Gray Cast iron	0	405.81	Primary
Kevlar 49 material	0	17226	Secondary

C) **Acceleration vs time curve**

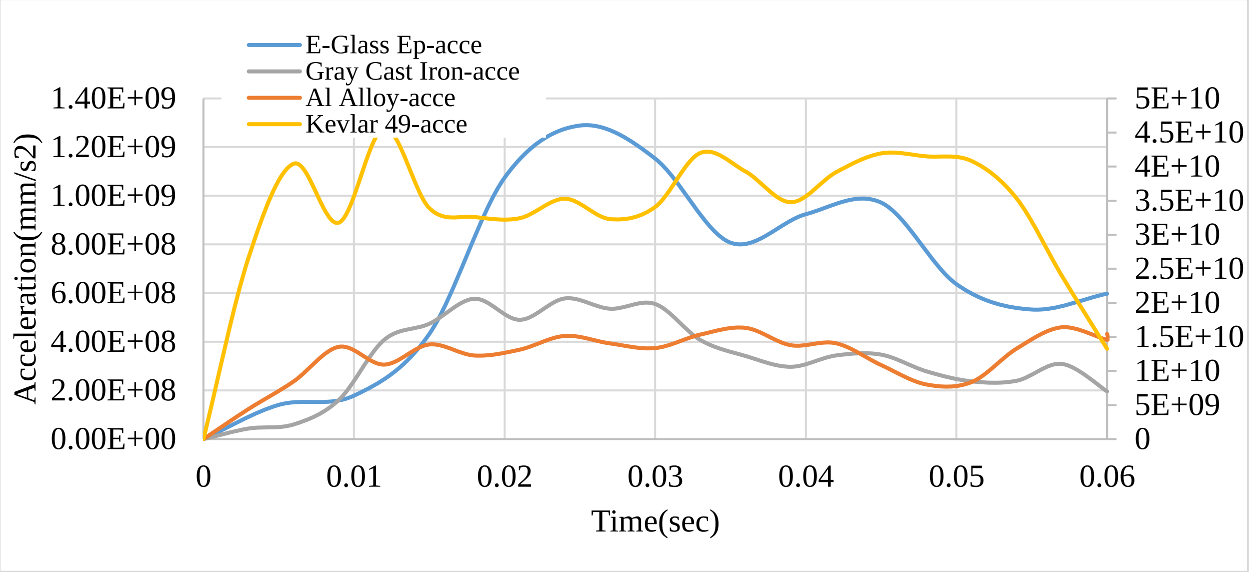


Figure 0-16 Acceleration vs time curve of all materials

Figure 4-16 shows the acceleration over time for all materials, with each line colored to differentiate between materials. This allows for a visual comparison of their acceleration profiles. Table 4-8 summarizes the minimum and maximum acceleration values, indicating that Gray Cast Iron and Kevlar 49 exhibit extremely high acceleration, with Gray Cast Iron reaching up to 5.78×10^{10} mm/s². The color of each line helps in quickly identifying which materials have the highest acceleration profiles.

Table 0-8 Result from graph of acceleration (mm/s^2)

Output Parameters	Minim over time	Maxim over time	axis
E-Glass epoxy	0	$1.29x10^9$	Primary
Aluminum Alloy (6061)	0	$1.64x10^{10}$	Secondary
Gray Cast iron	0	$5.78x10^{10}$	Primary
Kevlar 49 material	0	$4.56x10^{10}$	Secondary

D) Pressure vs time curve

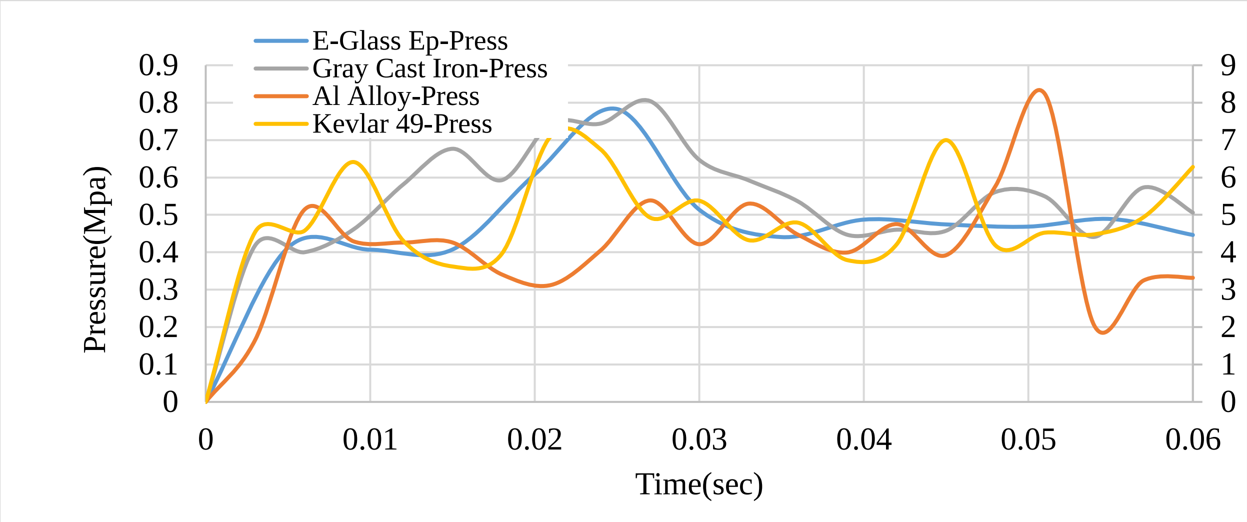


Figure 0-17 Pressure vs time curve of all materials

Figure 4-17 illustrates the dynamic pressure over time for all materials, with each line representing a different material. This facilitates a comparison of their pressure profiles. Table 4-9 provides the minimum and maximum pressure values, showing significant variations among materials. For instance, Aluminum Alloy (6061) experiences a maximum dynamic pressure of 8.235 MPa, while E-Glass Epoxy's maximum pressure is 0.783 MPa. The color differentiation in the graph helps in visually distinguishing between materials based on their pressure profiles.

Table 0-9 Result from graph of dynamic pressure (MPa)

Output Parameters	Minim over time	Maxim over time	axis
E-Glass epoxy	0	0.783	Primary
Aluminum Alloy (6061)	0	8.24	Secondary
Gray Cast iron	0	0.804	Primary
Kevlar 49 material	0	7.12	Secondary

E) Temperature vs time curve

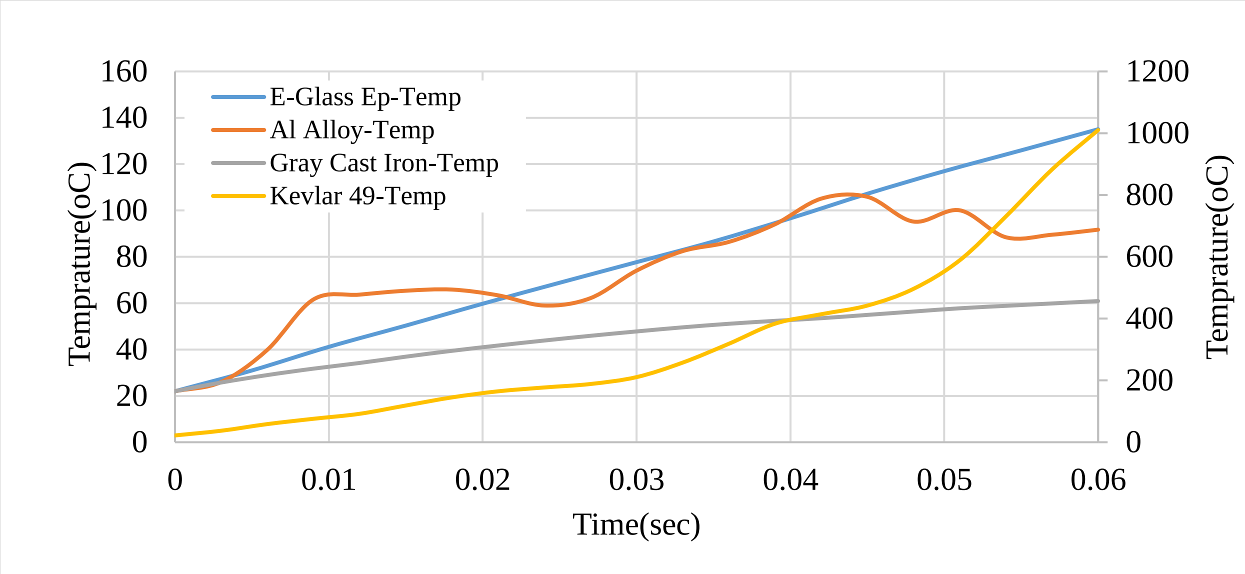


Figure 0-18 Temperature vs time curve of all materials

Figure 4-18 displays the temperature over time for all materials, with each line colored to represent a different material. This allows for a visual comparison of their temperature profiles. Table 4-10 summarizes the minimum and maximum temperature values, highlighting that Kevlar 49 operates at extremely high temperatures, reaching up to 1010.1°C. The color of each line helps in quickly identifying which materials experience higher temperatures over time.

Table 0-10 Result from graph of Temperature (°C)

Output Parameters	Minim over time	Maxim over time	axis
E-Glass epoxy	22	135.04	Primary
Aluminum Alloy (6061)	22	105.9	Secondary
Gray Cast iron	22	60.91	Primary
Kevlar 49 material	22	1010.1	Secondary

F) Equivalent Stress vs time

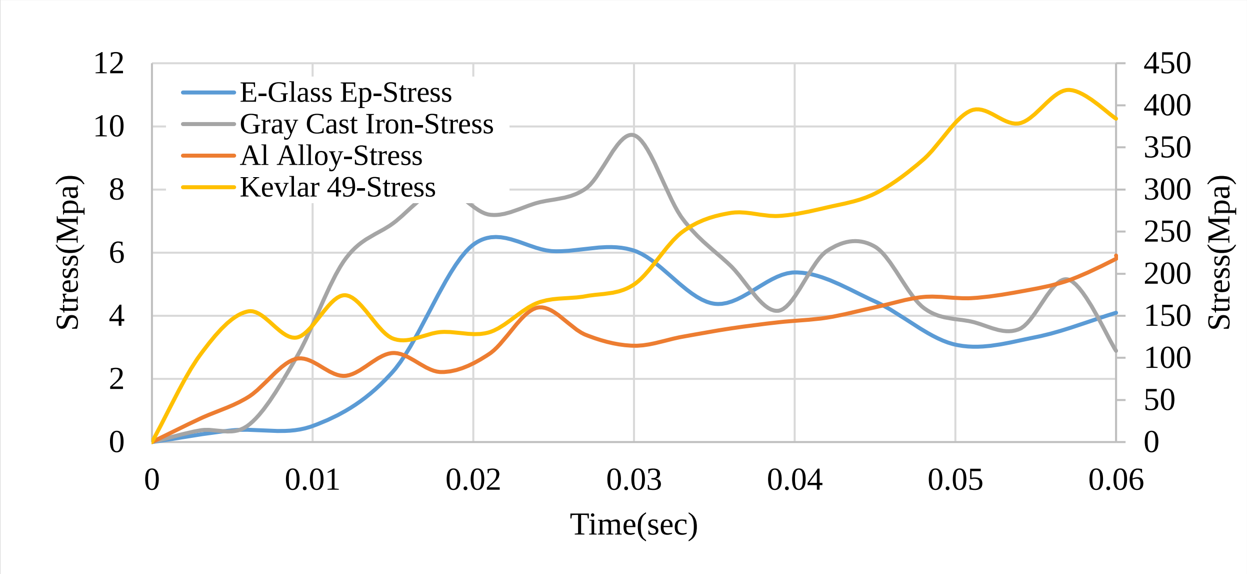


Figure 0-19 Equivalent Stress vs time curve of all materials

Figure 4-19 shows the equivalent stress over time for all materials, with each line colored to differentiate between materials. This enables a comparison of their stress profiles. Table 4-11 provides the minimum and maximum stress values, indicating that Kevlar 49 experiences the highest stress among the materials tested, with a maximum equivalent stress of 418.3 MPa. The color differentiation in the graph facilitates a quick identification of which materials are subjected to higher stresses over time.

Table 0-11 Result from graph of Equivalent Stress (^{o}C)

Output Parameters	Minim over time	Maxim over time	axis
E-Glass epoxy	0	6.25	Primary
Aluminum Alloy (6061)	0	221.58	Secondary
Gray Cast iron	0	9.72	Primary
Kevlar 49 material	0	418.3	Secondary

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1 Summary of the Result and Conclusions

5.1.1Summary of Result

The research examines the performance of four materials—E-Glass Epoxy, Aluminum Alloy (6061), Gray Cast Iron, and Kevlar 49—used in clutch friction disks. The analysis focuses on key parameters such as deformation, velocity, acceleration, dynamic pressure, temperature, and equivalent stress. These parameters are crucial for understanding how each material behaves under various conditions, which is vital for optimizing clutch performance and ensuring durability.

1) Material Performance Summary

E-Glass Epoxy: Exhibits a maximum deformation of 0.0012 mm, a maximum velocity of 1084.1 mm/s, a maximum acceleration of 1.29×10^{9} mm/s², a maximum dynamic pressure of 0.783 MPa, a maximum temperature of 135.04°C, and a maximum equivalent stress of 6.2538 MPa. It has a safety factor of 15.

Aluminum Alloy (6061): Shows a maximum deformation of 0.009253 mm, a maximum velocity of 11426 mm/s, a maximum acceleration of $.64\times10^{10}$ mm/s², a maximum dynamic pressure of 8.235 MPa, a maximum temperature of 105.9°C, and a maximum equivalent stress of 221.58 MPa. It has a minimum safety factor of 1.25.

Gray Cast Iron: Has a maximum deformation of 0.000347 mm, a maximum velocity of 405.81 mm/s, a maximum acceleration of 5.78×10^{10} mm/s², a maximum dynamic pressure of 0.804 MPa, a maximum temperature of 60.913°C, and a maximum equivalent stress of 9.72 MPa. It has a safety factor of 15.

Kevlar 49: Exhibits a maximum deformation of 0.01026 mm, a maximum velocity of 17226 mm/s, a maximum acceleration of 4.56×10^{10} mm/s², a maximum dynamic pressure of 7.12 MPa, a maximum temperature of 1010.1°C, and a maximum equivalent stress of 418.3 MPa. It has a safety factor of 7.289.

Consideration of Temperature, Availability, and Wear Resistance

Temperature: Kevlar 49 operates at extremely high temperatures, which may be a concern for durability. E-Glass Epoxy and Gray Cast Iron have more moderate temperature profiles, making them potentially more stable in high-temperature environments.

Availability: Aluminum Alloy (6061) and Gray Cast Iron are widely available due to their common use in various industrial applications. E-Glass Epoxy and Kevlar 49 might be less readily available but are still accessible for specialized applications.

Wear Resistance: Gray Cast Iron is known for its good wear resistance due to its high hardness, making it suitable for applications where friction is significant. Kevlar 49, while not typically known for wear resistance in the same way as metals, can offer durability in certain composite applications due to its high strength-to-weight ratio.

2) Better Material Selection

Based on these considerations, Gray Cast Iron might be a better choice for applications where high wear resistance and moderate temperature resistance are crucial. It offers a good balance of mechanical stability, high safety factor, and wear resistance. However, if high velocity and acceleration are required, Kevlar 49 could be considered despite its high operating temperature. For applications where weight is a significant factor, Aluminum Alloy (6061) might be preferred, although its safety factor is lower. E-Glass Epoxy is suitable for applications requiring moderate temperature resistance and high safety factors. Ultimately, the choice depends on specific operational requirements and constraints.

3) Time-Based Performance Comparison

- Deformation vs. Time: Kevlar 49 shows the highest deformation over time, while Gray Cast Iron shows the least. This suggests that Gray Cast Iron maintains its shape better under dynamic conditions.
- Velocity vs. Time: Kevlar 49 achieves the highest velocity, followed by Aluminum Alloy (6061). This indicates that these materials are suitable for high-speed applications.

- Acceleration vs. Time: Gray Cast Iron and Kevlar 49 exhibit extremely high acceleration profiles. This makes them suitable for applications requiring rapid changes in speed.
- Pressure and Temperature vs. Time: Significant variations are observed among materials, with Kevlar 49 operating at extremely high temperatures. This could be a concern for durability in certain applications.

5.1.2 Conclusions

In conclusion, this study provides a comprehensive analysis of the performance of four materials—E-Glass Epoxy, Aluminum Alloy (6061), Gray Cast Iron, and Kevlar 49—used in clutch friction disks. The analysis focuses on critical parameters such as deformation, velocity, acceleration, dynamic pressure, temperature, and equivalent stress. Based on the results, E-Glass Epoxy stands out as a promising material for clutch applications due to its balanced performance across these parameters-Glass Epoxy demonstrates a maximum deformation of 0.0012 mm, a maximum velocity of 1084.1 mm/s, a maximum acceleration of 1.29×10^{9} mm/s², a maximum dynamic pressure of 0.783 MPa, a maximum temperature of 135.04°C, and a maximum equivalent stress of 6.2538 MPa. Additionally, it has a safety factor of 15, indicating high reliability in clutch applications. While other materials like Kevlar 49 offer high velocity and acceleration, and Gray Cast Iron provides excellent wear resistance, E-Glass Epoxy's moderate temperature profile and high safety factor make it an attractive choice for applications where durability and stability are crucial. Therefore, E-Glass Epoxy is recommended as the target best material for clutch friction disks due to its well-rounded performance and high safety factor. Future research could explore hybrid materials or optimization techniques to further enhance its properties.

5.2 Recommendation and Future work

5.2.1 Recommendations

Based on the study's findings, Gray Cast Iron is recommended for applications where high wear resistance and moderate temperature resistance are crucial. It offers a good balance of mechanical stability, high safety factor, and wear resistance. However, if high velocity and acceleration are required, Kevlar 49 could be considered despite its high operating temperature. For applications where weight is a significant factor, Aluminum Alloy (6061) might be preferred, although its safety factor is lower. E-Glass Epoxy is suitable for applications requiring moderate temperature resistance and high safety factors.

5.2.2Future Work

The research on the performance of E-Glass Epoxy, Aluminum Alloy (6061), Gray Cast Iron, and Kevlar 49 in clutch friction disks provides valuable insights into their mechanical and thermal properties. However, there are several avenues that can be explored further to enhance the design and performance of clutch systems. The following future work directions aim to build upon the current research, addressing potential limitations and exploring new opportunities for improvement.

Experimental Validation: Conduct experimental tests to validate the simulation results. This would involve creating prototypes of clutch friction disks using each material and testing them under various conditions to confirm the simulated performance metrics.

Material Hybridization: Explore the potential of hybrid materials by combining different materials to leverage their strengths. For example, using a composite of Kevlar 49 and E-Glass Epoxy could offer a balance of high velocity and moderate temperature resistance.

Optimization Techniques: Apply optimization techniques, such as genetic algorithms or finite element analysis, to further improve the design of clutch friction disks. This could involve optimizing material thickness, shape, or composition to enhance performance.

Wear Resistance Enhancement: Investigate methods to enhance the wear resistance of materials like Kevlar 49, which shows high potential for high-speed applications but may lack in wear resistance compared to metals.

Thermal Management: Develop strategies for thermal management in clutch systems, particularly for materials like Kevlar 49 that operate at extremely high temperatures. This could involve designing cooling systems or using thermal interface materials to reduce heat buildup.

Cost-Effectiveness Analysis: Conduct a cost-effectiveness analysis of each material to determine which offers the best balance of performance and cost. This would be crucial for large-scale industrial applications where cost is a significant factor.

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APPENDIX

Detail materials mechanical properties

Table A-1 Detail materials mechanical properties

Property	E-Glass Epoxy	Aluminum Alloy (6061)	Gray Cast Iron	Kevlar 49
Density (kg/m^3)	2,500	2,700	7,200	1,440
Young's Modulus (GPa)	25	68	110	112
Poisson's Ratio	0.25	0.33	0.25	0.36
Bulk Modulus (GPa)	13	70	100	24
Shear Modulus (GPa)	8.5	26	45	6
Isotropic Secant Coefficient of Thermal Expansion (1/°C)	5×10^{-6}	23.6×10^{-6}	10.4×10^{-6}	-2×10^{-6}
Compressive Ultimate Strength (MPa)	450	310	700	2,620
Compressive Yield Strength (MPa)	250	275	450	400
Strain-Life Parameters	Non-linear behavior	Material-dependent	Brittle, limited data	Limited Data
S-N Curve	Fatigue resistant	Fatigue curve defined	Brittle, low fatigue	High fatigue strength
Tensile Ultimate Strength (MPa)	600	310	200	3,600
Tensile Yield Strength (MPa)	240	276	140	2,800