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Design and Analysis of Types of Differentials for Formula Vehicle Transmission using Additive Manufacturing

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ABSTRACT

The demand for electric vehicles (EVs) has surged due to their eco-friendly nature and energy efficiency. However, optimizing the power transmission system remains a key challenge in enhancing vehicle performance and cost-effectiveness The project focuses on the selection, design, and analysis of a differential transmission system for Formula vehicle. The differential plays a critical role in vehicle dynamics, directly impacting handling and overall performance. Various types of differentials are commonly used each offering unique advantages. It aims to bridge that gap by providing a structured approach to choosing the most suitable differential based on specific vehicle requirements. It includes a methodology covering differential type evaluation, system design, and performance analysis. The goal is to assist in making informed decisions that contribute to enhanced vehicle dynamics and competitiveness in the event. This project focuses on the design and analysis of an electric vehicle power transmission system, specifically on differential redesign and material modification, to improve power transmission efficiency and reduce material costs. The study involves redesigning the differential to optimize its structural integrity and weight, ensuring efficient power distribution to the wheels. Additionally, material modifications will be explored by replacing conventional materials with advanced lightweight and high-strength alternatives. The primary objective is to improve efficiency while achieving cost reduction without compromising durability and performance.

The project employs SolidWorks for 3D modelling of gears and design optimization and ANSYS for structural analysis. Various materials will be analysed for strength, weight reduction, and thermal stability. Finite Element Analysis (FEA) will be conducted to evaluate stress distribution, deformation, and overall efficiency under real-world loading conditions. Comparative studies between existing and redesigned differentials will be performed to validate improvements. The expected outcomes include a lighter, more efficient differential design with improved power transmission efficiency, reduced material costs, and enhanced durability. This research contributes to the ongoing advancements in EV powertrain development, making electric vehicles more sustainable and cost-effective. Furthermore, the project explores the integration of Additive Manufacturing in the differential design process. AM allows for lightweight, complex geometries and functional integration, which are otherwise difficult to achieve using traditional manufacturing methods. By applying Design for Additive Manufacturing (DfAM) principles, the project aims to reduce weight, improve heat dissipation, and enhance the structural integrity of the differential housing and internal components.

Keywords: Electric Vehicle, Power Transmission, Differential Redesign, SolidWorks, ANSYS.

INTRODUCTION

1.1 INTRODUCTION TO DIFFERENTIAL GEARS

A differential is a gear train with three drive shafts that has the property that the rotational speed of one shaft is the average of the speeds of the others. A common use of differentials is in motor vehicles, to allow the wheels at each end of a drive axle to rotate at different speeds while cornering. Other uses include clocks and analogue computers. Differentials can also provide a gear ratio between the input and output shafts (called the "axle ratio" or "diff ratio"). For example, many differentials in motor vehicles provide a gearing reduction by having fewer teeth on the pinion than the ring gear.

During cornering, the outer wheels of a vehicle must travel further than the inner wheels (since they are on a larger radius). This is easily accommodated when the wheels are not connected, however it becomes more difficult for the drive wheels, since both wheels are connected to the engine (usually via a transmission). Some vehicles (for example go-karts and trams) use axles without a differential, thus relying on wheel slip when cornering. However, for improved cornering abilities, many vehicles use a differential, which allows the two wheels to rotate at different speeds. The purpose of a differential is to transfer the engine's power to the wheels while still allowing the wheels to rotate at different speeds when required. In automotive engineering the electronic differential is a form of differential, which provides the required torque for each driving wheel and allows different wheel speeds. It is used in place of the mechanical differential in multi-drive systems. When cornering, the inner and outer wheels rotate at different speeds, because the inner wheels describe a smaller turning radius. The electronic differential uses the steering wheel command signal and the motor speed signals to control the power to each wheel so that all wheels are supplied with the torque they need.

Problem Statement

Electric vehicle (EV) differentials require materials that can withstand high torque and rotational speeds while maintaining low weight and high durability. Traditional materials like mild steel may not provide the optimal balance of strength, weight, and safety for modern EV demands. Therefore, there is a need to evaluate alternative materials for differential gear components to enhance performance and reliability. This project addresses the problem of identifying the most suitable material—among mild steel, alloy steel 8620, aluminum 356, and aluminum 7075—for an EV differential gear setup by analyzing their mechanical behavior under identical loading and boundary conditions using CAD modeling and finite element analysis.

Objectives

- The objective of this project is to Redesign the differential system to enhance power transmission efficiency.
- Optimize structural integrity while minimizing material usage.
- Replace conventional materials with lightweight, high-strength alternatives to achieve significant weight reduction without sacrificing durability.
- Focus on cost optimization to ensure the redesigned system remains economically viable.
- Conduct structural analysis using SolidWorks and ANSYS to evaluate:
    - Stress distribution

- Deformation
- Strength and stability under real-world conditions

- Perform a comparative analysis between the existing and redesigned differentials to validate improvements in:

- Efficiency
- Weight reduction
- Overall performance

CHAPTER 2: LITERATURE REVIEW

The purpose of this literature review is to give foundation data on the issues to be considered in this thesis and to accentuate the relevance of the present study. **Gong et al. (2018)** presented a study on the optimization of an electric vehicle differential system, focusing on efficiency improvement by reducing mechanical losses using advanced lubrication techniques. Their research aimed at improving the power transmission efficiency of the differential by employing low-friction materials and optimized lubrication methods. The study highlighted the importance of reducing heat generation, which is a critical factor in the performance and longevity of differential components. The researchers proposed a model that analysed friction losses within the differential gears and bearings, utilizing computational fluid dynamics (CFD) and finite element analysis (FEA) to validate their findings. The experimental results indicated a 10-15% reduction in mechanical losses when compared to conventional differential systems. Additionally, the study emphasized the significance of lightweight materials, such as aluminium and magnesium alloys, in improving energy efficiency without compromising strength. The paper concluded that a well-optimized differential could contribute significantly to the overall efficiency of electric vehicles, reducing energy consumption and improving driving range.

Kim et al. (2019) investigated a novel electronically controlled differential system for EVs, emphasizing torque vectoring to improve vehicle stability and cornering performance. Their research introduced an innovative electronic differential (e-differential) that replaced traditional mechanical differentials with advanced control algorithms and sensor-based monitoring. The study focused on real-time torque distribution between the wheels, which enhanced traction and reduced wheel slip, particularly in dynamic driving conditions. The researchers utilized MATLAB/Simulink simulations to assess the effectiveness of the proposed system, and their findings indicated that electronically controlled differentials improved lateral stability by 20% when compared to traditional mechanical differentials. Practical implementation of the system was tested using prototype electric vehicles, where improvements in acceleration performance and energy efficiency were observed. The study concluded that electronic differentials have the potential to revolutionize EV drivetrain technology by enhancing vehicle handling and reducing mechanical complexity.

CHAPTER 3: METHODOLOGY

The objective of this study is to develop and analyse an electric vehicle (EV) differential gear setup using various materials to determine the most efficient and reliable option under static loading conditions. The methodology adopted for this project is detailed below:

3.1 Design and Modelling in SolidWorks

- A complete differential gear setup, including gears and bevel gears, was modelled using SolidWorks CAD software.

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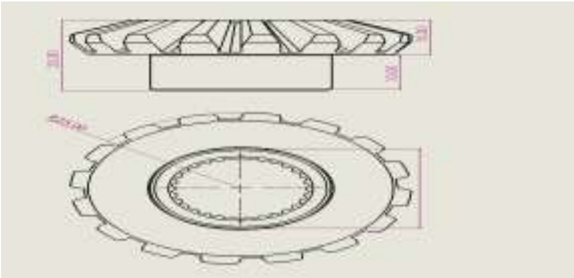

Fig 3.1: Differential Drawing of Helical Gear

Figure 3.1 shows the differential drawing of the helical gear.

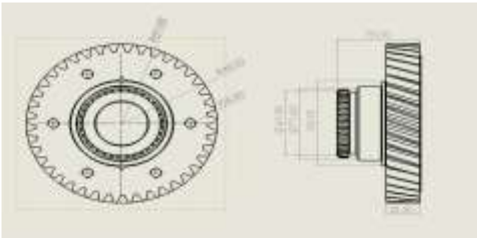

Fig 3.2: Dimensions of Helical Gear

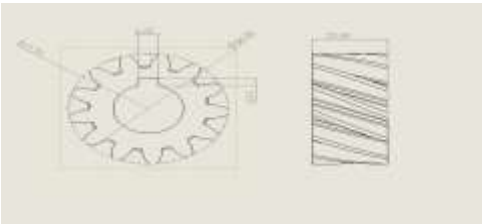

Fig 3.3: Dimensions of Pinion Gear

Accurate geometrical features and dimensions were considered to replicate real-world differential system functionality.

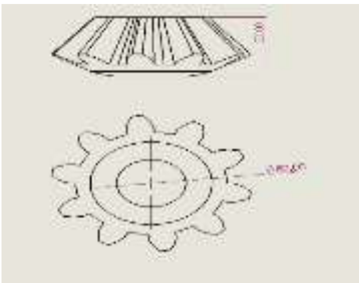

Fig 3.4 Differential Drawing of Bevel Gear

Figure 3.4 shows the Differential Drawing of Bevel Gear

Material Selection

- The baseline material selected for the analysis was Mild Steel, commonly used in mechanical components.
- Three alternative materials were chosen for performance comparison:
  - Alloy Steel 8620 – known for high strength and toughness.
  - Aluminium Alloy 356 (Al-356) – lightweight and moderately strong.
  - Aluminium Alloy 7075 (Al-7075) – high strength-to-weight ratio, suitable for high-performance applications.

Importing to ANSYS Workbench for Simulation

- The SolidWorks model was imported into ANSYS Workbench for structural analysis.
- The same geometry was used for all materials to ensure a consistent basis for comparison.

Boundary Conditions and Load Application

- A static load of 10 MPa and a rotational speed of 2000 RPM were applied to simulate operational conditions of the differential.
- Fixed supports were applied at appropriate locations to replicate real-world mounting constraints.

Mesh Generation

- A fine mesh was generated using tetrahedral elements to ensure accurate results.
- Mesh refinement was applied near gear teeth to capture stress concentration areas.

Structural Analysis

- For each material, simulations were conducted under identical boundary conditions.
- The following parameters were recorded:
- Total Deformation

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- Equivalent (von-Mises) Stress
- Strain
- Safety Factor

Fig 3.7: Assembly of Pinion Gear with Helical Gear

Meshing

The figure 3.8 shows a 3D finite element mesh generated in Ansys 2024 R1, using tetrahedral (Tet) elements. These unstructured tetrahedral meshes are well-suited for complex geometries like differential assemblies, offering good adaptability to curved and detailed surfaces.

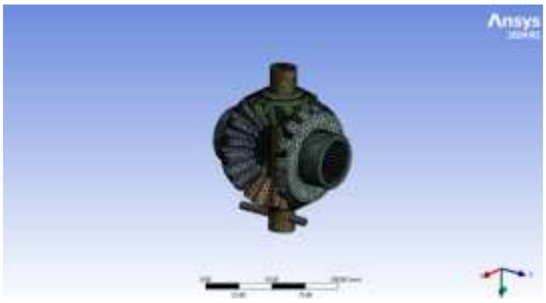

Fig 3.8: Meshing of Differential Gear

Boundary conditions

The boundary conditions applied in this Ansys simulation include:

- Fixed Support on one side of the differential housing (gray region).
- Pressure loads of 10 MPa applied on two separate internal surfaces (highlighted in red).
- Rotational Velocity is applied to a shaft or gear (highlighted in yellow) to simulate motion.

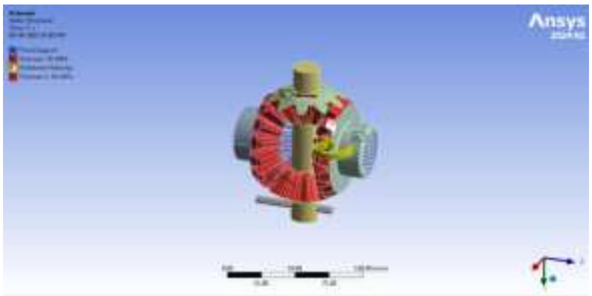

Fig 3.9: Boundary Conditions of Differential Gear

Results of Mild steel

Deformation

The total deformation results of a differential gear assembly of Mild Steel in ANSYS 2024 R1 under structural loading is shown in figure 4.1. The maximum deformation is approximately 0.0056 mm, occurring at the gear teeth, indicating localized stress concentration under applied pressure and rotational velocity. The deformation is minimal, suggesting good structural stiffness.

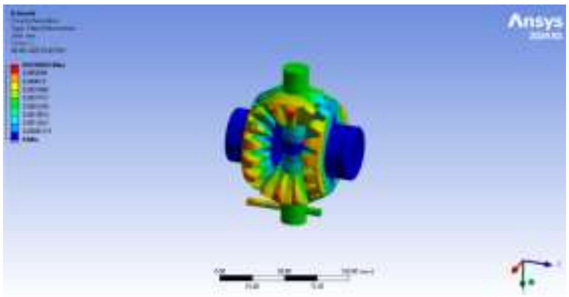

Fig 4.1: Total Deformation Analysis of Differential Gear (Material: Mild Steel)

Stress

This ANSYS 2024 R1 plot in the figure 4.2 shows the equivalent (von-Mises) stress distribution in a differential gear assembly of Mild Steel. The maximum stress is approximately 146.56 MPa, concentrated around the gear teeth where load transmission occurs. Most of the component remains in a lower stress range, indicating effective load distribution.

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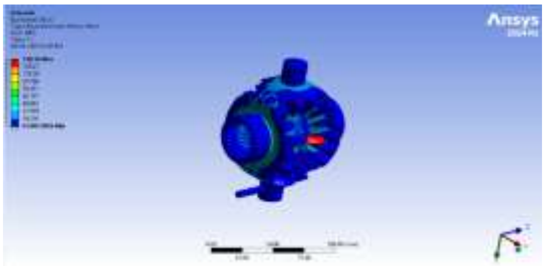

Fig 4.2: Equivalent (von-Mises) Stress Distribution in a Differential Gear (Material: Mild Steel)

Strain

This ANSYS 2024 R1 simulation shows the equivalent elastic strain distribution in a differential gear made of mild steel in figure 4.3. The maximum strain is approximately 0.00076679 mm/mm, located near the gear tooth roots, where deformation due to loading is most significant. The low strain values confirm the material's elastic behavior under

1. Deformation (mm)

the applied loads, remaining within the safe limits of mild steel.

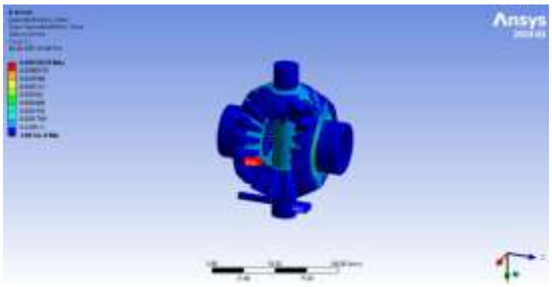

Fig4.3: Equivalent Elastic Strain Distribution in a Differential Gear Assembly (Material: Mild Steel)

Safety Factor

This ANSYS simulation as illustrated in figure 4.4 displays the safety factor distribution in a differential gear made of mild steel. The minimum safety factor is 1.7058, indicating that the structure remains within safe operational limits under the applied loads. Most regions show high safety factors (blue areas), suggesting the component is generally overdesigned and structurally sound.

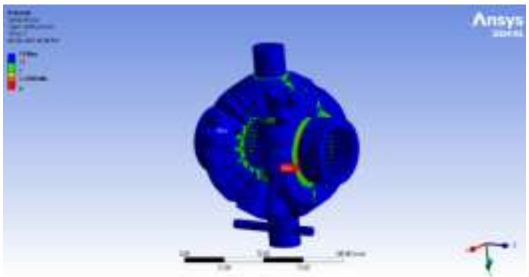

Fig 4.4: Safety factor distribution in the Differential Gear Assembly (Material: Mild Steel)

Table 4.1: Comparison of Materials

	Mild steel	8620 steels	Al 356	Al 7075
Deformation(mm)	0.005680	0.005532	0.016079	0.015922
Stress (MPa)	146.56	146.85	145.75	145.75
Strain	0.00076679	0.00075085	0.0021361	0.0021152
Safety factor	1.7058	2.5195	1.7976	3.4511

4.6 Graphs

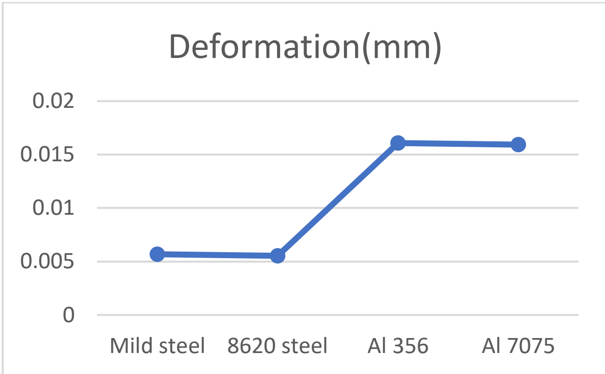

Fig 4.17: Deformation Graph of Materials

- **Mild Steel**: 0.005680 mm
- **8620 Steel**: 0.005532 mm
- **Al 356**: 0.016079 mm
- **Al 7075**: 0.015922 mm

Explanation: Deformation measures how much the component bends or stretches under load. The steels (mild and 8620) show minimal deformation (less than 0.006 mm), indicating high stiffness. The aluminium alloys (Al 356 and Al 7075) deform more (around 0.016 mm), reflecting their lower stiffness compared to steel. The slight difference between Al 356 and Al 7075 suggests similar elastic properties, but Al 7075's marginally lower deformation hints at a slightly higher modulus of elasticity or better load distribution.

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Stress (MPa)

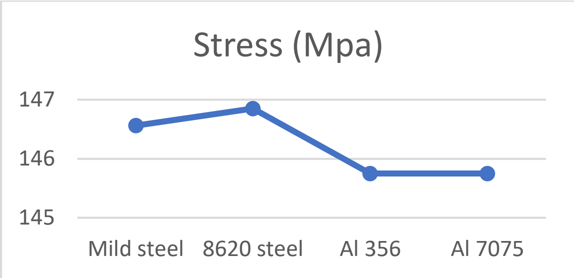

Fig 4.18: Equivalent (von-Mises) Stress Graph of Materials

- Equivalent (von-Mises) Stress Graph of Materials is shown in figure 4.18
- **Mild Steel**: 146.56 MPa
- **8620 Steel**: 146.85 MPa
- **Al 356**: 145.75 MPa
- **Al 7075**: 145.75 MPa

Explanation: Stress represents the internal resistance to the applied 10 MPa pressure and rotational load. All materials exhibit stresses close to 146 MPa, which is consistent across the group. This suggests the stress is dominated by the applied load and geometry rather than material properties. The values are below the yield strength of these material, indicating no plastic deformation i.e., the component remains elastic and returns to its original shape after load removal.

Strain

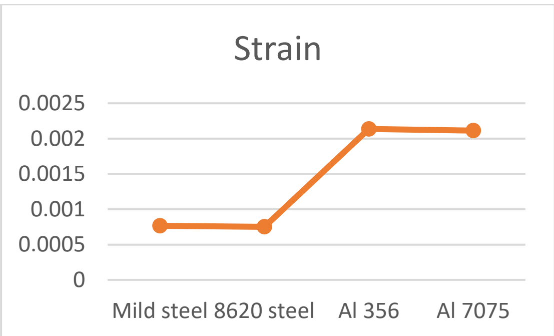

Fig 4.19: Variation of Strain in Materials

- Variation of Strain in Materials is illustrated in figure 4.19
- **Mild Steel**: 0.00076679
- **8620 Steel**: 0.00075085
- **Al 356**: 0.0021361
- **Al 7075**: 0.0021152

Explanation: Strain is the ratio of deformation to original length, a measure of how much the material stretches. The steels show very low strain (around 0.00075–0.00077), reflecting their high stiffness and low ductility under these conditions. The aluminium alloys exhibit higher strain (around 0.0021), consistent with their lower Young's modulus (e.g., Al 7075 ~70 GPa vs. steel ~200 GPa). This indicates aluminium deforms more elastically, which is expected and aligns with its use in lightweight applications where some flexibility is acceptable.

Safety Factor

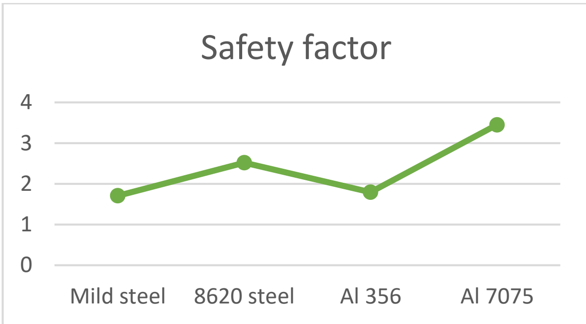

Fig 4.20: Safety Factor Graph of Materials

- Safety Factor Graph of Materials is shown in figure 4.20
- **Mild Steel**: 1.7058
- **8620 Steel**: 2.5195
- **Al 356**: 1.7976
- **Al 7075**: 3.4511

Explanation: The safety factor is the ratio of a material's yield strength to the maximum stress it experiences. A value above 1 indicates the component can withstand the load without failing.

  - **Mild Steel (1.7058)**: Marginally safe, suggesting it's close to its yield limit (~250 MPa). This low factor indicates it's the least robust option for long-term reliability.

- **8620 Steel (2.5195)**: A higher factor, reflecting its greater yield strength, making it more durable and suitable for high-stress applications.
- **Al 356 (1.7976)**: Slightly better than mild steel, but still on the lower side, indicating its yield strength is adequate but not optimal for this load.
- **Al 7075 (3.4511)**: The highest safety factor, due to its high yield strength suggesting it's the safest choice, offering a significant margin against failure.

- **Implication**: A safety factor above 2 is typically desired for critical components. Al 7075 and 8620 steel meet this threshold, while mild steel and Al 356 are borderline, potentially risking failure under dynamic or variable loads.

4.7 Gears Analysis Results

4.7.1 Gear Results

Results of Mild steel

Deformation

The figure 4.21 displays the total deformation of a gear assembly under loading conditions, with a maximum deformation of 0.013565 mm occurring at the gear teeth. The deformation is concentrated along the edges, indicating typical stress distribution due to meshing and rotational forces.

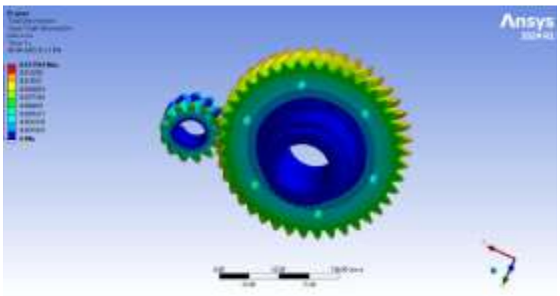

Fig 4.21: Deformation Analysis Result of Helical & Pinion Gear (Material: Mild Steel)

Stress

The figure 4.22 shows the equivalent (von-Mises) stress distribution in a gear assembly, with a maximum stress of 195.1 MPa. The stress is primarily concentrated around the gear teeth and inner hub regions, indicating areas of high load transfer and potential failure under extreme conditions.

Fig 4.22: Stress Analysis Result of Helical & Pinion Gear (Material: Mild Steel)

Strain

The figure 4.23 represents the equivalent elastic strain distribution in a gear system under load. The maximum strain observed is approximately 0.00098144 mm/mm, occurring primarily near the gear teeth and hub interface, indicating regions of highest elastic deformation during operation.

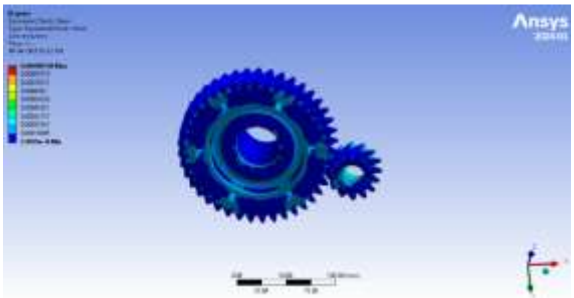

Fig 4.23: Strain Analysis Result of Helical & Pinion Gear (Material: Mild Steel)

Safety Factor

The figure 4.24 shows the safety factor distribution of the gear assembly under loading conditions. The minimum safety factor is approximately 1.28, indicating that some areas, especially around the gear teeth, are closer to the failure threshold, while most of the structure remains in the safe zone.

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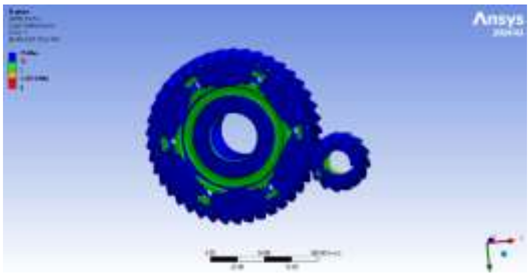

Fig 4.24: Safety Factor Analysis Result of Helical & Pinion Gear (Material: Mild Steel)

Table 4.2: Comparison of Results

	Mild steel	8620 steels	Al 356	Al 7075
Deformation(mm)	0.013565	0.013213	0.038381	0.038006
Stress (Mpa)	195.1	195.34	194.55	194.55
Strain	0.00008144	0.00095874	0.0027557	0.0027288
Safety factor	1.2814	1.8942	1.3467	2.5855

4.8 Graphs

Deformation

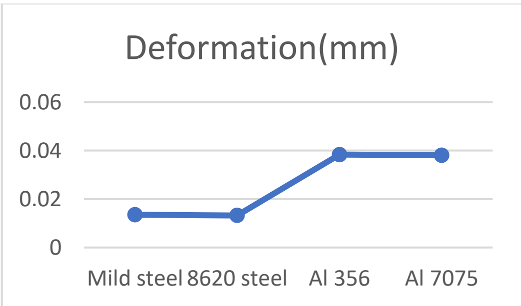

Fig 4.37: Deformation graph of materials

- Deformation graph of materials is shown in figure 4.37
- **Mild Steel**: 0.013565 mm
- **8620 Steel**: 0.013213 mm
- **AI 356:** 0.038381 mm
- **AI 7075**: 0.038006 mm
- Deformation measures how much the gear displaces under the applied load. Lower deformation is better as it indicates higher stiffness.
- Mild Steel and 8620 Steel show the least deformation (0.013 mm), meaning they are stiffer under the given load.
- AI 356 and AI 7075 (aluminium alloys) deform significantly more (0.038 mm), which is expected because aluminium has a lower modulus of elasticity (stiffness) compared to steel. The modulus of elasticity for steel is typically around 200 GPa, while for aluminium alloys, it's around 70 GPa.
- Between the aluminium alloys, AI 7075 deforms slightly less than AI 356, likely due to its higher strength and stiffness.

Stress (MPa)

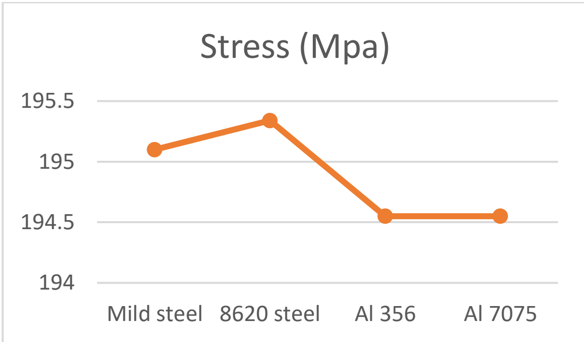

Fig 4.38: Stress graph of materials

- Figure 4.39 depicts the Stress graph of materials
- **Mild Steel:** 195.1 MPa
- **8620 Steel**: 195.34 MPa
- **AI 356:** 194.55 MPa
- **AI 7075:** 194.55 MPa
- The von Mises stress indicates the material's response to the applied load. A lower stress value is better, but it must be compared to the material's yield strength to assess safety.
- All materials experience similar stress levels (~194.55–195.34 MPa), which makes sense because the geometry, loading, and boundary conditions are the same for all materials. The slight variations are due to differences in material properties like stiffness and Poisson's ratio.
- To evaluate if these stresses are safe, we need to compare them to the yield strengths of the materials

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Strain

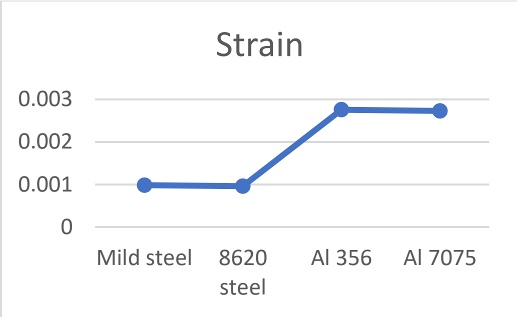

Fig 4.39: Strain graph of materials

- **Mild Steel**: 0.00098144
- **8620 Steel**: 0.00095874
- **AI 356**: 0.0027557
- **AI 7075**: 0.0027288
- Strain measures the elastic deformation of the material (change in length per unit length). Lower strain indicates less deformation. Mild Steel and 8620 Steel have much lower strain (0.00096–0.00098) compared to AI 356 and AI 7075 (0.0027–0.0028). This aligns with the deformation results, as strain is directly related to deformation.
- Aluminium alloys (AI 356 and AI 7075) have higher strain because of their lower modulus of elasticity. The relationship between stress and strain is given by Hooke's Law: where (E) is the modulus of elasticity. Since aluminium has a lower (E), it experiences higher strain for the same stress.

Safety Factor

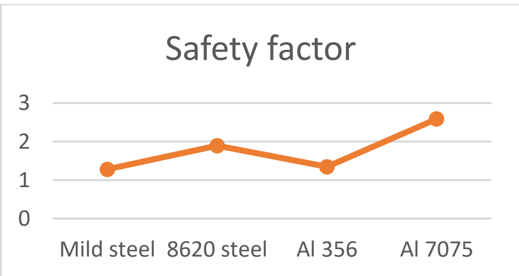

Fig 4.40: Safety Factor graph of materials

- Figure 4.40 shows the Safety Factor graph of materials
- **Mild Steel:** 1.2814
- **8620 Steel**: 1.8942
- **Al 356**: 1.3467
- **Al 7075**: 2.5855
- The safety factor is calculated as: Yield Strength/Maximum Stress

A higher safety factor indicates a safer design. Typically, a safety factor above 1.5 is considered acceptable for most engineering applications, though this depends on the industry and application

Al 7075 has the highest safety factor (2.5855), making it the safest material under these conditions. This is because AI 7075 has a high yield strength

8620 Steel has a safety factor of 1.8942, also relatively safe. 8620 steels, often used in gears, has a yield strength of around 370 MPa. Mild Steel (1.2814) and AI 356 (1.3467) have the lowest safety factors, indicating they are closer to failure. Mild steel typically has a yield strength of around 250 MPa.

3.5 3D PRINTING OF GEARS

Fig 3.10 3D Printing of Pinion Gear

Fig 3.11 Printing of Gears

- Figure 3.10 &3.11 depicts the 3D printing of Gears

CHAPTER 5: CONCLUSIONS

In this project, an electric vehicle differential gear setup was developed using SolidWorks and analyzed using ANSYS Workbench. Mild steel was considered as the existing material, while Alloy Steel 8620, Al-356, and Al-7075 were selected as alternative materials to improve the efficiency of the component. The Bevel gears were analyzed under the same boundary conditions, and results such as deformation, stress, strain, and safety factor values were calculated.

The results indicate that all materials can handle the static load (10 MPa, 2000 rpm), with stresses well below yield points. However, Al 7075 offers the best safety margin (3.4511), making it the most reliable for long-term use, followed by 8620 steel (2.5195). Mild steel and Al 356, with safety factors near 1.7–1.8, are viable but riskier under variable conditions. For an EV differential, the choice depends on balancing weight, cost, and durability—Al 7075 excels for performance EVs, while 8620 steel suits durability-focused designs.

5.2 Future work

This future work aims to bridge the gap between simulation and real-world application, optimizing the EV differential for performance, efficiency, and scalability. By focusing on dynamic testing, thermal management, material innovation, and integration with advanced EV systems. The future scope of this project lies in advancing electric vehicle (EV) power transmission systems to be more efficient, intelligent, and adaptable across diverse applications. As EV adoption grows, there will be increasing demand for multi-speed gearboxes, integrated smart control systems, and modular drivetrains that can cater to passenger cars, commercial vehicles, and off-road platforms. The integration of AI for predictive gear shifting, digital twin simulations for real-time monitoring, and sustainable materials for lightweighting will drive innovation. This project can also serve as a foundation for further academic research, industry collaboration, and the development of scalable, high-performance, and eco-friendly EV powertrain solutions.

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