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Comparative Material Analysis and Stress Evaluation of a Reverse Engineered Gearbox

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Abstract

The gearbox is a vital component in electric vehicles (EVs), directly affecting power transmission efficiency, performance, and reliability. In this study, a real-time EV gearbox was reverse engineered to obtain accurate geometric dimensions and operational characteristics. The gearbox consists of four gears with different tooth numbers and thicknesses. Detailed measurements and material characterization were carried out to develop an accurate structural model. Among the gears, the second gear was identified as the most critical component due to its higher stress concentration and lower safety margin during operation. The structural performance of the gear was evaluated using theoretical calculations, finite element analysis in ANSYS 2022, and numerical validation through MATLAB. Stress distribution, deformation, and safety factors were analyzed under operating loads. Different engineering materials were also compared to determine the most suitable option for gearbox applications. The study demonstrated good agreement between analytical and numerical results, with AISI D2 providing the best overall structural performance and reliability.

Keywords: Electric Vehicle Gearbox, Reverse Engineering, Finite Element Analysis, Material Selection, Structural Performance.

I. INTRODUCTION

Electric vehicles (EVs) have emerged as a sustainable alternative to conventional internal combustion engine vehicles due to their high energy efficiency, reduced emissions, and lower operating costs. As the demand for EVs continues to grow worldwide, the performance and reliability of drivetrain components have become increasingly important. Among these components, the gearbox plays a vital role in transmitting power from the electric motor to the wheels while ensuring efficient speed and torque conversion. An optimized gearbox design contributes significantly to vehicle efficiency, driving performance, and operational durability.

Despite the advantages of electric vehicles, several engineering challenges remain in gearbox design and development. The primary problem identified in this study is the need to optimize gearbox performance to satisfy the increasing demands of modern transportation systems. The gearbox must efficiently transmit power while minimizing energy losses and maintaining structural integrity under varying operating conditions. Components such as gears are subjected to repeated loading, stress concentrations, and wear, which can affect their reliability and service life if not properly designed and analyzed.

Furthermore, the selection of suitable materials and the optimization of gear geometry are critical factors influencing gearbox performance. The gearbox must withstand different torque and speed requirements while maintaining durability and safety throughout its operational life. Addressing these challenges through reverse engineering, material evaluation, and numerical analysis can improve drivetrain efficiency, enhance vehicle reliability, and support the continued advancement of electric mobility technologies. Therefore, this study focuses on the structural assessment and material optimization of an electric vehicle gearbox to identify the most suitable design and material combination for improved performance.

II. LITERATURE REVIEW

Gear tooth stress analysis has been an important area of research for improving the performance and reliability of transmission systems. Traditional analytical approaches such as the Lewis

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equation provided a foundation for estimating bending stresses in gear teeth; however, limitations in accurately predicting local stress distributions encouraged further investigations. Spitas and Costopoulos [2] proposed a modified spur gear tooth design with a circular root fillet and reported improved fatigue resistance compared to conventional profiles. Hiremagalur and Ravani [3] examined the influence of backup ratio on root stresses and gear failure mechanisms. Beghini and Santus [4] focused on reducing transmission error through profile optimization techniques, while Chen and Tsay [5] employed finite element analysis to evaluate contact and bending stresses in helical gears. Chien-Hsing Li and Hong-Shun Chiou [6] integrated finite element and optimization tools for automated gear design, whereas Kapelevich and Kleiss [7] introduced Direct Gear Design to enhance gear performance beyond conventional design limitations.

Further advancements were achieved through numerical simulation and finite element techniques. Parker and Vijayakar [8] investigated the dynamic behavior of spur gears under varying loads and speeds, identifying tooth contact loss as a major source of nonlinearity. Simon [9] developed finite element procedures for stress and deflection analysis in hypoid gears, while Zhang and Fang [10] studied tooth contact and load distribution in crossed-axis helical gears considering manufacturing errors and profile modifications. Guigand and Icard [1] proposed a simulation method for loaded face gear meshing to improve load distribution and reduce transmission errors. These studies collectively demonstrated that finite element analysis, optimization methods, and advanced gear design approaches significantly improve the prediction of stress behavior, enhance structural reliability, and support the development of high-performance gearbox systems.

III. DESIGN OF GEAR GEOMETRIC PARAMETERS

The electric vehicle (EV) transmission system studied consists of a high-speed electric motor connected to a two-stage helical gear arrangement. The motor delivers 30 kW power at 4000 rpm, while the gearbox provides an overall reduction ratio of 7.55 to achieve the required wheel speed and torque. Helical gears are preferred due to their smooth operation, low noise, and high load-carrying capacity, making them suitable for EV applications.During operation, the gears experience varying loads caused by acceleration, deceleration, and changing road conditions, leading to fluctuating stresses and potential fatigue damage. Special attention is given to the secondary driving gear on the intermediate shaft, which has 18 teeth, a 38 mm face width, a 2.75 mm module, a 12° helix angle, and a 20° pressure angle. These parameters significantly influence gear performance and durability.The gears are manufactured from 20CrMnTi steel and undergo carburizing, quenching, and tempering to improve hardness and wear resistance. However, fatigue failure can still occur under prolonged service conditions. Therefore, analyzing stress distribution, material behavior, and operating conditions is essential for improving gearbox reliability, efficiency, and service life in electric vehicles.

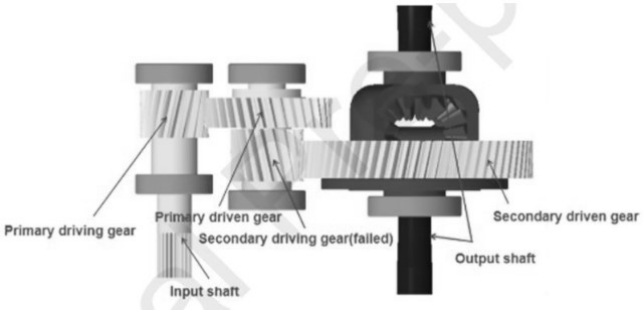


Fig 1: Gear box in EV

Table 1: gear geometrical parameters.

Parameter	Primary Driving Gear	Primary Driven Gear	Secondary Driving Gear	Secondary Driven Gear
Number of Teeth	17	35	18	66
Normal Module (mm)	2.75	2.75	2.75	2.75
Teeth Width (mm)	38	24	42	30

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Pressure Angle (°)	20	20	20	20
Helix Angle (°)	12	12	12	12

The formulae and parameters are used from a Hand Book of Thin gear Design by G.M.Maitra and Machine Design Data Book – P.S.G. College of Technology.

Pitch circle diameter for pinion, d1 = m*z1 mm

Base circle diameter for Pinion, db1 = d1*cosα mm

Tip circle diameter for pinion, da1 = d1 + 2m mm

Root circle diameter for pinion, df1 = d1 – 2*1.25 mm

Centre distance, a = (d1 + d2)/2 or m (z1+z2)/2

Diametral pitch pd = z/d or 1/m

The design bending stress and induced deformation equations were implemented in MATLAB to evaluate the performance of different gear materials under identical loading conditions. The MATLAB program was developed to calculate the bending stress developed in the gear tooth and the corresponding deformation based on the material properties, geometric parameters, and applied load. By varying the material properties such as Young's modulus and yield strength, the effect of each material on gear performance was analyzed.

Design Bending Stress

$$Sb = \frac{F_t * Cos\theta * K_v * K_0 * K_m}{b * m^3}$$

Induced deformation

$$Def = \frac{F_t * Cos\theta * l^3}{3 * E * I}$$

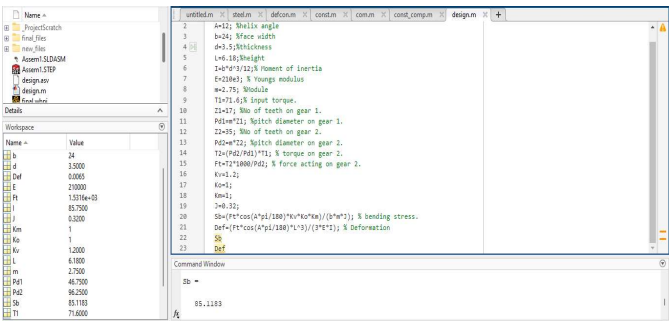


Fig 2: Matlab design output for structural steel.

The calculated bending stress values were used to assess the load-carrying capability of the gear, while the induced deformation values provided information regarding the stiffness and structural behavior of the material. The results obtained from MATLAB were compared for all selected materials to identify the most suitable material with lower deformation, higher strength, and improved safety factor for electric vehicle gearbox applications.

IV. 3d modeling

The complete gearbox assembly was developed using SOLIDWORKS software based on dimensions obtained from theoretical design calculations. All components were modeled in millimeters to ensure dimensional accuracy and consistency throughout the design process. The gearbox consists of four gears mounted on multiple shafts and arranged in a two-stage transmission system. Individual gear models were created using the Sketch and Part Design modules, where the calculated tooth profiles, shaft dimensions, hub features, and face widths were converted into accurate three-dimensional solid models. The parametric modeling capabilities of SOLIDWORKS enabled easy modification of dimensions and ensured precise representation of each component. The developed models provide a reliable foundation for further structural analysis, motion studies, and performance evaluation of the gearbox system.

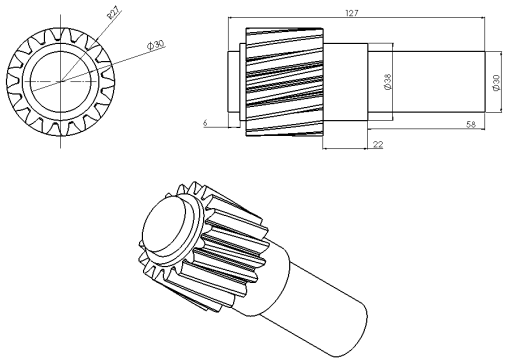


Fig 3: Gear 1 detail drawing.

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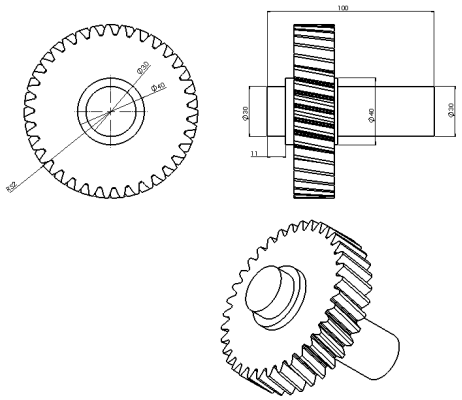


Fig 4: Gear 2 detail drawing.

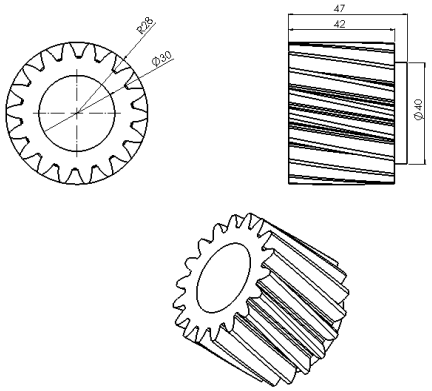


Fig 5: Gear 3 detail drawing.

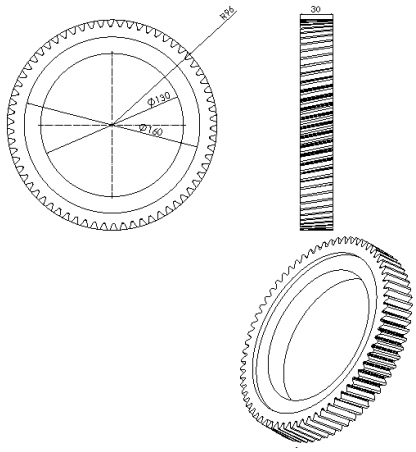


Fig 6: Gear 4 detail drawing.

Gear 1 and Gear 2 form the first stage of the transmission system and are responsible for initial power transfer and speed reduction. Gear 1 is mounted on a 30 mm diameter shaft with a face width of 30 mm and a tip circle diameter of 54 mm, while Gear 2 is supported on a 30 mm diameter shaft with a total shaft length of 100 mm and a tip circle radius of 52 mm. Gear 3 and Gear 4 constitute the second stage of the transmission system. Gear 3 incorporates a hub with an outer diameter of 40 mm and an inner diameter of 30 mm, whereas Gear 4 is designed with a larger hub diameter of 130 mm and a face width of 30 mm to improve load distribution and structural rigidity. These gears are carefully designed to ensure smooth meshing, efficient torque transmission, and reliable operation under varying loading conditions.

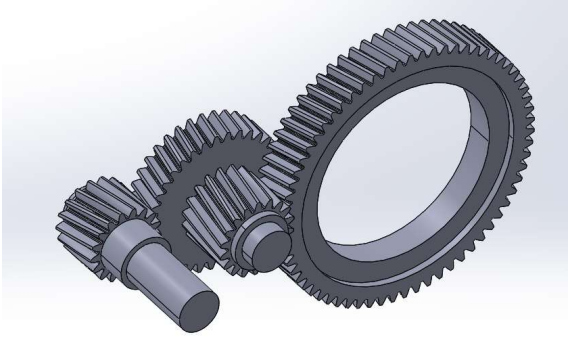


Fig 7: Assembly model of gear box.

After modeling the individual components, the complete gearbox assembly was created using the SOLIDWORKS Assembly module. Appropriate mating constraints such as concentric, coincident, and distance mates were applied to achieve proper alignment and positioning of gears and shafts. The spacing between shaft stages was maintained according to design calculations to avoid interference and ensure smooth power transmission. The assembly environment enabled verification of gear meshing, component interaction, and overall system functionality before manufacturing. In addition, SOLIDWORKS provides facilities for motion simulation, stress analysis, and design validation, allowing the gearbox assembly to be evaluated under operating conditions. The final assembly model serves as an effective platform for structural assessment, performance optimization, and future design improvements of the electric vehicle transmission system.

The three-dimensional gearbox model created in SOLIDWORKS was exported in IGES format and imported into ANSYS Workbench for finite element analysis. The IGES file preserved all geometric details, including gear teeth profiles,

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shaft configurations, and meshing arrangements, ensuring accurate representation of the gearbox assembly. After importing the geometry, material properties, connections, meshing parameters, boundary conditions, and loading conditions were defined. Modal Analysis and Harmonic Analysis were performed to investigate the dynamic behavior, vibration characteristics, and structural response of the gearbox under operating conditions. The imported model provided a reliable platform for evaluating the performance of the transmission system through numerical simulation.

A tetrahedral meshing technique was employed to discretize the gearbox geometry due to its suitability for complex gear profiles and irregular geometries. The generated finite element model consisted of 12,249 elements and 21,594 nodes, providing a good balance between computational efficiency and solution accuracy. Fine meshing was applied in critical regions such as gear tooth contact zones and load-bearing areas to improve the accuracy of stress and deformation predictions. The quality of the mesh plays a significant role in obtaining reliable simulation results and accurately capturing the structural behavior of the gearbox assembly.

For the analysis, a torque of 71,600 N-mm was applied to the first gear to represent the actual operating load transmitted through the gear train. The fourth gear hub was completely fixed, while appropriate displacement constraints were applied to the shaft supports to simulate realistic operating conditions. Seven different materials, namely 20MnCrTi Steel, CPM M4, AISI D2, AISI 4340, A48 Class 40, SS 303, and Structural Steel, were considered for evaluation.

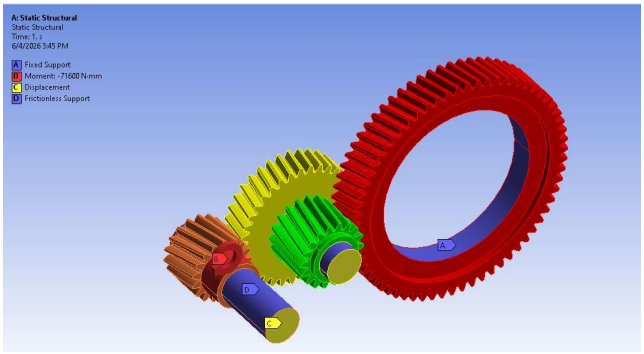


Fig 8: Load and boundary condition on gear box.

Table 2: material properties

Materials	E G.Pa	Poisson's ratio	density Kg/m3	Yield strength M.Pa
20Mn CrTi steel [22]	207	0.25	7850	85
CPM M4 [32]	210	0.3	7970	250
AISI D2[24]	210	0.3	7700	1654
AISI 4340 [25]	190	0.3	8030	472.3
A 48 class 40 [26]	110	0.29	7150	128
SS 303 [27]	193	0.25	8000	415
structural steel	200	0.3	7750	250

Their mechanical properties, including Young's modulus, Poisson's ratio, density, and yield strength, were incorporated into the analysis. The comparative study of these materials enabled the assessment of stress distribution, deformation, and structural performance, helping to identify the most suitable material for electric vehicle gearbox applications.

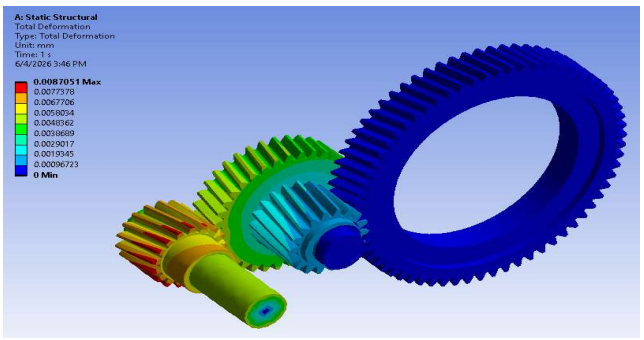


Fig 9: deformation on AISI D2 gear box.

The figure above illustrates the total deformation of the AISI D2 gear assembly under the applied torque loading condition. Blue regions indicate the minimum deformation, while deformation increases toward the gear teeth. The maximum deformation occurs at the tips of the gear teeth due to the applied load and gear meshing action. The maximum total deformation obtained

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is 0.0088 mm, while most regions of the gearbox experience nearly zero deformation.

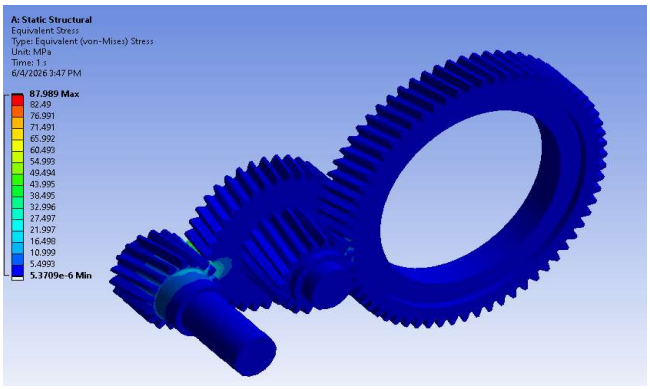


Fig 10: stress on AISI D2gear box.

The figure above shows the stress distribution in the CPM M4 gear assembly under the applied torque condition. The red color indicates the maximum stress, while the blue color represents the minimum stress regions. The highest stress is observed at the 2nd gear teeth, where the load is transmitted during gear meshing. The maximum equivalent stress developed is 89.31 MPa, indicating the critical stress location in the gear system.

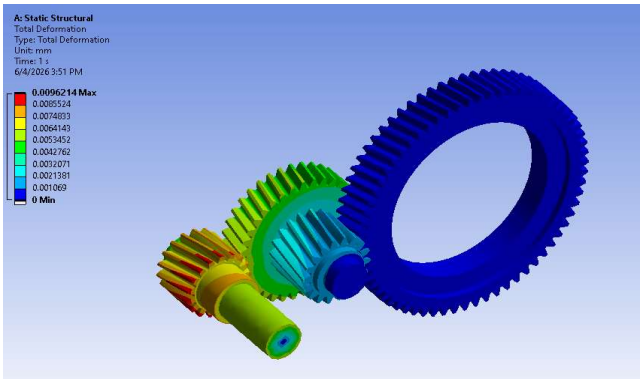


Fig 11: deformation on A 48 class 40 gear box.

The figure above illustrates the total deformation of the A48 Class 40 gear assembly under the applied torque loading condition. The blue regions indicate minimum deformation, while deformation increases toward the gear teeth due to load transmission. The maximum deformation occurs at the tips of the gear teeth, where the bending effect is highest. The maximum total deformation obtained is 0.0096 mm, while most parts of the gearbox experience negligible deformation.

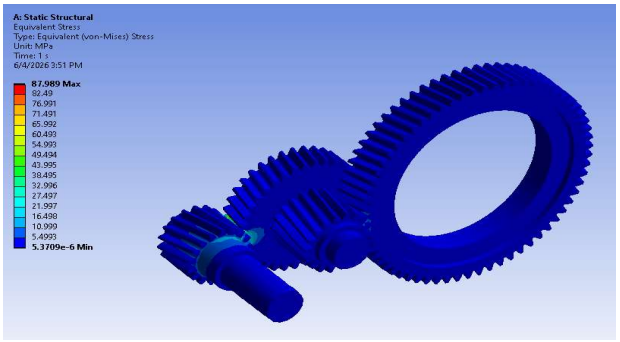
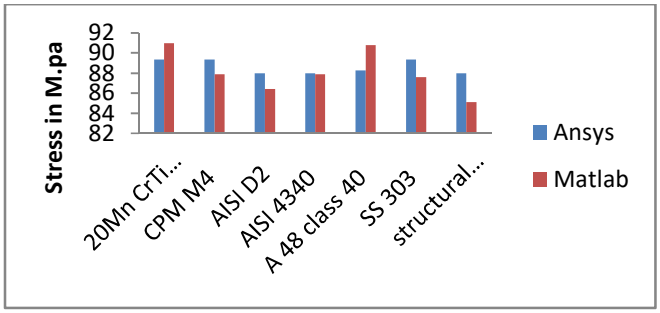


Fig 12: stress on A 48 class 40 gear box.

The figure above shows the stress distribution in the A48 Class 40 gear assembly under the applied torque condition. The red color represents the maximum stress, while the blue color indicates the minimum stress regions. The highest stress occurs at the 2nd gear teeth, where the gear meshing forces are concentrated. The maximum equivalent stress obtained is 87.99 MPa, indicating the critical stress location within the gear assembly.

V. Results and discussion

In this study, a comprehensive structural analysis of the gearbox is performed using ANSYS 2022, a widely used finite element analysis software capable of accurately simulating complex mechanical systems. The analysis incorporates both theoretical calculations and numerical simulations to evaluate the structural behavior and performance of the gearbox under applied loading conditions. By combining analytical and simulation-based approaches, a detailed understanding of the gearbox response is obtained, enabling effective design evaluation and optimization. In addition, graphical outputs such as contour plots and charts are used to clearly illustrate the distribution of deformation and stress throughout the gearbox components, facilitating better interpretation of the analysis results.



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Fig 13:Max Stress on Gear 2.

The stress results obtained from ANSYS and MATLAB show close agreement, confirming the accuracy and reliability of the structural analysis performed on the gearbox. The small variation between the two methods validates the numerical models and demonstrates that they accurately represent the actual mechanical behavior of the gearbox under loading conditions. Furthermore, the maximum stress of 89.36 MPa is significantly lower than the allowable stress limits of the selected materials, indicating that the gearbox operates safely within its design limits. These results confirm that the gearbox design is structurally sound, reliable, and suitable for long-term operation without risk of excessive deformation or failure.

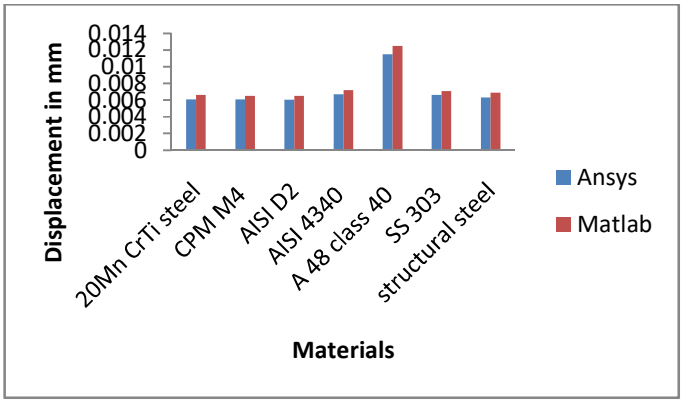


Fig 14: Max Displacement on Gear 2.

The deformation values obtained from ANSYS and MATLAB simulations show excellent agreement, confirming the accuracy and reliability of the numerical analysis performed on the gearbox. The small variation between the results demonstrates the robustness of the simulation methodology and validates the predicted structural behavior of the gearbox components. Among the materials analyzed, AISI D2 exhibited the minimum deformation of 0.00603 mm, indicating superior stiffness and resistance to deformation under applied loading conditions. This low deformation value confirms that the gearbox can maintain its dimensional stability and structural integrity during operation, making the design highly reliable, durable, and suitable for long-term engineering applications.

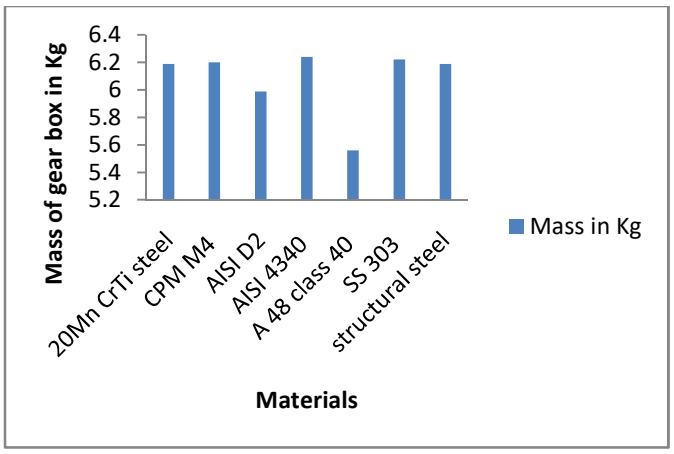


Fig 15: Mass of gear box for different materials.

The figure presents a comparative analysis of the gearbox mass for different materials used in its construction. The results indicate that the gearbox made from A48 Class 40 material has the lowest mass among all the materials considered in the study. With a total mass of 5.56 kg, it is the lightest configuration and offers a significant advantage in applications where weight reduction is an important design requirement.The reduced mass of the A48 Class 40 gearbox can contribute to improved efficiency, easier handling, and lower inertia during operation. Therefore, based on the mass comparison, A48 Class 40 emerges as the most lightweight and weight-efficient material option for the gearbox model while still meeting the required structural performance criteria.

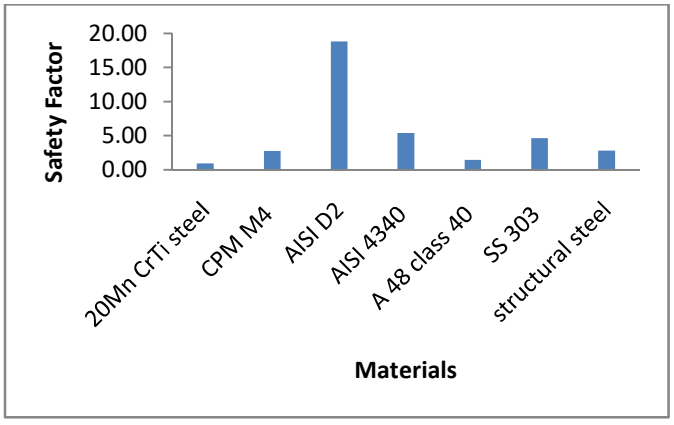


Fig 16: Safety factor for different materials.

The figure shows the safety factor distribution of the gearbox for different materials. Among all the materials analyzed, AISI D2 exhibits the highest safety factor of 18.8, indicating superior structural reliability and load-carrying capability. The safety

factor represents the margin between the operating stress and the material failure limit; therefore, a higher value signifies safer operation under applied loading conditions. The excellent performance of AISI D2 is attributed to its high strength, hardness, wear resistance, and durability, which enable it to withstand stresses more effectively than the other materials considered. Based on the results, AISI D2 is identified as the most suitable material for gearbox applications requiring high safety, reliability, and long service life.

CONCLUSION

This study investigated the structural performance of a reverse-engineered electric vehicle gearbox using theoretical calculations, ANSYS 2022, and MATLAB. The results showed excellent agreement between ANSYS and MATLAB, validating the accuracy of the analysis. The gearbox exhibited low deformation and stress values within allowable limits, confirming its structural safety and reliability under operating conditions. Among the materials evaluated, AISI D2 provided the best performance, with the highest safety factor (18.8) and the lowest deformation (0.00603 mm), making it the most suitable material for enhancing gearbox strength, durability, and service life. Overall, the proposed gearbox design is structurally sound and suitable for electric vehicle transmission applications.

Future Scope

The findings of this study provide a valuable basis for future improvements in electric vehicle gearbox design. Future research may focus on optimizing gearbox geometry for reduced weight and improved performance, developing advanced materials with higher strength and wear resistance, integrating smart sensors for condition monitoring and predictive maintenance, conducting detailed dynamic and thermal analyses under real operating conditions, and performing experimental validation to verify and enhance the accuracy of numerical simulation results. These advancements can further improve gearbox reliability, efficiency, durability, and service life.

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