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Design Modification of Bending Strength of Spur Gear in Worst Loading Conditions with Material Change

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Abstract

Spur gears are extensively used in power transmission systems due to their simple geometry, efficient torque transfer capability, and reliable operational performance. However, under severe loading conditions, bending stress concentration at the tooth root becomes a major factor influencing gear failure and structural durability. This study presents the design modification and bending strength evaluation of a spur pinion under worst loading conditions through material substitution between steel and aluminium alloy. Analytical design calculations were performed based on predefined geometric parameters including module, number of teeth, face width, and operating pressure. A three-dimensional CAD model was developed using Solid Edge ST7 and imported into ANSYS Workbench for finite element analysis. Comparative evaluation was conducted to assess equivalent stress, deformation characteristics, weight reduction, and operational suitability. The simulation results revealed that aluminium alloy produced nearly equivalent stress values compared with steel while significantly reducing component weight. Although steel exhibited lower deformation and higher stiffness, aluminium demonstrated acceptable structural performance with improved weight efficiency and corrosion resistance. The findings indicate that aluminium alloy can serve as an effective lightweight alternative for pneumatic actuator spur pinion applications while maintaining safe operating conditions.

Keywords: Spur Gear; Spur Pinion; Finite Element Analysis; Aluminium Alloy; Bending Stress; Material Comparison.

How to Cite This Article

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Introduction

Spur gears are among the most widely utilized mechanical transmission components in industrial systems due to their simple structure, efficient torque transfer capability, ease of manufacturing, and reliable operational characteristics. These gears are commonly employed in automotive assemblies, machine tools, pneumatic actuators, conveyor systems, and industrial automation equipment where controlled rotational motion and power transmission are required. In applications involving pneumatic actuation, the spur pinion is exposed to repeated loading conditions that generate bending stresses at the tooth root region, which is generally considered the most critical failure location.

Under severe operating conditions, excessive loading may result in tooth deformation, crack initiation, and eventual mechanical failure. Traditional design approaches mainly rely on analytical calculations; however, such methods are often insufficient for accurately predicting localized stress concentration. Finite Element Analysis (FEA) has emerged as an effective approach for evaluating structural behavior under realistic loading environments. The advancement of simulation tools enables engineers to assess stress distribution, deformation characteristics, and design optimization before manufacturing.

Material selection also plays a vital role in determining gear performance. Conventional steel gears provide superior stiffness and mechanical strength but contribute significantly to overall system weight. Aluminium alloys offer an alternative solution because of their lower density, improved corrosion resistance, and easier machinability. Reducing component weight in pneumatic systems can improve dynamic response and energy efficiency while maintaining acceptable structural performance.

This study investigates the bending strength of a spur pinion subjected to worst-case loading conditions by comparing steel and aluminium alloy materials using finite element simulation. CAD modelling and numerical analysis are performed to evaluate deformation, equivalent stress, weight reduction, and overall suitability for lightweight actuator applications.

Literature Review

Previous studies on spur gear analysis indicate that bending failure remains one of the most dominant failure mechanisms in gear transmission systems. Classical analytical methods, particularly Lewis bending theory, have been extensively used to estimate nominal tooth bending stress and evaluate gear design performance. However, analytical formulations generally assume simplified loading conditions and may not accurately represent localized stress behavior near the tooth root.

Recent developments in computational analysis have introduced Finite Element Analysis as an effective technique for studying gear performance under realistic operational conditions. Researchers reported that FEA provides improved prediction accuracy by capturing stress concentration zones and deformation behavior across complex tooth geometries.

Several investigations explored geometric optimization approaches including modification of tooth profiles and incorporation of stress-relieving features to reduce peak bending stresses. These approaches demonstrated improved fatigue life and enhanced load-bearing capability.

Material-based optimization has also received increasing attention. Steel continues to dominate industrial gear manufacturing due to its high strength and rigidity; however, aluminium alloys have shown advantages in applications where weight reduction and corrosion resistance are important. Comparative studies indicate that aluminium gears can significantly decrease rotational inertia while maintaining acceptable stress levels.

Although existing literature presents analytical and simulation-based approaches for gear design improvement, limited studies specifically address spur pinion replacement in pneumatic actuator systems under worst loading conditions. Therefore, this work focuses on evaluating material substitution using finite element simulation to determine whether lightweight aluminium components can provide acceptable structural performance without compromising operational reliability.

Methodology

The proposed methodology combines analytical design calculations, computer-aided modelling, and finite element simulation to evaluate the bending strength performance of spur gears under severe loading conditions.

Step 1: Design Parameter Identification

Initial design inputs were established based on application requirements including module (1.25 mm), number of teeth (16), face width (32 mm), and operating pressure (8 bar). Torque calculations were performed to verify loading feasibility and establish analysis conditions.

Step 2: Analytical Design Calculation

Gear design equations were applied to calculate pitch circle diameter, tangential force, and bending stress using standard mechanical design relations. These calculations established baseline loading values for simulation.

Step 3: CAD Model Development

A three-dimensional spur pinion model was created using Solid Edge ST7 software. The geometry was developed according to calculated dimensions while maintaining manufacturing feasibility.

Step 4: Finite Element Model Preparation

The CAD geometry was imported into ANSYS Workbench for numerical evaluation. A tetrahedral meshing strategy was implemented with refined mesh density near the tooth root to capture stress concentration accurately.

Step 5: Loading and Boundary Conditions

Worst-case loading conditions were simulated by applying force at the tooth tip region. Appropriate constraints were introduced to represent realistic operating conditions and ensure analysis stability.

Step 6: Material Comparison and Validation

Two material configurations—steel and aluminium alloy—were evaluated independently. Parameters including equivalent stress, total deformation, and component weight were compared to determine performance suitability.

Step 7: Result Evaluation

Simulation outputs were analyzed and validated to identify the most efficient material option considering strength, weight reduction, corrosion resistance, and practical implementation in pneumatic actuator applications.

Design And Input Data

- Module = 1.25 mm
- Number of teeth = 16
- Face width = 32 mm
- Pressure = 8 bar
- Steel torque capacity ≈ 46.5 Nm
- Actual torque ≈ 35.7 Nm Equation 1: Pitch circle diameter $d = m \times z = 1.25 \times 16 = 20$ mm

Equation 2: Tangential force relation $F_t = 2T / d$

Equation 3: Lewis bending relation $\sigma = F_t / (b \times m \times y)$

CAD Model Development

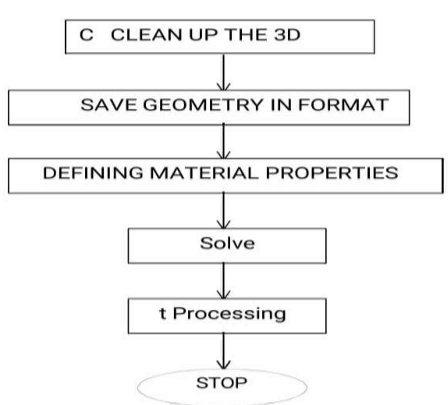


Fig. 1. *Spur pinion development stage*

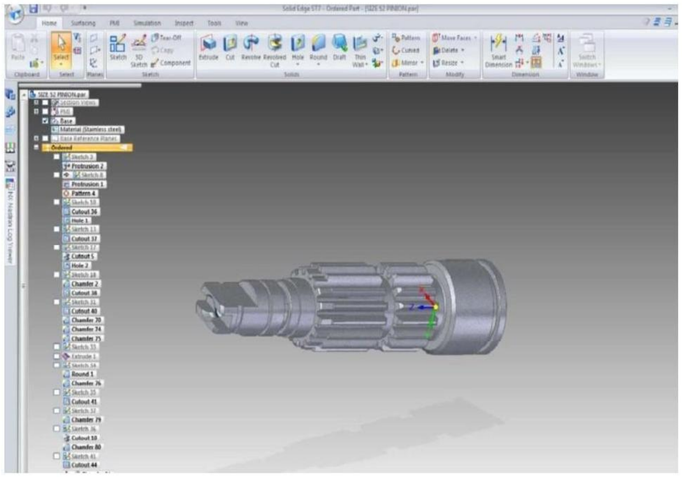


Fig. 2. Spur pinion development stage

Finite Element Analysis

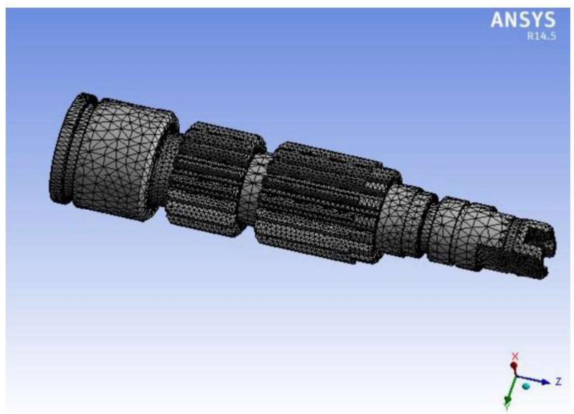


Fig. 3. Spur pinion development stage

FEA Meshing and Boundary Conditions

Finite element model used approximately 124000 nodes and 75000 elements. Fine mesh was concentrated near tooth root.

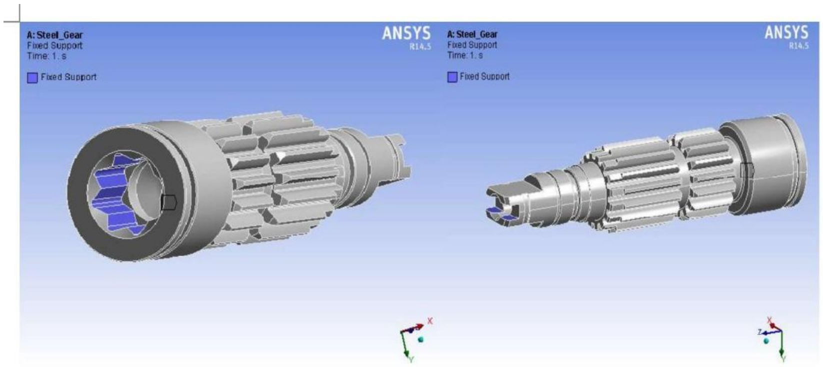


Fig 4. Spur Gear Model with Fixed Support Condition for Finite Element Analysis

Properties of Outline Row 3: Aluminum Alloy

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	2770	kg m^-3		
3	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
7	Derive from	Young's ...			
8	Young's Modulus	7.1E+10	Pa		
9	Poisson's Ratio	0.33			
10	Bulk Modulus	6.9608E+10	Pa		
11	Shear Modulus	2.6692E+10	Pa		
12	Alternating Stress R-Ratio	Tabular			
16	Tensile Yield Strength	280	MPa		
17	Compressive Yield Strength	280	MPa		
18	Tensile Ultimate Strength	310	MPa		
19	Compressive Ultimate Strength	0	Pa		

***Fig. 5.** Meshing and support application*

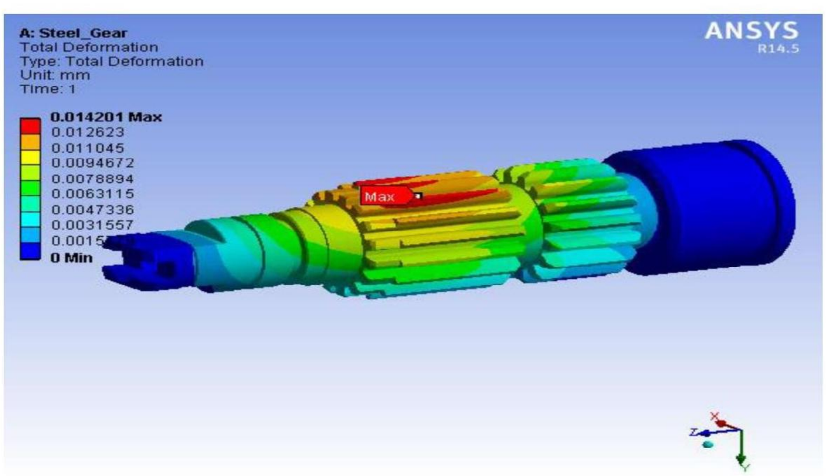
Results And Findings

Properties of Outline Row 3: Structural Steel

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	7850	kg m^-3		
3	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
7	Derive from	Young's ...			
8	Young's Modulus	2E+11	Pa		
9	Poisson's Ratio	0.3			
10	Bulk Modulus	1.6667E+11	Pa		
11	Shear Modulus	7.6923E+10	Pa		
12	Alternating Stress Mean Stress	Tabular			
16	Strain-Life Parameters				
24	Tensile Yield Strength	250	MPa		
25	Compressive Yield Strength	250	MPa		
26	Tensile Ultimate Strength	460	MPa		
27	Compressive Ultimate Strength	0	MPa		

***Fig. 6.** Stress/deformation output*

- Steel Deflection:



- Aluminum Deflection

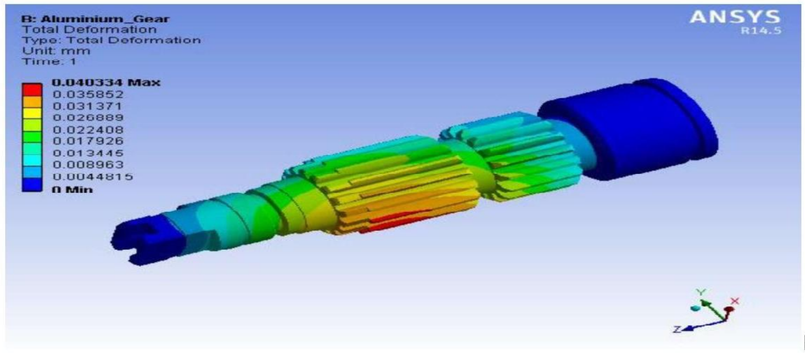


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Fig. 7. Stress/deformation output

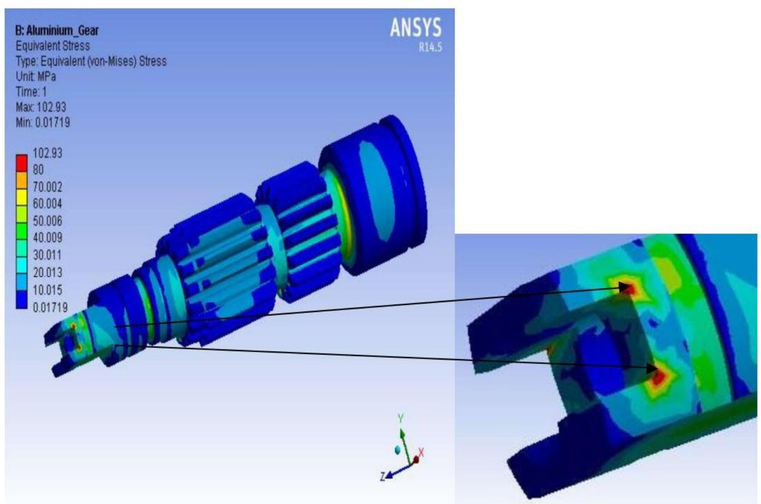
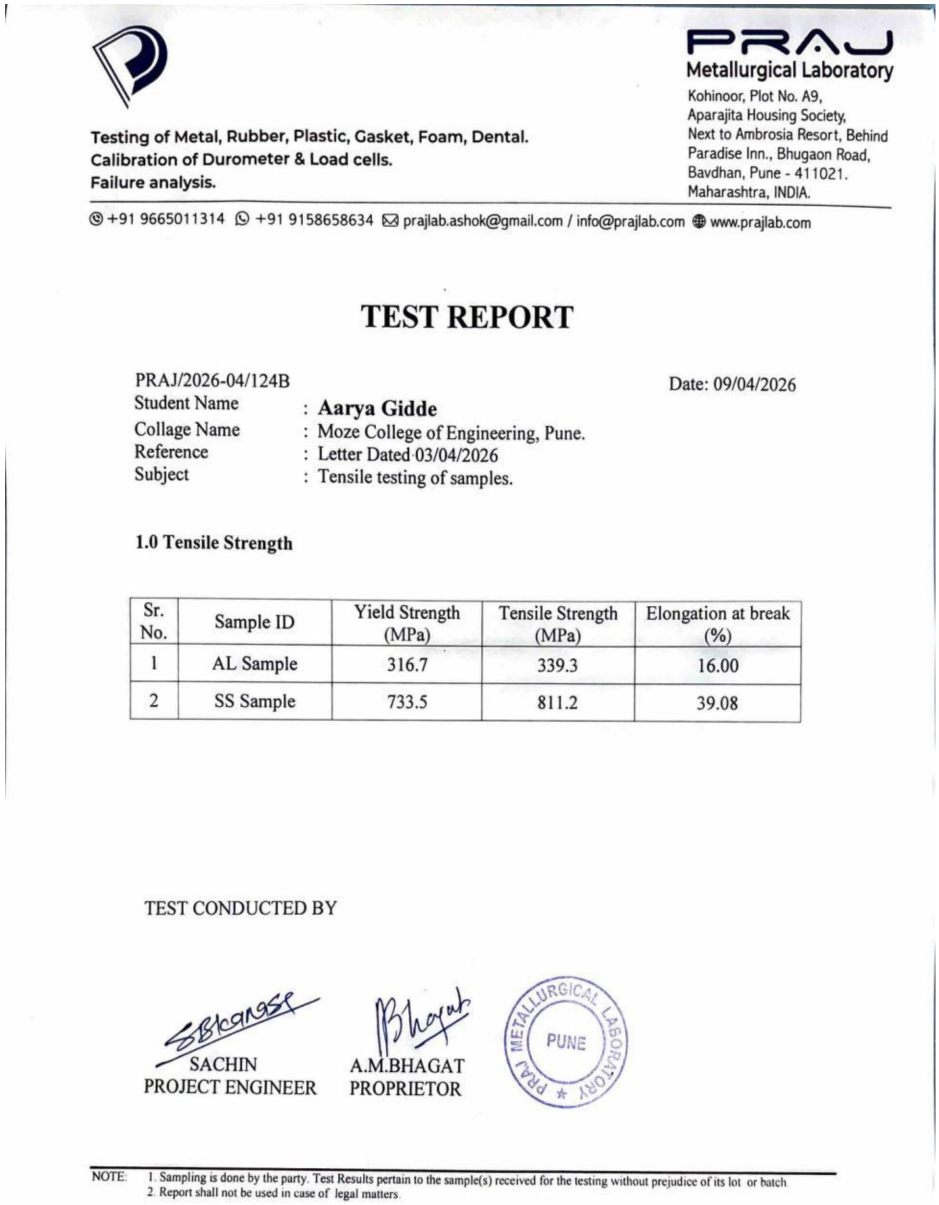


Fig.8. Stress/deformation output

Result Comparison Table

Parameter	Steel	Aluminium	Preferred	Comment
Max Deflection	0.014 mm	0.04 mm	Steel	Steel stiffer
Max Stress	103 MPa	102 Mpa	Equivalent	Stress almost same
Weight	181.3 g	63.8 g	Aluminium	Major reduction
Corrosion Resistance	Moderate	Better	Aluminium	Longer service life

Material Validation



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TEST REPORT

PRAJ/2026-04/124B Date: 09/04/2026

Student Name : **Aarya Gidde**
Collage Name : Moze College of Engineering, Pune.
Reference : Letter Dated 03/04/2026
Subject : Tensile testing of samples.

1.0 Tensile Strength

Sr. No.	Sample ID	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation at break (%)
1	AL Sample	316.7	339.3	16.00
2	SS Sample	733.5	811.2	39.08

TEST CONDUCTED BY

SACHIN
PROJECT ENGINEER

A.M.BHAGAT
PROPRIETOR

PRAJ METALLURGICAL LABORATORY PUNE

NOTE: 1. Sampling is done by the party. Test Results pertain to the sample(s) received for the testing without prejudice of its lot or batch
2. Report shall not be used in case of legal matters.

Fig. 8. *Tensile laboratory report*

Discussion

The finite element analysis results indicate that steel demonstrates superior stiffness characteristics compared with aluminium alloy under identical loading conditions. The maximum deformation observed in aluminium was slightly higher; however, the increase remained minimal relative to the overall tooth geometry and did not adversely affect operational performance. The equivalent stress values obtained for both materials were nearly identical and remained safely below the measured yield strength limits, confirming structural reliability under worst loading conditions. Although steel provides greater rigidity and lower deflection, aluminium offers several practical advantages for pneumatic actuator applications. The significant reduction in component weight contributes to lower rotational inertia, resulting in improved dynamic response and energy efficiency. Additionally, aluminium provides easier machinability and enhanced corrosion resistance, which may improve manufacturing flexibility and long-term service performance. Therefore, despite a moderate increase in deformation, aluminium demonstrates acceptable mechanical behavior while delivering substantial application-level benefits.

Conclusion

This study evaluated the bending strength performance of a spur pinion under worst loading conditions through material substitution between steel and aluminium alloy using analytical calculations and finite element analysis. The comparative results showed that aluminium achieved nearly equivalent stress performance while providing a substantial reduction in component weight. Although steel remained mechanically stronger and exhibited lower deformation due to its higher stiffness, aluminium maintained deformation within acceptable operating limits and satisfied structural requirements. Additional benefits including reduced inertia, improved corrosion resistance, and easier manufacturing support the suitability of aluminium for lightweight mechanical applications. Based on the overall performance evaluation, aluminium is recommended as a practical alternative for pneumatic actuator spur gear applications where weight reduction and operational efficiency are prioritized without compromising structural safety.

References

1. Lewis's gear bending theory references.
2. Finite element analysis of spur gear tooth.
3. Material tensile report used for validation.
4. Project input data from spur gear presentation.

Appendix

Additional ANSYS screenshots, CAD snapshots and raw tensile observations may be attached during submission if required by department.