

Analysis of Gear Strength in Machine Construction

Yuki Alvandi Pratama⁽¹⁾, Beny Gusman⁽¹⁾, Muhamad Adriansyah⁽¹⁾, Amiko⁽¹⁾, Fardin Hasibuan⁽¹⁾, Eddy Efiano⁽²⁾

Yukialvandi096@gmail.com⁽¹⁾, beny.gusmal.ali@gmail.com⁽¹⁾, muhamadadriansyah1303@gmail.com⁽¹⁾,
amikosaputra1@gmail.com⁽¹⁾, fardin.hasibuan123456@gmail.com⁽¹⁾, eddy_elfiano@eng.uir.ac.id⁽¹⁾

¹⁾ Program Studi Teknik Mesin, Universitas Riau Kepulauan, Indonesia

²⁾ Departement of Mechanical Engineering, Universitas Riau Kepulauan, Indonesia

*Corresponding author: amikosaputra1@gmail.com

Paper History

Received: February 2nd 2025

Received in revised form: April 20th 2026

Accepted: April 21th 2026

ABSTRACT

Gears are essential components in mechanical transmission systems, responsible for transferring power between shafts in various types of machinery. The strength of gears plays a critical role in the efficiency and reliability of these systems, as improper load handling can lead to material failure or gear damage. This study aims to analyze the strength of gears by considering several factors such as material properties, geometry, and operational conditions. The materials tested in this research include carbon steel SAE 1045, alloy steel SAE 4140, and stainless steel (SS 304), all of which are commonly used in gear applications. The gear geometry analyzed includes variations in module (2 mm and 3 mm), the number of teeth (20 teeth), and the pressure angle (20 degrees). The research methodology includes Finite Element Analysis (FEA) to simulate stress distribution on gears under both dynamic and static loading conditions, along with experimental testing to validate the simulation results. The results show that SAE 4140 alloy steel exhibits superior tensile strength and wear resistance compared to SAE 1045 carbon steel, though at a higher cost. Stainless steel (SS 304) offers excellent corrosion resistance but lower tensile strength, making it less suitable for high-load applications. Additionally, increasing the gear size (3 mm module) reduces stress on the teeth but increases the overall size and weight of the gear. This study provides important insights into material selection and gear design, helping to improve the strength and durability of mechanical transmission systems.

KEY WORDS: *Gear strength, material properties, carbon steel, tensile strength, machine transmission*

1.0 INTRODUCTION

Gears are essential components in mechanical transmission systems, responsible for transferring power between shafts in

various types of machinery [1]. The strength of gears plays a critical role in the efficiency and reliability of these systems, as improper load handling can lead to material failure or gear damage. This study aims to analyze the strength of gears by considering several factors such as material properties, geometry, and operational conditions. The materials tested in this research include carbon steel SAE 1045, alloy steel SAE 4140, and stainless steel (SS 304), all of which are commonly used in gear applications [2]. The gear geometry analyzed includes variations in module (2 mm and 3 mm), the number of teeth (20 teeth), and the pressure angle (20 degrees). The research methodology includes Finite Element Analysis (FEA) to simulate stress distribution on gears under both dynamic and static loading conditions, along with experimental testing to validate the simulation results. The results show that SAE 4140 alloy steel exhibits superior tensile strength and wear resistance compared to SAE 1045 carbon steel, though at a higher cost. Stainless steel (SS 304) offers excellent corrosion resistance but lower tensile strength, making it less suitable for high-load applications. Additionally, increasing the gear size (3 mm module) reduces stress on the teeth but increases the overall size and weight of the gear. This study provides important insights into material selection and gear design, helping to improve the strength and durability of mechanical transmission systems.

Gears are fundamental mechanical elements used in a wide range of applications to transmit power and motion between shafts [3]. These components are integral to the functioning of machines across various industries, from automotive systems to industrial machinery, aerospace, and robotics. The primary function of gears is to alter the direction and magnitude of rotational movement, enabling machines to perform specific tasks efficiently. The performance and longevity of gear systems are highly dependent on the strength of the gears themselves, which must withstand substantial mechanical stresses during operation [4].

The design and analysis of gear strength are critical aspects of mechanical engineering, as gears are often subjected to complex loading conditions that can result in failure if not properly accounted for. Gear failures can lead to significant operational downtime, increased maintenance costs, and even safety hazards. Therefore, understanding the factors that influence gear strength such as material properties, geometry, and operating conditions is essential to ensuring the reliability and durability of gear systems.

1.1 Material Selection for Gears

The selection of material for gears plays a crucial role in their performance and longevity. Various materials, such as carbon steel, alloy steel, and stainless steel, are commonly used in gear manufacturing. Each material has distinct properties that make it suitable for specific applications. For example, carbon steel is often preferred for its cost-effectiveness and reasonable strength, while alloy steels, such as SAE 4140, offer superior tensile strength, wear resistance, and fatigue resistance [8]. Stainless steel, known for its excellent corrosion resistance, is typically chosen for applications in harsh environments but may be less suited for high-load applications due to its relatively lower strength compared to alloy steels. Understanding the material properties is, therefore, critical for optimizing gear performance.

1.2 Gear Geometry and Load Distribution

In addition to material selection, gear geometry significantly impacts the stress distribution and load-bearing capacity of the gear teeth. The key geometric parameters that influence gear strength include the module, the number of teeth, the pressure angle, and the pitch diameter. The module, which defines the size of the gear teeth, affects the load distribution and the potential for tooth contact stress. A higher module can reduce the stress on each tooth but may result in larger gear sizes, which could increase the weight and size of the machinery. The pressure angle, typically ranging from 14.5° to 20° , also influences the load-carrying capacity and tooth contact pattern. Therefore, a proper balance must be found between these geometric parameters to ensure the gear teeth can withstand operational stresses without failure.

1.3 Loading Conditions and Operational Factors

Gears are subjected to a variety of loading conditions, including static, dynamic, and cyclic loads. Dynamic loading, often caused by changes in speed and direction of rotation, generates fluctuating forces on the gear teeth, which can lead to fatigue and failure over time. Static loads, such as those caused by continuous torque transmission, can also cause permanent deformation or fracture if the material strength is insufficient. Moreover, operational factors such as speed, lubrication, and temperature play a significant role in gear performance. Inadequate lubrication can lead to increased wear and higher operating temperatures, while excessive speeds can cause heat build-up and material degradation. Understanding these loading conditions is vital for predicting gear performance and designing gears that can withstand the stresses imposed during operation.

1.4 Finite Element Analysis (FEA) in Gear Design

Advancements in computational tools have made it possible to simulate the behaviour of gears under various loading conditions using Finite Element Analysis (FEA). FEA allows engineers to model the stress distribution within a gear and identify critical areas that are prone to failure. By simulating different operating scenarios, such as varying loads, speeds, and materials, FEA helps to optimize gear designs for maximum strength, durability, and efficiency. This computational approach, combined with experimental testing, provides a comprehensive understanding of gear behaviour and supports the development of more reliable and efficient gear systems.

1.5 Objective of the Study

The objective of this study is to conduct a detailed analysis of gear strength by evaluating the effects of material selection, gear geometry, and operational conditions on gear performance. Specifically, the study investigates the performance of gears made from carbon steel (SAE 1045), alloy steel (SAE 4140), and stainless steel (SS 304). The analysis includes the effect of different gear geometries, such as variations in module and pressure angle, on the stress distribution and potential for failure. Additionally, the study employs Finite Element Analysis (FEA) to simulate the behaviour of gears under dynamic and static loading conditions, with experimental validation to ensure the accuracy of the simulation results.

2.0 METHODOLOGY

The analysis of gear strength involves a comprehensive approach that includes material selection, geometric design evaluation, and simulation of operational conditions. This study combines Finite Element Analysis (FEA) with experimental testing to evaluate the performance and durability of gears made from different materials under varying loading conditions. The methodology is divided into the following steps:

2.1 Material Selection

Material selection plays a crucial role in the performance of gears. Three materials were selected for this study: carbon steel SAE 1045, alloy steel SAE 4140, and stainless steel (SS 304). These materials were chosen based on their common usage in gear manufacturing, each offering a different balance between strength, wear resistance, and cost.

2.2 Gear Geometry Design

The geometry of the gears was designed using standard gear parameters, which include the module, number of teeth, and pressure angle. For this study, gears with the following parameters were considered:

1. Module (m): Two different modules were selected: 2 mm and 3 mm. The module is a key factor in gear design that affects the tooth size and load distribution. A larger module distributes the load more evenly, reducing stress on the teeth but increasing the overall size of the gear.
2. Number of Teeth (z): Gears with 20 teeth were chosen for the analysis to ensure a balance between load-bearing capacity and operational efficiency.
3. Pressure Angle (α): A pressure angle of 20 degrees was selected, which is a common value for gears used in high-load applications. The pressure angle affects the tooth contact and stress distribution.

2.3 Finite Element Analysis (FEA) Simulation

Finite Element Analysis (FEA) was used to simulate the stress distribution and performance of the gears under different loading conditions. The FEA process involves several steps:

1. Modeling the Gears: The gear models were created using CAD software, with precise geometric details such as the number of teeth, pressure angle, and module. The models were then imported into FEA software (e.g., ANSYS or ABAQUS) for stress analysis.

2. Meshing: A fine mesh was applied to the gear model to ensure accurate results, particularly in areas where stress concentrations are expected (e.g., tooth roots and contact points).
3. Material Properties: The material properties for each gear material was assigned based on the mechanical properties provided by the material manufacturer and literature. These properties include Young's modulus, Poisson's ratio, yield strength, and tensile strength.
4. Loading Conditions: The gears were subjected to both static and dynamic loading conditions. Static loads were applied to simulate steady-state torque transmission, while dynamic loads were applied to replicate the effects of speed variations and shock loading during operation.
5. Boundary Conditions: The boundary conditions included fixing one of the gear shafts and applying rotational motion to the other shaft, simulating real-life operational conditions.
6. Post-Processing: The FEA software was used to analyze the results, including stress distribution, maximum stress values, and potential areas for failure. The results were used to assess the strength and durability of the gears under various loading scenarios.

2.4 Experimental Testing

In addition to the FEA simulations, experimental testing was conducted to validate the results. The gears were fabricated from the selected materials and subjected to mechanical testing under controlled conditions. The experimental procedure included:

1. Testing Setup: A gear testing rig was used to simulate the operational conditions of the gears. The gears were mounted on shafts, and torque was applied to measure the load-bearing capacity and failure point.
2. Load Application: Both static and dynamic loads were applied using hydraulic systems to simulate real-life operating conditions. Torque was gradually increased to identify the maximum load the gears could withstand before failure.
3. Measurement: Strain gauges and displacement sensors were used to monitor the deformation of the gears during testing. The experimental results were compared to the FEA simulation data to validate the accuracy of the models.

2.5 Analysis of Results

The results from both FEA simulations and experimental testing were analyzed to determine the following:

1. Stress Distribution: The stress distribution across the gear teeth was analyzed to identify areas of high stress that could lead to fatigue or failure. The effect of different materials and gear geometries on stress levels was examined.
2. Failure Modes: The potential failure modes, including tooth fracture, surface wear, and material fatigue, were evaluated. The study also focused on understanding how material properties and geometry influence the likelihood of each failure mode.
3. Comparative Performance: A comparison was made between the three materials—SAE 1045, SAE 4140, and SS 304—in terms of their ability to handle load, wear resistance, and durability. The impact of different gear

geometries (module and pressure angle) on the overall strength and performance of the gears was also evaluated.

2.6 Validation of Results

To ensure the reliability of the simulation results, a validation process was carried out. The experimental results were compared with the FEA predictions, and any discrepancies were addressed by refining the models and repeating the simulations. This helped in confirming the accuracy of the stress predictions and failure modes identified in the simulations.

The analysis focused on the performance and strength of gears made from carbon steel (SAE 1045), alloy steel (SAE 4140), and stainless steel (SS 304). The results are based on the Finite Element Analysis (FEA) simulations and experimental testing, which examined factors such as stress distribution, wear resistance, load-bearing capacity, and fatigue life.

3.0 RESULT

The analysis focused on the performance and strength of gears made from carbon steel (SAE 1045), alloy steel (SAE 4140), and stainless steel (SS 304). The results are based on the Finite Element Analysis (FEA) simulations and experimental testing, which examined factors such as stress distribution, wear resistance, load-bearing capacity, and fatigue life

Table 1: Material properties and gear performance

Material	Yield Strength (MPa)	Maximum Stress (MPa)	Maximum Torque (N·m)	Fatigue Life (Cycles)	Wear Resistance (Test Duration)
SAE 1045	250	180	2,000	500,000	Moderate (600 hours)
SAE 4140	600	140	3,500	1,000,000	High (1,000 hours)
SS 304	520	220	1,500	500,000	High wear (400 hours)

3.1. FEA Simulation Results

3.1.1 Stress Distribution.

The stress distribution in the gear is presented in Table 2.

Table 2: Effect of gear geometry on stress distribution

Gear Geometry	Module Size (mm)	Pressure Angle (°)	Maximum Stress (MPa)	Improvement in Stress (%)
SAE 1045	2	14.5	180	N/A
SAE 1045	3	20	155	13.9%
SAE 4140	2	14.5	140	N/A
SAE 4140	3	20	120	14.3%
SS 304	2	14.5	220	N/A
SS 304	3	20	190	13.6%

SAE 1045 (Carbon Steel), The FEA simulation results showed that gears made from SAE 1045 experienced moderate stress under static loading, with the maximum stress recorded at 180 MPa at the tooth root. This is close to the yield strength of the material (250 MPa), indicating that the material is at risk of failure under high loads. Under dynamic loading conditions, the stress increased, and areas of concentrated stress were observed at the tooth contact points.

SAE 4140 (Alloy Steel): Gears made from SAE 4140 exhibited lower stress concentrations, with a maximum stress of 140 MPa under static loading, significantly below the yield strength (600 MPa) of SAE 4140. This material showed improved performance, especially in dynamic loading scenarios, where it withstood higher fluctuations in stress without reaching critical levels.

SS 304 (Stainless Steel): The maximum stress observed in SS 304 gears was 220 MPa, which is higher than both SAE 1045 and SAE 4140. This indicates that SS 304 gears are more susceptible to failure under high loads, as their yield strength (520 MPa) is lower compared to alloy steel.

3.1.2 Wear Resistance and Fatigue Analysis

Wear resistance and test duration are presented in Table 3.

Table 3: Wear resistance test results

Material	Wear Rate (mm ³ /h)	Test Duration (hours)	Observations
SAE 1045	0.02	600	Moderate wear at tooth contact points
SAE 4140	0.005	1,000	Minimal wear, consistent performance
SS 304	0.05	400	High wear rate, significant damage

SAE 1045 Under cyclic loading, SAE 1045 showed moderate wear, with significant surface damage occurring at the tooth contact points after 500,000 cycles. Fatigue cracking was observed at the root of the teeth, which aligned with the predicted areas of stress concentration in the FEA simulations.

SAE 4140: The FEA results indicated minimal wear and high fatigue resistance for SAE 4140, which sustained more than 1,000,000 cycles without showing signs of cracking or material degradation. This material's superior tensile strength and fatigue resistance made it highly durable under both static and dynamic conditions.

SS 304: SS 304 demonstrated the highest rate of wear among the three materials. After only 300,000 cycles, wear was evident at the tooth contact points, and fatigue cracks began to form. These findings are consistent with the material's lower tensile strength and resistance to fatigue.

3.1.3 Effect of Gear Geometry (Module and Pressure Angle)

The FEA analysis also revealed that increasing the module from 2 mm to 3 mm resulted in a reduction of the maximum stress across all materials. For instance, the stress in SAE 4140 dropped by 15%, indicating that larger teeth help distribute the load more evenly, improving the gear's strength. Pressure Angle (20°): The FEA results confirmed that a 20° pressure angle provided better load distribution compared to smaller pressure angles (14.5° or 15°). The higher-pressure angle led to a larger contact area between the teeth, reducing the stress on individual teeth and increasing the overall load capacity of the gear.

3.2. Experimental Testing Results

3.2.1 Load-Carrying Capacity

SAE 1045: The experimental tests confirmed the FEA results, with gears made from SAE 1045 experiencing failure at a maximum torque of 2,000 N·m. The failure occurred due to tooth fracture at the root, consistent with the stress concentrations predicted by FEA.

SAE 4140: Gears made from SAE 4140 showed a much higher load-bearing capacity, with the maximum torque reaching

3,500 N·m before failure. The failure mode was primarily fatigue cracking at the tooth surface, which correlated with the FEA predictions of fatigue initiation points.

SS 304: The SS 304 gears failed at 1,500 N·m, and the failure mode was a combination of surface wear and fatigue cracking, as predicted by the FEA results.

3.2.2. Wear Resistance

The experimental wear tests showed that SAE 4140 exhibited superior wear resistance. After 1,000 hours of operation, the wear was minimal, and the tooth profile remained largely intact. In contrast, SAE 1045 experienced noticeable wear after 600 hours, and SS 304 showed rapid wear, particularly in high-load regions, after only 400 hours of operation.

3.2.3. Fatigue Testing

SAE 4140 showed exceptional fatigue resistance, with no visible cracks even after 1,500,000 cycles under variable loading conditions. This aligns with the FEA results, where no fatigue cracks were observed in SAE 4140 under cyclic loading. SAE 1045 and SS 304 both showed fatigue cracks after 500,000 cycles, which is consistent with their lower fatigue resistance compared to SAE 4140. The test results are presented in Table 4.

Table 4: Fatigue Life Test Results

Material	Fatigue Life (Cycles)	Test Conditions	Failure Mode
SAE 1045	500,000	Variable loading	Tooth root fatigue cracking
SAE 4140	1,000,000	Variable loading	No cracks, excellent fatigue resistance
SS 304	500,000	Variable loading	Fatigue cracks at tooth root

3.3. Comparative Performance of Materials

1. **Strength:** SAE 4140 demonstrated the highest tensile strength and resistance to fatigue, followed by SAE 1045 and SS 304. The higher tensile strength of SAE 4140 allowed it to withstand much higher loads before failure.
2. **Wear Resistance,** SAE 4140 also showed superior wear resistance, with negligible material degradation during wear tests, while SS 304 exhibited the highest wear rate, particularly under high torque conditions. SAE 1045 exhibited moderate wear resistance.
3. **Corrosion Resistance,** SS 304 excelled in corrosion resistance, making it suitable for use in environments where corrosion is a primary concern. However, under high-load applications, its lower strength made it less suitable than SAE 4140 and SAE 1045.

3.4. Impact of Gear Geometry

Module and Pressure Angle Effects: Increasing the module from 2 mm to 3 mm significantly reduced stress concentrations and improved load distribution. A 20° pressure angle further enhanced the gear's strength by increasing the contact area between the teeth and reducing localized stress. The combination of a larger module and higher-pressure angle showed a clear improvement in gear performance, making the gears more durable and capable of handling higher loads without failure.

4.0 DISCUSSION

The results of this study provide valuable insights into the performance of gears made from different materials (SAE 1045, SAE 4140, and SS 304) under varying loading conditions. The

findings reveal important conclusions regarding material selection, gear geometry, and the impact of operational factors such as stress distribution, wear resistance, and fatigue life. The following key observations were made:

1. Impact of Material Selection

The choice of material is critical in determining the overall performance of gears, particularly in high-load applications. SAE 1045 (Carbon Steel): Although SAE 1045 is widely used for general-purpose gears, the results from this study suggest that it is not the best choice for high-performance gear applications. While it can handle moderate loads, its relatively low tensile strength and limited fatigue resistance made it prone to failure under dynamic loading conditions. The FEA simulations indicated higher stress concentrations at the tooth root, which were confirmed by experimental testing, where the gears failed due to tooth fracture at a maximum torque of 2,000 N·m. Furthermore, SAE 1045 exhibited moderate wear, especially after cyclic loading, which supports the observation that it is better suited for lower-load applications. SAE 4140 (Alloy Steel): SAE 4140 demonstrated superior performance in all key aspects, including load-bearing capacity, wear resistance, and fatigue life. The FEA simulations showed a significantly lower stress concentration and better load distribution compared to SAE 1045, which was confirmed by the experimental testing. The gears made from SAE 4140 withstood a maximum torque of 3,500 N·m before failure, showcasing its ability to handle heavy loads. Additionally, the alloy steel exhibited minimal wear after prolonged testing and showed excellent resistance to fatigue, remaining free of cracks even after 1,000,000 cycles. This material's high tensile strength and fatigue resistance make it the optimal choice for high-performance gear applications, such as those found in automotive, aerospace, and heavy machinery. SS 304 (Stainless Steel): SS 304 performed well in terms of corrosion resistance, but its lower tensile strength and fatigue resistance made it less suitable for high-load gear applications. While the material showed excellent resistance to corrosion and would be ideal for use in environments exposed to harsh conditions (e.g., marine or chemical applications), it was unable to withstand high torque loads. The maximum torque that SS 304 gears could bear was 1,500 N·m, and they exhibited rapid wear under dynamic loading conditions. The material's lower fatigue resistance was evident, with fatigue cracks initiating after 500,000 cycles. These findings suggest that SS 304 is more suited for non-load-bearing applications where corrosion resistance is a primary concern, rather than high-load gear systems.

2. Effect of Gear Geometry on Performance

Gear geometry plays a critical role in the performance and durability of gears. The results from both the FEA simulations and experimental tests confirmed that certain geometric modifications could significantly improve the performance of gears. Module Size: Increasing the module from 2 mm to 3 mm resulted in a noticeable reduction in the maximum stress experienced by the gears. For example, the maximum stress in SAE 4140 dropped by 15% when the module was increased. This is because a larger module spreads the load over a larger tooth area,

reducing the localized stress and improving the gear's load-bearing capacity. requirements. Pressure Angle (20°): The use of a 20° pressure angle was beneficial in improving the load-carrying capacity and overall performance of the gears. The larger pressure angle increased the tooth contact area, leading to better load distribution and reduced stress concentrations. This change resulted in improved efficiency, as gears with a larger pressure angle can carry higher loads with less likelihood of failure due to localized stress. The findings suggest that a pressure angle of 20° is optimal for most high-load gear applications, providing a good balance between strength and efficiency.

3. Wear Resistance and Fatigue Behavior

The wear and fatigue tests revealed the significant impact of material choice on the long-term performance of gears under cyclic loading conditions. SAE 4140's Performance: SAE 4140 stood out as the best material in terms of wear resistance and fatigue life. The alloy steel showed minimal wear even after extended testing, with no visible signs of cracking after 1,000,000 cycles. This is in line with the material's excellent fatigue properties and high resistance to surface wear. The relatively low stress concentrations observed in the FEA simulations, coupled with the material's ability to withstand repeated loading, contribute to its extended lifespan in demanding applications. SAE 1045's Wear and Fatigue Behavior: In comparison, SAE 1045 showed moderate wear and was more prone to fatigue cracking, especially under dynamic loading. The experimental testing revealed noticeable wear after 600 hours and fatigue cracks after 500,000 cycles. These results highlight that while SAE 1045 may be sufficient for low-load applications, it is not the most durable choice when higher performance is required. SS 304's Wear Resistance: SS 304 demonstrated the highest wear rate of the three materials, with significant wear observed after only 400 hours of testing. Additionally, fatigue cracks were evident after just 500,000 cycles. The material's poor performance in wear resistance and fatigue suggests that while SS 304 is suitable for corrosion-resistant applications, it is not recommended for high-load or high-wear environments.

4. Corrosion Resistance vs. Mechanical Properties

One of the main advantages of SS 304 is its excellent corrosion resistance, which was evident in the experimental testing. However, the trade-off between corrosion resistance and mechanical properties (strength and fatigue resistance) becomes apparent when the material is subjected to high mechanical stresses. In environments where corrosion is not a major concern and higher mechanical performance is needed, materials like SAE 4140 should be prioritized

5.0 CONCLUSION

The discussion highlights the importance of material selection and gear geometry optimization in enhancing gear performance. SAE 4140 alloy steel emerged as the superior material for high-load, high-performance applications, offering excellent wear resistance, high strength, and resistance to fatigue. SAE 1045 is more suitable for moderate-load applications but lacks the

durability needed for demanding gear systems. SS 304, while ideal for corrosion-resistant applications, should be avoided in high-load gear systems due to its lower strength and fatigue resistance. The results also emphasize that modifying gear geometry, such as increasing the module size and adopting a larger pressure angle, significantly improves the gear's performance and lifespan

REFERENCE

- [1] ASTM International. (2021). Standard Guide for Gear Lubrication. ASTM D2710-19. ASTM International
- [2] Bhaumik, S., & Roy, P. K. (2021). "Development of Wear Resistance Gears for Industrial Applications." *Journal of Materials Engineering and Performance*,
- [3] Harris, T. A., & Kotzalas, M. N. (2006). *Advanced Gear Manufacturing and Finishing*. CRC Press.
- [4] Juvinall, R. C., & Marshek, K. M. (2012). *Fundamentals of Machine Component Design* (5th ed.). Wiley.
- [5] Klaus, H., & Wulf, C. (2009). "Finite Element Simulation of Gear Teeth: Contact and Stress Analysis." *Computational Mechanics*,
- [6] Munjal, M. L., & Kacker, R. N. (2006). *Gear Geometry and Applied Theory* (2nd ed.). Wiley.
- [7] Reddy, J. N. (2005). *An Introduction to the Finite Element Method* (3rd ed.). McGraw-Hill.
- [8] Sahoo, B. K., & Saha, A. K. (2014). "Effect of Gear Material Properties on Fatigue Life and Wear Resistance." *International Journal of Materials Science and Engineering*, 2(2), 129-138.
- [9] Shigley, J. E. (2003). *Mechanical Engineering Design* (7th ed.). McGraw-Hill.
- [10] Zhang, L., & Zhang, X. (2017). "Experimental Investigation on Gear Fatigue Strength and Wear Behavior of Hardened Gears." *Tribology International*4, pp. 87–94, Oct. 2024, doi: 10.55606/jtmei.v3i4.4391.