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"FINITE ELEMENT BASED STRUCTURAL AND THERMAL PERFORMANCE EVALUATION OF INVOLUTE SPUR GEARS USING DIFFERENT ENGINEERING MATERIALS"

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ABSTRACT

Involute spur gears are widely used in mechanical power transmission systems due to their high efficiency, reliability, and simplicity of design. During operation, spur gear teeth are subjected to significant contact stresses, deformation, and thermal effects, which govern their fatigue life and overall performance. The present work focuses on a comparative finite element analysis (FEA) of involute spur gears to evaluate their structural and thermal behavior under identical loading and boundary conditions. Three engineering materials Structural Steel, Aluminium Alloy, and Titanium Alloy—were considered to assess their influence on von Mises stress, total deformation, temperature distribution, and total heat flux. The numerical simulations reveal that all three materials experience comparable von Mises stress levels, indicating that stress concentration is primarily governed by gear geometry and applied load. Structural Steel exhibits the lowest deformation due to its higher stiffness, whereas Aluminium Alloy shows relatively higher deformation but remains within acceptable limits. Thermal analysis demonstrates negligible variation in peak temperature among the materials; however, Aluminium Alloy exhibits the highest heat flux, indicating superior heat dissipation capability. Considering the combined effects of stress safety, deformation limits, thermal performance, and weight reduction, Aluminium Alloy emerges as the most suitable material for involute spur gear applications. The results highlight the effectiveness of finite element analysis as a reliable tool for material selection and performance optimization of spur gears.

Key Words: *Involute spur gear; Finite element analysis; Von Mises stress; Deformation; Thermal analysis; Heat flux; Material selection.*

I. INTRODUCTION

Gears are utilized for an extensive variety of mechanical applications. They have fluctuated application beginning from material weaving machines aeronautics businesses. They are the most widely recognized methods for transmitting power. They change the rate of turn of hardware shaft and furthermore the pivot of revolution. For rapid apparatus, for example, a vehicle transmission, they are the ideal medium for low vitality misfortune and high exactness. Their capacity is to change over info given by prime mover into a yield with bring down speed and comparing higher torque. Toothed gears are utilized to transmit the power with high speed proportion. Amid this stage, they experience high stress at the purpose of contact.

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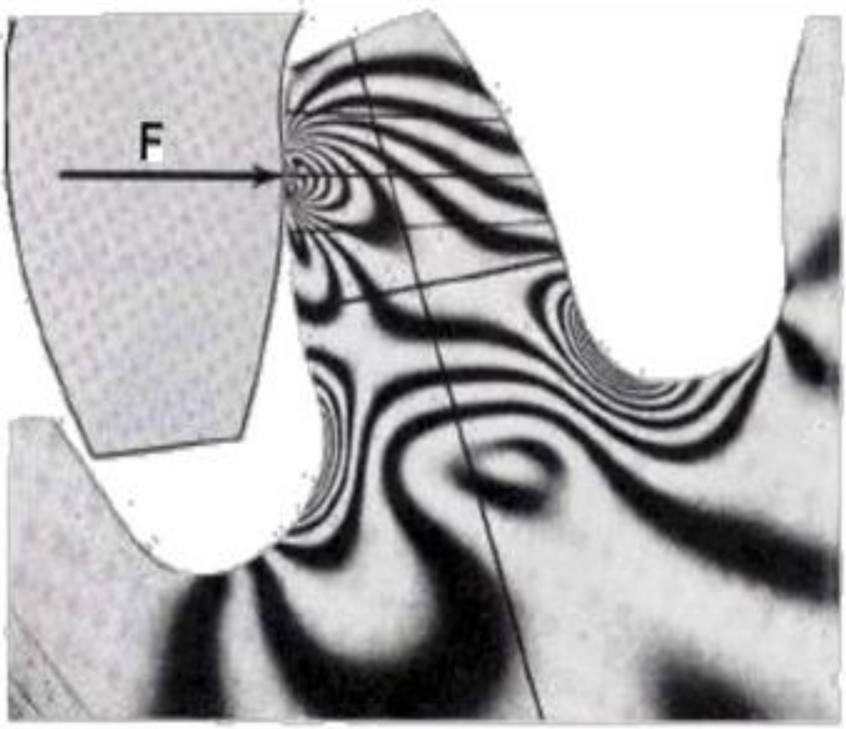

Fig 1. Involute Spur gear

It is a marvel in which little particles are expelled from the surface of the tooth because of the high contact stresses that are available between mating teeth. Setting is really the fatigue disappointment of the tooth surface. Hardness is the essential property of the rigging tooth that gives protection from setting. As such, setting is a surface fatigue disappointment because of numerous redundancies of high contact stress, which happens on outfit tooth surfaces when a couple of teeth is transmitting power. Apparatus teeth disappointment because of contact. Fatigue is a typical marvel watched. Indeed, even a slight decrease in the stress at root results in incredible increment in the fatigue life of an apparatus. For a long time, equip configuration has been enhanced by utilizing enhanced material, solidifying surfaces with warm treatment and carburization, and shot peening to enhance surface complete and so forth.

Hardly any more endeavors have been made to enhance the toughness and quality by modifying the pressure edge, utilizing the awry teeth, changing the geometry of root filet bend et cetera. Some exploration work is additionally done utilizing the stress redistribution methods by presenting the stress alleviating highlights in the stressed zone to the benefit of decrease of root filet stress in goad adapt. This likewise guarantees trade capacity of existing apparatus frameworks.

The investigations in which blend of round and curved stress soothing highlights are utilized acquired preferable outcomes over utilizing roundabout stress diminishing highlights alone which are utilized by before specialists. In this examination work, an air balance molded stress alleviating highlight is attempted. A limited component display with a fragment of three teeth is considered for investigation and a stress calming highlight of different sizes are presented on adapt teeth at different areas.

Adapting is a standout amongst the most basic parts in mechanical power transmission frameworks. The exchange of intensity between gears happens at the contact between the mating teeth. Amid activity, fit gears" teeth flanks are submitted to high contact pressures and because of the rehashed stresses, harm on the teeth flanks, notwithstanding tooth breakage at the base of the tooth are a standout amongst the most regular reasons for outfit disappointment.

This fatigue disappointment of the tooth chooses the unwavering quality of the apparatus. Be that as it may, by acquainting stress mitigating highlights with the apparatus, the purposes of stress focus can be diminished which upgrades life of rigging. An examination is done on goad outfit with involutes profile by including stress diminishing highlights of various shapes and best among them is proposed.

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II. Literature Review

Prashant Kumar Singh et al. [1] investigated the wear behavior and operational performance of polymer gears manufactured from Acrylonitrile Butadiene Styrene (ABS), High Density Polyethylene (HDPE), and Polyoxymethylene (POM). The experiments were conducted at different torque levels and rotational speeds. Their results showed that the wear rate of polymer gears increases with applied torque, whereas it decreases with increasing rotational speed, indicating a strong dependency of wear on operating conditions.

Yang Yu et al. [2] proposed an advanced gear fault diagnosis methodology combining a novel recurrence analysis technique known as Local Oscillatory-Decay (LOD) with a diagnostic finite element–based support stress intensity factor (SIF) gear contact model. The outcomes demonstrated that this hybrid approach provides high precision and reliability in crack detection, making it an effective tool for gear fault identification.

Marina Franulović et al. [3] examined the effect of pitch deviations on the load-carrying capacity of high contact-ratio spur gears using both experimental and analytical approaches. Photoelastic analysis was employed experimentally, while systematic calculations were performed analytically. Their findings significantly improve load-capacity prediction accuracy and support gear design optimization.

Naresh K. Raghuwanshi et al. [4] studied the influence of back contact on the mesh stiffness of spur gears using finite element analysis. The results indicated that mesh stiffness slightly increases when back contact occurs, which can notably affect the vibration response of the gear system.

Paras Kumar et al. [5] analyzed the bending stress and contact stress of spur gear teeth using AGMA standards to assess fatigue failure. The study revealed that the highest probability of bending and contact fatigue failure occurs in the single-tooth contact region. A comparison between analytical and FEA results showed good agreement, with contact fatigue life found to be lower than bending fatigue life.

Miryam B. Sánchez et al. [6] evaluated the effect of contact path inclination on cross-sectional stiffness of spur gears through analytical methods. The study also examined bending and contact stresses using Hertzian contact theory. The analytical results closely matched FEA predictions, demonstrating improved accuracy in stiffness estimation and dynamic behavior assessment.

Dattatray B. Vaitkar et al. [7] determined gear contact stresses using both finite element simulations and experimental photoelastic techniques. The study highlighted the influence of pressure angle, contact ratio, bending stress, and gear geometry on gear performance, emphasizing design strategies for reducing contact stress and extending gear life.

Xiang Dai et al. [8] investigated static and dynamic tooth root strains in spur gear pairs using a combined FEA and experimental vibration analysis approach. The numerical predictions showed good correlation with experimental observations, validating the adopted modeling techniques.

Santosh S. Patil et al. [9] experimentally studied contact stresses in meshing helical gear pairs and validated the results using FEA. The study introduced a Gear Dynamic Stress Test Rig (GDSTR) as a reliable experimental setup for contact stress evaluation. It was observed that friction significantly affects contact stress and cannot be neglected, although minor wear misalignment and vibration were noted as experimental limitations.

Miryam B. Sánchez et al. [10] analyzed the contact stress and bending strength of spur gears under load conditions based on ISO 6336, using the principle of minimum elastic potential energy. Both analytical and finite element methods were employed, yielding consistent and reliable results.

Ankur Saxena et al. [11] examined the effects of shaft misalignment and frictional forces on mesh stiffness in spur gear systems. The study further extended the analysis to damaged gear pairs, highlighting the impact of misalignment on stiffness variation and gear performance.

Putti Srinivasa Rao et al. [12] computed contact stresses in spur gears using both ANSYS simulations and Hertzian

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analytical theory for aluminum, grey cast iron, and structural steel gears. The results indicated that aluminum gears exhibit lower contact stress and deformation, making them suitable for both driving and driven applications.

III. Methodology & Material Description

3.3.1 Structural Steel

The Structure Steel covers a variety of corrosion resistant steels that contain a minimum of 11% Chromium. By changing the Chromium content and adding other elements like Nickel, Molybdenum, Titanium and Niobium, it changes the mechanical and physical properties of the steel.

3.3.2 Aluminium Alloy

Aluminum has great welding capacity and produces a uniform and harder case. Auxiliary Steel has great parity of toughness, quality and malleability. Particular assembling controls are utilized for surface readiness, synthetic sythesis, rolling and warming procedures. These procedures grow top notch materials that are suited to creation procedures, for example, warm treating, manufacturing, penetrating, welding, machining, and chilly drawing.

3.3.3 Titanium Materials

Titanium is a chemical element with symbol Ti and atomic number 22. It is a lustrous transition metal with a silver color, low density, and high strength. Titanium is resistant to corrosion in sea water, and chlorine.

3.3.4 Carbon Fiber

These are generally utilized as composite materials. The ask for lightweight weight composite materials has prompted the improvement of those materials. These are generally utilized inferable from their openness and financial preparing methods got for making of segments.

IV. Results & Discussion

In the present analysis, the von Mises stress, total deformation, temperature distribution, and total heat flux were evaluated for three different materials, namely Structural Steel, Aluminium Alloy, and Titanium Alloy. The computed von Mises stresses for Aluminium Alloy, Structural Steel, and Titanium Alloy were found to be 66.255 MPa, 66.924 MPa, and 65.553 MPa, respectively. These results indicate that all three materials experience comparable stress levels under the applied loading conditions.

The total deformation values obtained for Structural Steel, Aluminium Alloy, and Titanium Alloy were 0.027328 mm, 0.076619 mm, and 0.05645 mm, respectively. As expected, Structural Steel exhibits the lowest deformation due to its higher elastic modulus, whereas Aluminium Alloy shows higher deformation owing to its relatively lower stiffness.

Thermal analysis revealed that the maximum temperatures for Structural Steel, Aluminium Alloy, and Titanium Alloy were 127.10^{0}C, 126.99^{0}C, and 126.97^{0}C, respectively, demonstrating negligible variation in temperature distribution among the selected materials. Similarly, the total heat flux values were found to be 1.1081 W/mm^2 for Structural Steel, 1.1145 W/mm^2 for Aluminium Alloy, and 1.1134 W/mm^2 for Titanium Alloy.

Based on the combined assessment of mechanical and thermal performance, Aluminium Alloy emerges as the most suitable material among those investigated. Although it exhibits higher deformation compared to Structural Steel, the deformation and stress levels remain within acceptable limits, while offering the highest heat flux dissipation. Additionally, the lightweight nature of Aluminium Alloy, coupled with its adequate strength and thermal performance, makes it a favorable choice for heavy-duty applications where weight reduction and thermal efficiency are critical design considerations.

Figure 2 illustrates the von Mises stress variation across different contour levels (Dark Blue to Red) for Aluminium Alloy, Structural Steel, and Titanium Alloy. For all three materials, the stress magnitude increases progressively from the lower contour regions to the higher contour regions, indicating a consistent stress gradient under the applied loading condition.

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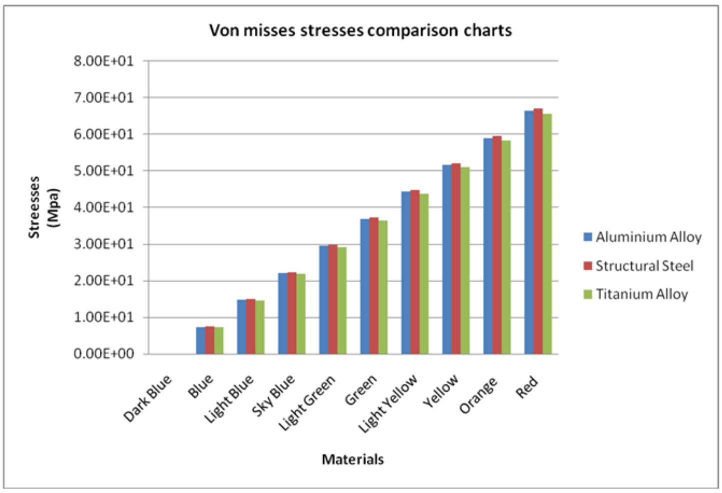

Fig. 2. Thermal Von misses comparison Table for different materials

At each contour level, the von Mises stress values of Structural Steel are marginally higher, followed by Aluminium Alloy, while Titanium Alloy exhibits slightly lower stresses. However, the variation among the three materials is minimal throughout the contour range. This indicates that material selection has a negligible influence on stress concentration, and the component geometry and loading condition dominate the stress response. Hence, from a strength perspective, all three materials satisfy the stress requirements safely.

Figure 3 presents the total deformation distribution across contour levels for Structural Steel, Titanium Alloy, and Aluminium Alloy. A clear separation in deformation behavior is observed among the materials. Structural Steel consistently exhibits the lowest deformation across all contour bands due to its higher elastic modulus. Titanium Alloy shows intermediate deformation, while Aluminium Alloy experiences the highest deformation at corresponding contour levels.

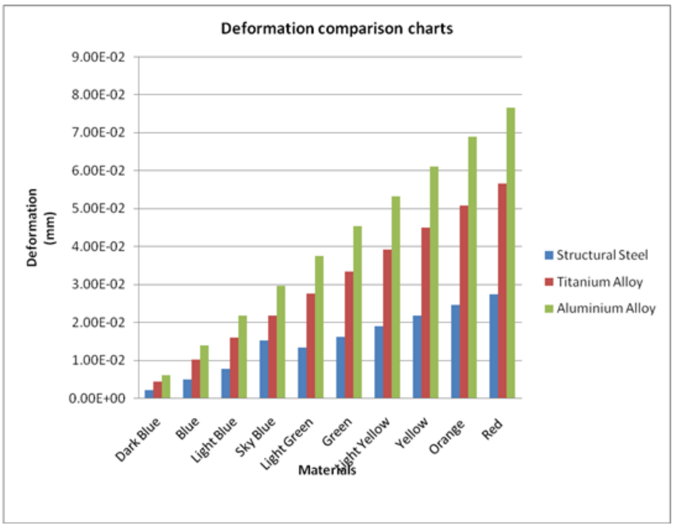

Fig. 3. Deformation comparison Table for different materials

The progressive increase in deformation from dark blue to red contours confirms elastic response under increasing load intensity. Although Aluminium Alloy shows higher deformation, the magnitude remains within acceptable limits, indicating that structural integrity is maintained. This behavior is expected due to the lower stiffness of Aluminium Alloy compared to the other materials.

Figure 4 shows the temperature variation across contour bands for the selected materials. The temperature rises

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gradually from lower to higher contour regions for all materials, reflecting uniform thermal loading conditions. Titanium Alloy records the highest temperature values at each contour level, followed by Structural Steel, whereas Aluminium Alloy consistently exhibits the lowest temperature rise. This trend highlights the influence of thermal conductivity, where Aluminium Alloy dissipates heat more effectively, resulting in lower temperature accumulation. The small temperature difference among materials also indicates stable thermal behavior under the given operating conditions.

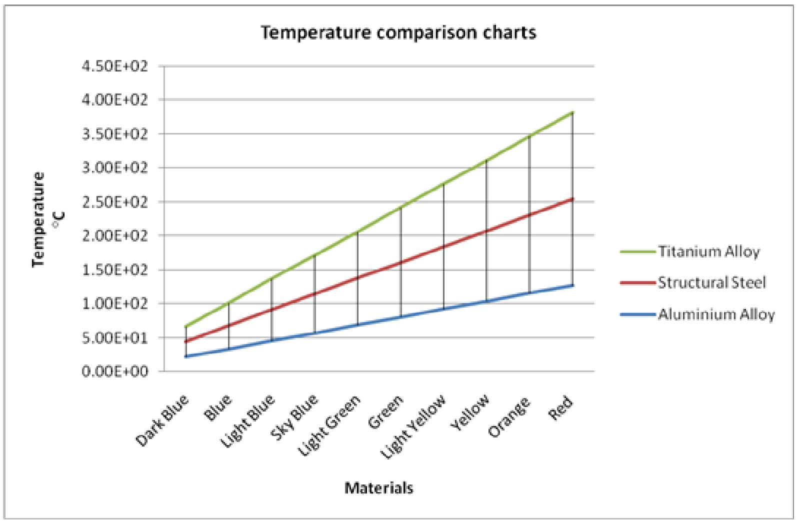

Fig. 4. Temperature comparison Table for different materials

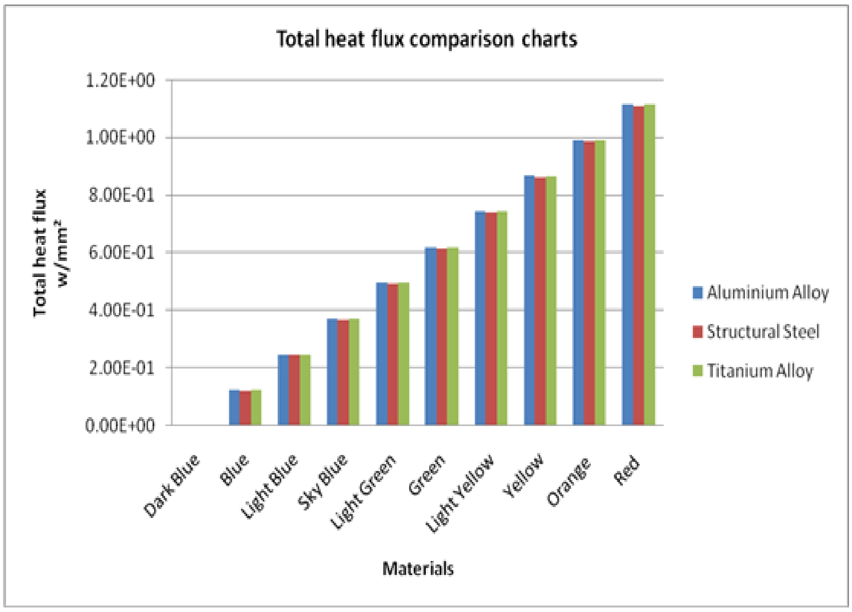

Fig. 5. Total heat flux comparison Table for different materials

Figure 5 compares the total heat flux distribution for Aluminium Alloy, Structural Steel, and Titanium Alloy across contour levels. The heat flux increases steadily from dark blue to red contours for all materials, corresponding to higher thermal gradients. Among the materials, Aluminium Alloy shows the highest heat flux values throughout the contour range, followed closely by Titanium Alloy and Structural Steel. This confirms the superior heat transfer capability of Aluminium Alloy, which enables efficient dissipation of generated heat and reduces thermal concentration within the component.

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V. Conclusion

The present investigation focused on the structural and thermal performance evaluation of involute spur gears using finite element analysis. By combining analytical design calculations with numerical simulations, the study assessed the influence of material properties on stress distribution, deformation behavior, temperature rise, and heat flux under identical loading and boundary conditions. The comparative analysis of Structural Steel, Aluminium Alloy, and Titanium Alloy provides clear insights into material suitability for spur gear applications, leading to the following conclusions:

- Finite Element Analysis (FEA) proved to be an effective and reliable tool for predicting the mechanical and thermal response of involute spur gears under realistic operating conditions. The numerical results accurately captured von Mises stress, total deformation, temperature distribution, and heat flux behavior.
- The maximum von Mises stress values for Structural Steel (≈ 66.9 MPa), Aluminium Alloy (≈ 66.3 MPa), and Titanium Alloy (≈ 65.6 MPa) were found to be closely comparable, indicating that stress concentration is primarily governed by gear geometry and applied load rather than material selection when operating conditions remain unchanged.
- Structural Steel exhibited the minimum total deformation (≈ 0.027 mm) due to its higher elastic modulus, followed by Titanium Alloy (≈ 0.056 mm), whereas Aluminium Alloy showed the highest deformation (≈ 0.077 mm). Despite this, the deformation of Aluminium Alloy remained well within permissible limits, ensuring safe structural performance.
- Thermal analysis showed negligible variation in the maximum temperature among the three materials, with peak temperatures of approximately 127 °C recorded for Structural Steel, Aluminium Alloy, and Titanium Alloy, indicating stable and uniform thermal behavior during gear operation.
- Aluminium Alloy demonstrated the highest total heat flux (≈ 1.1145 W/mm^2), compared to Structural Steel (≈ 1.1081 W/mm^2) and Titanium Alloy (≈ 1.1134 W/mm^2), confirming its superior heat dissipation capability and reduced thermal accumulation.
- Considering stress safety, deformation limits, thermal efficiency, and weight reduction advantages, Aluminium Alloy emerged as the most suitable material among those investigated for involute spur gear applications, particularly in heavy-duty and high-performance mechanical systems.

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