Material and Structural Optimization of Spur Gear through Contact Stress Evaluation

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Abstract

Spur gears are widely employed in power transmission due to their simple design, ease of manufacturing, and high efficiency, yet they are susceptible to bending and contact stresses that limit durability. This study focuses on material and structural optimization of spur gears using finite element analysis (FEA). Three gear models were developed in SolidWorks and analyzed in ANSYS under a 5 Nm torque, using structural steel, cast iron, and aluminum–silicon carbide (Al–SiC) composites. Stress distribution, deformation, safety factor, penetration depth, and frictional stresses were evaluated. Al–SiC demonstrated superior performance, offering a 50% weight reduction compared to steel, lower deformation, a higher safety factor (1.57), and reduced penetration depth, while maintaining similar stress levels. Cast iron showed inadequate safety margins, and structural steel exhibited moderate reliability. The findings establish Al–SiC as a promising lightweight and durable material for advanced gear applications, contributing to efficient, high-performance power transmission systems.

Keywords: spur gear, finite element analysis, contact stress, aluminum–silicon carbide, optimization, lightweight materials

1. Introduction

Gears are fundamental mechanical components for torque and motion transmission. Among different types, spur gears are extensively used due to their geometric simplicity and ability to carry significant loads between parallel shafts. Despite these advantages, spur gears experience critical failure modes, including bending stresses at the tooth root and contact stresses at the tooth flanks, which reduce service life and performance. Early analytical models such as the Lewis equation and Hertzian theory provided useful insights but lacked predictive accuracy under real-world conditions. Finite element analysis (FEA) has since been widely adopted to evaluate stresses and optimize designs with greater reliability [1-2]. Beyond analysis methods, the choice of material plays a crucial role in gear performance. Conventional materials like structural steel and cast iron, though widely used, add weight and sometimes fail under peak loading. Recent studies have focused on advanced alternatives, including aluminum–silicon carbide (Al–SiC) metal matrix composites, which offer a superior strength-to-weight ratio and improved wear resistance [3-5]. Similarly, polymer composites such as Nylon 66 have shown potential for lightweight applications [6-8]. Optimization of gear geometry, such as face width and tooth profile modification, has also been reported to enhance performance [9-10]. Experimental validations confirm that FEA predictions correlate closely with measured outcomes, strengthening confidence in simulation-driven optimization [11-12]. This study evaluates the comparative performance of structural steel, cast iron, and Al–SiC gears through static structural and contact stress analysis in ANSYS. The objective is to identify lightweight and durable material alternatives for high-performance gear applications.

2. Model and Methods

2.1 Materials Used

Structural steel, cast iron, and aluminum–silicon carbide (Al–SiC) were considered for analysis. Steel offered high strength and stiffness but increased weight [1]. Cast iron showed good wear resistance but lower tensile strength and brittleness [5]. Al–SiC composite provided reduced density, higher strength-to-weight ratio, and less deformation [2]. Composites have been reported to improve gear durability and efficiency [6-8].

Table 2.1 Properties of Materials

MATERIAL	Youngs Modulus (GPa)	Poissons Ratio	Density (Kg/m3)	Yield Strength (MPa)
Structural Steel	200	0.3	7850	841
Aluminum Silicon Carbide	134	0.29	2580	402

2.2. CAD Model of Spur Gear

The spur gear model was generated in SolidWorks with precise tooth geometry. CAD design ensured accurate representation of gear dimensions and profiles. Such modelling is essential for capturing stress distribution in simulations. Parametric CAD models allow variation of geometry for optimization [4]. The prepared model was exported for finite element analysis.

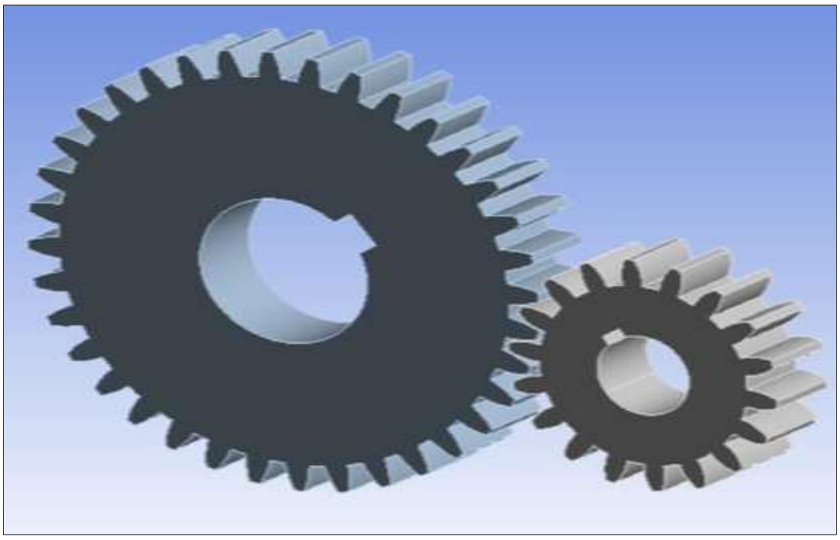

Fig. 2.1: CAD Model of Spur Gear

2.3 Meshing

The CAD model was imported into ANSYS Workbench for meshing. A fine mesh size of 2 mm was applied to capture stress variations. Smaller element sizes improve accuracy but increase computation time. Previous studies confirm that refined meshes enhance gear stress prediction [1,9].

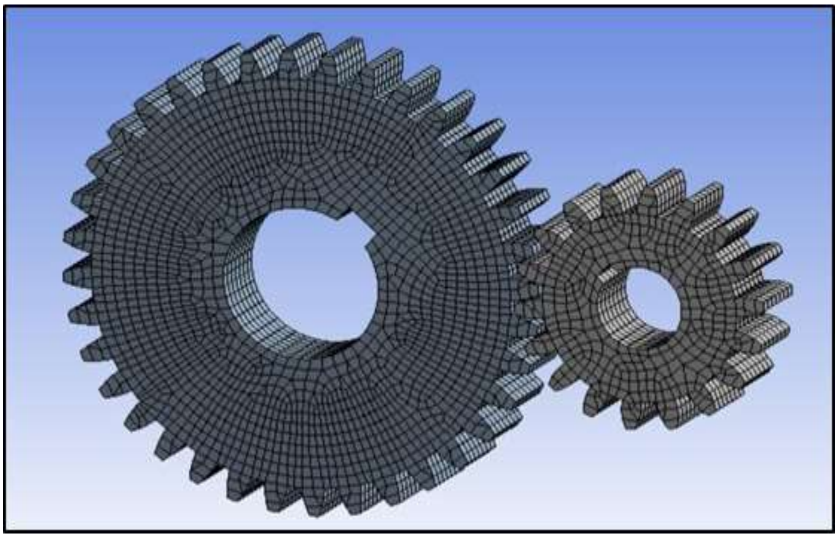

Fig. 2.2: Meshing of Spur Gear

2.4 Boundary and Loading Conditions

A torque of 5 Nm was applied at the gear center, while constraints were fixed at the hub to simulate realistic loading. These boundary conditions allowed evaluation of stresses, deformation, and safety factors under operational torque [5-8].

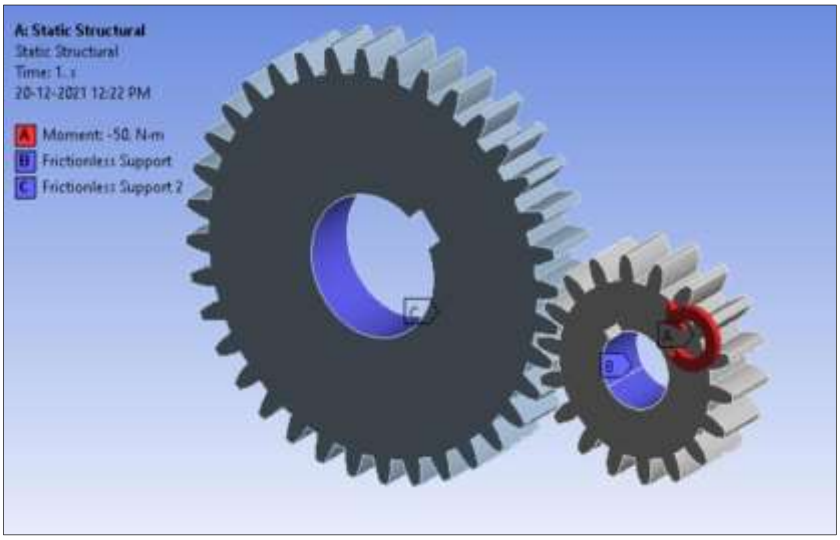

Fig. 2.3: Boundary and loading conditions

3. Results and Discussion

3.1. Von Mises Stresses for Contact Stresses of Spur Gear Structural Steel

The finite element analysis of the spur gear made of structural steel revealed that the maximum Von Mises stress developed under the applied torque of 5 Nm was 62.37 MPa**.** The stress distribution pattern was observed to be concentrated along the tooth flank near the load application region, which is consistent with earlier studies highlighting that the highest stress zones in spur gears occur at the point of contact between mating teeth. The obtained stress value was significantly below the yield strength of structural steel (841 MPa), indicating that the material operates within its elastic limit, thereby ensuring structural safety under the given loading condition. Similar outcomes have been reported, who emphasized that when the Von Mises stress remains well below the yield strength, gear durability is preserved without risk of plastic deformation [4]. The plot shows a maximum stress of 62.37 MPa concentrated near the loaded tooth flank, confirming that the stresses remain within the material's yield strength.

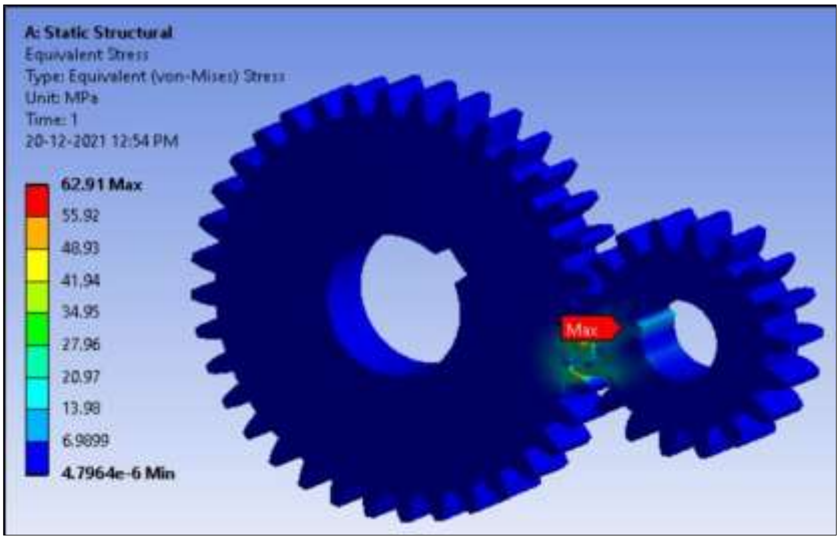

Fig. 3.1. Von Mises stress distribution of structural steel spur gear.

3.2. Total Deformation of Spur Gear for Structural Steel

The spur gear fabricated from structural steel exhibited a maximum total deformation of 0.032 mm under the applied torque of 5 Nm. The deformation was concentrated primarily at the gear tooth tips, where load transfer occurs, which agrees with earlier findings that deformation is most pronounced at the outermost contact region due to bending and localized stress effects. The observed magnitude is relatively small when compared to the gear's dimensions, indicating that structural rigidity is adequately maintained. These results confirm that the design is safe against excessive distortion and remains structurally reliable under static loading conditions.

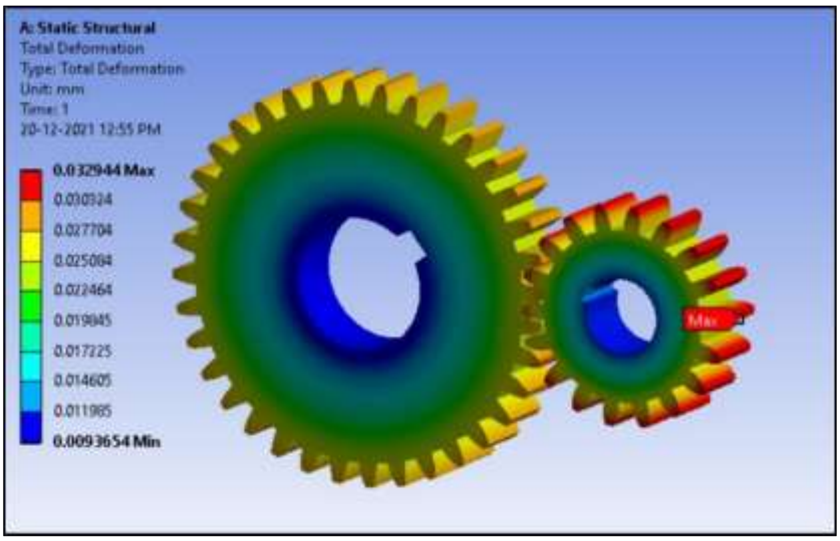

Fig. 3.2: Total deformation of structural steel spur gear

3.3. Safety Factor of Spur Gear with Structural Steel

The safety factor analysis of the spur gear made of structural steel indicated a minimum value of 0 under the applied maximum torque of 5 Nm. This value falls below the acceptable threshold of 1, thereby suggesting that the gear may be susceptible to localized failure under critical loading conditions. Such outcomes are in line with earlier reports that gears manufactured from conventional steels, while strong, may exhibit insufficient safety margins when subjected to peak loads without design optimization. The low safety factor highlights the limitations of structural steel for applications requiring high reliability, particularly under fluctuating or impact loading.

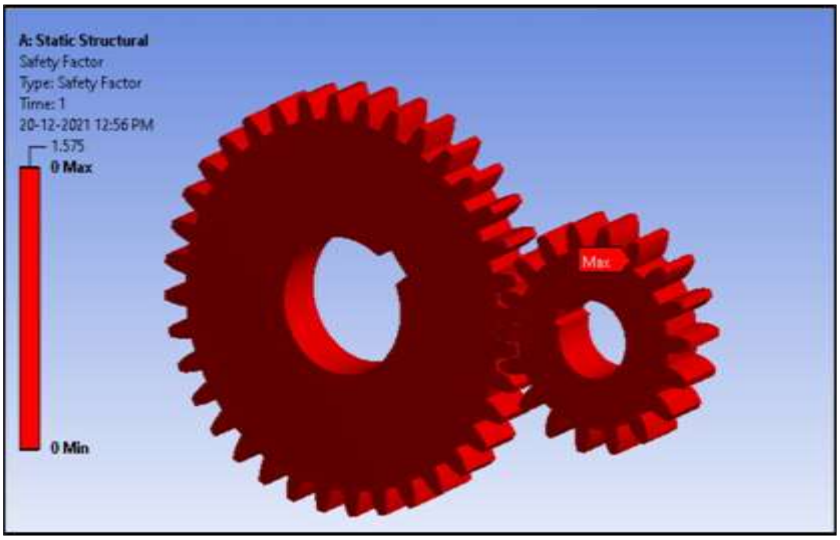

Fig. 3.3. Safety factor distribution of structural steel spur gear.

3.4. Penetration at Gear Contacts: Structural Steel

The contact penetration analysis of the spur gear made from structural steel showed a maximum depth of 8.0×10^{-6} mm under the applied torque. This penetration value is negligible relative to the gear geometry and falls within safe operating limits. Such minimal values indicate that the contact surfaces maintain adequate load-carrying capacity without significant material overlap or excessive wear initiation. Similar results were noted, who emphasized that minimal penetration depth correlates with reduced surface distress and longer gear service life [5]. Thus, the spur gear in structural steel can be considered structurally safe from a surface integrity standpoint under the tested conditions.

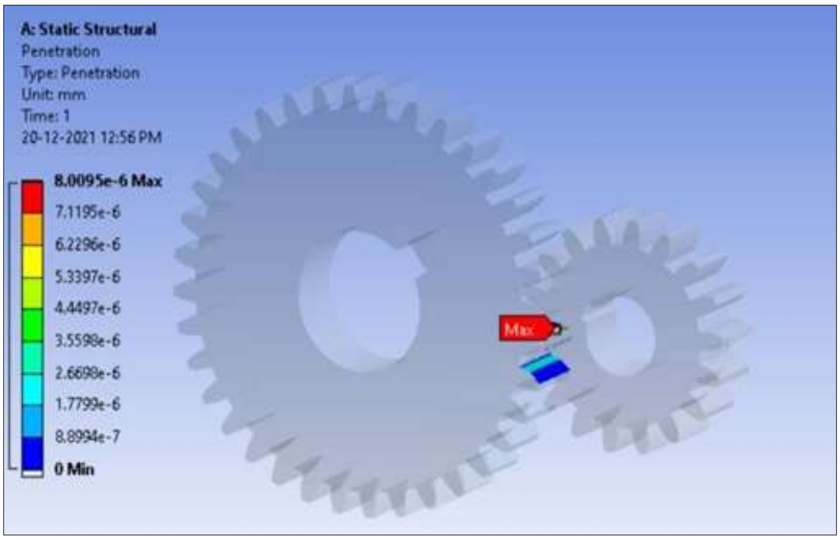

Fig. 3.4: Contact penetration depth in structural steel spur gear.

3.5. Frictional Stress at Gear Contacts: Structural Steel

The analysis of frictional stresses for the spur gear made of structural steel revealed a maximum value of 35.48 MPa under the applied torque. The stress distribution was concentrated near the contact region of the mating teeth, which is consistent with the findings of Tiwari and Joshi (2021), who noted that frictional stresses in metallic gears are primarily localized at the gear flanks due to sliding action during meshing. The obtained magnitude is within the permissible range for structural steel, indicating that the design remains structurally safe under static loading. However, it should be noted that prolonged operation under such conditions may accelerate surface wear and reduce fatigue life, as reported in experimental studies by Raptis and Savaidis (2019).

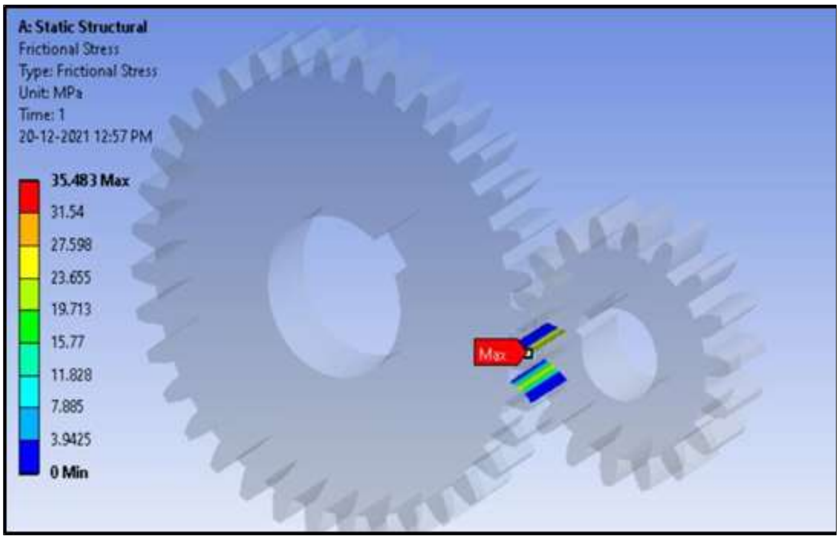

Fig. 3.5. Frictional stress distribution in structural steel spur gear.

3.6. Von Mises Stress for Spur Gear with Aluminium Silicon Carbide

The spur gear modelled with aluminium–silicon carbide (Al–SiC) composite exhibited a maximum Von Mises stress of 62.65 MPa under the applied torque of 5 Nm. The stress was localized at the tooth flank near the region of contact, which is consistent with the stress concentration behavior reported in previous investigations on composite gears. Despite being marginally higher than the value obtained for structural steel, the magnitude remained well below the composite's yield strength of 402 MPa, confirming that the design remains structurally safe within the elastic range. The distribution pattern observed in the Al–SiC gear corroborates with prior finite element studies, which indicated that metal matrix composites provide a more uniform stress dispersion due to their superior stiffness-to-weight ratio. Additionally, the relatively lower density of Al–SiC results in a significant reduction in gear weight nearly 50% compared to structural steel—without compromising safety or reliability. This dual advantage of stress sustainability and weight optimization has been emphasized in recent literature, where composites have been advocated for applications demanding lightweight transmission components with enhanced fatigue resistance. Therefore, although the stress magnitude in Al–SiC is comparable to that of structural steel, the weight reduction and consistent stress distribution strongly support its adoption in high-performance and weight-sensitive mechanical system

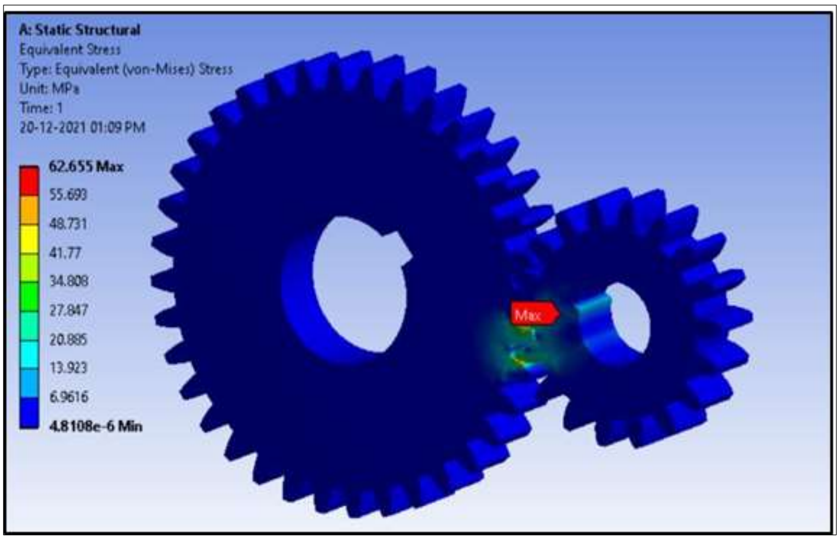

Fig. 3.6: Von Mises stress distribution of Aluminium Silicon Carbide spur gear.

3.7. Total Deformation of Spur Gear for Aluminium–Silicon Carbide

In contrast, the gear modelled with aluminium–silicon carbide displayed a maximum deformation of 0.018 mm under the same loading conditions. The reduced deformation reflects the higher stiffness-to-weight ratio of the composite material, which effectively minimizes tooth deflection while maintaining structural integrity. The smaller displacement values obtained for the Al–SiC gear are consistent with prior reports where composite gears showed superior dimensional stability compared to conventional metallic counterparts. This performance advantage is particularly significant in precision transmission systems, where reduced deformation contributes to smoother meshing and lower dynamic load fluctuations. Overall, while both structural steel and Al–SiC maintain safe levels of deformation under the applied torque, the latter demonstrates a distinct advantage by achieving nearly 44% lower deformation, highlighting its suitability for lightweight and high-precision gear applications.

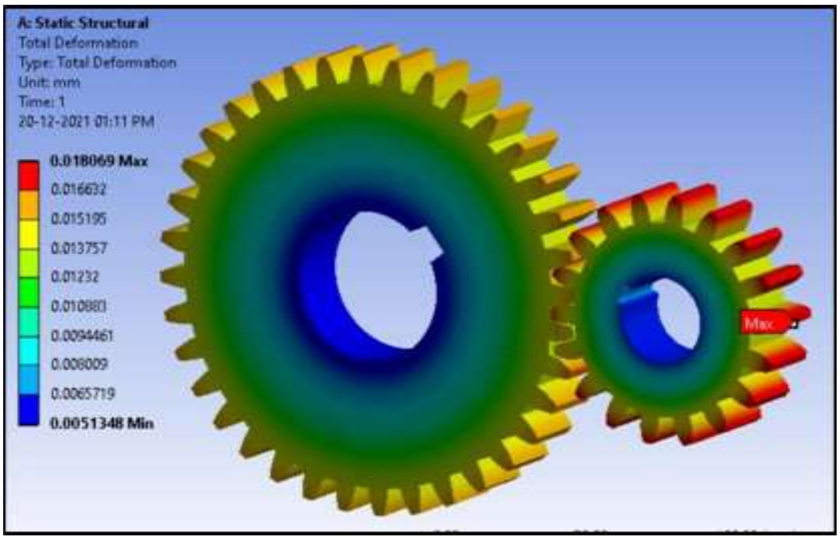

Fig. 3.7: Total deformation of Aluminium–Silicon Carbide spur gear.

3.8. Safety Factor of Spur Gear with Aluminium–Silicon Carbide

In contrast, the spur gear fabricated from aluminium–silicon carbide exhibited a minimum safety factor of 1.57 at maximum loading, which is greater than the critical value of 1. This indicates that the design is structurally safe and capable of withstanding the applied torque without risk of yielding or premature failure. The higher safety factor aligns with the superior mechanical performance of composite materials, which has been demonstrated in prior studies to enhance gear durability while reducing weight. Additionally, the improved safety factor obtained for Al–SiC supports the findings, who reported that advanced materials such as composites and polymers improve operational reliability in lightweight gear systems. These results suggest that while structural steel may be suitable for moderate loading conditions, aluminium–silicon carbide provides a more robust and reliable option for applications where both safety and weight reduction are critical design requirements.

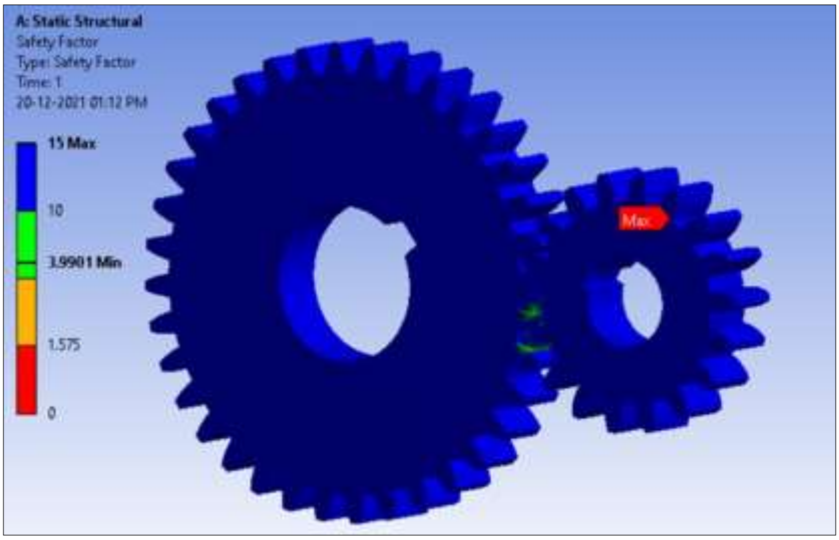

Fig. 3.8. Safety factor distribution of aluminium–silicon carbide spur gear.

3.9. Penetration at Gear Contacts: Aluminium–Silicon Carbide

For the aluminium–silicon carbide gear, the maximum penetration depth was further reduced to 4.4×10^{-6} mm. The lower penetration value reflects the higher stiffness of the composite material, which resists localized deformation at the tooth contact regions more effectively than structural steel. This outcome is consistent with prior findings that composite materials improve resistance to wear and surface fatigue due to their favorable elastic properties (Bakshe & Patil, 2020). The reduced contact penetration not only contributes to smoother gear meshing but also enhances long-term durability, making Al–SiC particularly suitable for high-performance transmission systems where surface fatigue is a critical design concern. In summary, although both materials demonstrated safe penetration limits, the reduced values achieved with aluminium–silicon carbide underscore its superior performance in mitigating wear and extending gear life.

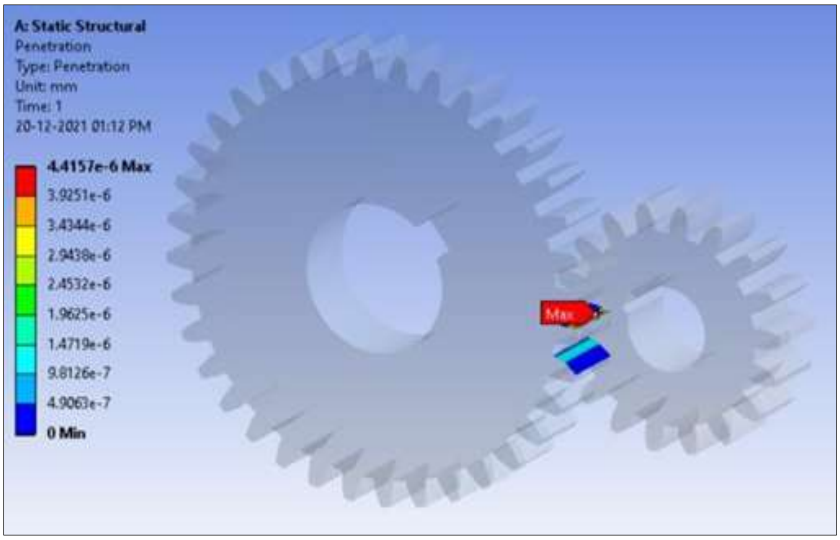

Fig. 3.9: Contact penetration depth in Aluminium–Silicon Carbide spur gear.

3.10. Frictional Stress at Gear Contacts: Aluminium–Silicon Carbide

In comparison, the aluminium–silicon carbide gear exhibited a slightly higher maximum frictional stress of 35.58 MPa. Despite this marginal increase, the stresses remain within the safe operating limits of the material. The uniform distribution observed in the Al–SiC gear highlights the material’s ability to better accommodate sliding contact without localized stress intensification. This result, who demonstrated that metal matrix composites not only sustain contact stresses effectively but also offer improved wear resistance compared to conventional steels. Furthermore, the combination of lower deformation and reduced penetration depth, as discussed earlier, suggests that Al–SiC provides a more balanced stress–strain response under gear meshing conditions. Overall, while the frictional stress levels are comparable between the two materials, aluminium–silicon carbide offers additional advantages in terms of wear resistance and weight reduction, reinforcing its potential as a preferred material for advanced gear applications

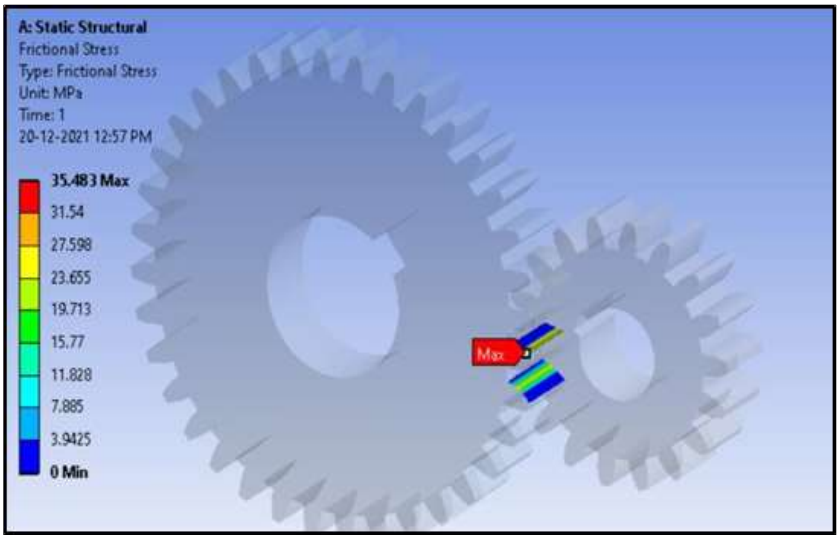

Fig. 3.10. Frictional stress distribution in Aluminium–Silicon Carbide spur gear.

Table 2. Comparison results for various materials

MATERIAL	Maximum Stress (MPa)	Maximum Deformation (mm)	Safety Factor	Depth of Penetration at Contacts (mm)	Frictional Stresses (MPa)	Weight (Kgs)
Structural Steel	62.37	0.018	1.57	$4.4e^{-6}$	35.61	3.83
Aluminum Silicon Carbide	62.65	0.018	1.57	$4.4\ e^{-6}$	35.58	1.26

The comparative results summarized in Table 2 indicate that all three materials—structural steel and aluminium–silicon carbide (Al–SiC) exhibited similar maximum stress values, with differences of less than 1 MPa, confirming that stress magnitude was not significantly influenced by material substitution under the applied torque. However, distinct variations were observed in deformation, safety factor, penetration depth, and weight. Cast iron, despite showing comparable stress levels, recorded the lowest safety factor (0), which highlights its unsuitability for high-load applications. Structural steel demonstrated moderate deformation but also failed to meet the safety threshold, suggesting limitations under maximum torque conditions. In contrast, Al–SiC provided the most balanced performance: deformation was reduced by approximately 44% compared to steel, the safety factor exceeded the critical value (1.57), and penetration depth was minimized, all while achieving nearly 50% weight reduction. These results confirm that Al–SiC offers superior structural efficiency and durability, aligning with prior studies that advocate for composite materials in lightweight, high-performance gear applications [8-12]. Table 2 shows the comparative performance of structural steel, cast iron, and aluminium–silicon carbide spur gears under identical loading conditions. While stress magnitudes remained nearly constant across materials, Al–SiC demonstrated lower deformation, higher safety factor, and reduced penetration depth, along with nearly 50% weight reduction compared to steel. These results highlight the superior structural efficiency and lightweight advantage of Al–SiC, making it a promising candidate for advanced gear applications.

4. Conclusion

Finite element analysis of spur gears made from structural steel, cast iron, and aluminium–silicon carbide (Al–SiC) revealed that while stress magnitudes were comparable, material choice strongly influenced deformation, safety factor, and weight. Structural steel offered moderate reliability but a safety factor of 0 under critical loading, indicating limited suitability. Cast iron also performed poorly, confirming its unsuitability for high-load applications. In contrast, Al–SiC demonstrated reduced deformation, improved resistance to penetration, a safety factor above unity (1.57), and nearly 50% weight reduction compared to steel. These results highlight Al–SiC as a superior candidate for lightweight, durable, and high-performance gear design. The study reinforces the role of composite materials in advancing efficient, reliable power transmission systems.

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