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Improving the Load Carrying Capacity through Asymmetric Spur Gear using WC-Fe Metal Matrix Composite for Automobile Applications

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Abstract
Gears are the components that have been used for a century to transmit power from one place to another place. Symmetric spur gears are commonly used in the gearbox to transmit power between two parallel shafts. In order to increase the load carrying capacity of the spur gear with reduced noise and vibration, its profile can be modified. This can be achieved by changing the gear tooth design into asymmetric form. Asymmetrically toothed gears are used in power transmission for transmitting the power in one direction. These teeth help to improve the load carrying and power transmitting capacity of the gear. The strength can be further increased by changing the material used in gears. This can be made possible by using Metal Matrix Composite as a gear material. The metal matrix composites have high stiffness and strength to weight ratio compared to the Alloy Steel. The main objective of this project is to increase the load carrying capacity of the spur gear by using WC-Fe metal matrix composite material. The symmetric and asymmetric gear modeling has been done for existing car gear (Maruthi 800) using Ansys parametric design language software. The contact stress, bending stress and von Mises stress of the composite, as well as conventional gear material, is analyzed and the results are compared to find the percentage increase in strength of the gear.

Keywords- Symmetric and asymmetric spur gear, Metal matrix composite, von Mises stress.

1. Introduction

Gears, integral to mechanical systems, serve as the linchpin in power transmission through their meshing teeth. This process involves the transfer of rotational motion between interlocking gears, adjusting torque and speed based on gear ratios. The gears are widely applicable across diverse industries, from automotive transmissions to industrial machinery, gears play a vital role. (Habermehl et al., 2020; Petrescu et al., 2017) Ensuring effective power transmission through gears requires meticulous attention to key requirements, with the choice of gear material emerging as a critical factor (Behrens et al., 2017). High strength is paramount to withstand transmitted forces and torques, given that gears often operate under substantial loads (Li, 2008). The selected material must exhibit superior mechanical properties, including durability to resist wear and fatigue over extended usage (Davis, 2005; Liu et al., 2020). Additionally, the gear material must possess sufficient toughness to absorb dynamic shock loads without catastrophic failure (Holmes et al., 2016). Commonly, metals like steel and alloys, with their favorable combination of strength, durability, and toughness, are employed in gear manufacturing (Maity & Chakraborty, 2013), influencing heat dissipation (Jiang et al., 2023) and lubricant compatibility (Herdan, 1997). The enhancement of gear strength is a fundamental consideration in mechanical design, and several techniques can be employed for this purpose (Biernacki, 2015; Delibaş et al., 2017). Material selection takes precedence, as opting for high-strength materials, such as specialized steels and alloys, lays the foundation for subsequent strengthening processes (Ivanov & Shishkin, 2021). Precision in manufacturing, achieved through accurate machining and shaping techniques, minimizes stress concentrations and potential points of failure (Choi et al., 2021; Yanase et al., 2018) Surface finishing processes, like grinding, improves fatigue resistance, contributing to overall strength (Bergstedt et al., 2020). Coating technologies, such as nitriding or advanced materials like ceramics, provide an additional layer of protection and strength, enhancing wear resistance and reducing friction (Qiu et al., 2015; Roelandt et al., 1985; Zhai et al., 2021) Material selection emerges as the pivotal parameter among various techniques to enhance gear strength. The choice of materials fundamentally dictates a gear's ability to withstand mechanical stresses involved in power transmission (Khurana et al., 2017). High-strength materials set the stage for subsequent processes like heat treatment (Hu et al., 2020; Panza-Giosa, 2009) and precision machining (Chen et al., 2018; König et al., 1984), optimizing the gear's strength and durability. The success of other strengthening techniques hinges upon the initial selection of materials aligned with the demanding requirements of power transmission applications.

Mao et al. (2019) developed a composite gear consisting of non-reinforced POM (Polyoxymethylene) and 28% GFR POM (glass fibre reinforced POM) gear pairs. Significant performance enhancements were observed for the GFR POM gears, with an increase of around 50% in load carrying capacity when compared to the non-reinforced POM gears. Catera et al. (2020) developed multiple joining technologies for steel and carbon fibre reinforced polymer materials in a hybrid gear. They observed that the interference fitting technology allows to achieve a higher stiffness, while the adhesive bonding is characterized by an increased energy dissipation capacity. Goriparthi et al. (2021) developed a composite gear comprising of POM, carbon nanotubes, and polytetrafluoroethylene, and they observed a significant improvement in the load bearing capacity and life of the gears, when compared with POM gear. Additionally, the composite gears exhibited a significant improvement in strength, stiffness and wear resistance. Siva et al. (2021) developed spur gears composed of Aluminium alloy 6061 composite with varying weight percentages of titanium carbide and performed comparison of strength with respect to conventional cast iron spur gear. The modelling results reveal that addition of titanium carbide results in higher tensile strength, impact strength and hardness values.

In this work, the metal matrix composite WC-Fe is used as a material for the asymmetric spur gear and the symmetric spur gear uses EN 24 alloy steel as a gear material. The reason for selecting these materials is that they impart the superior mechanical properties, including durability to resist wear and fatigue over extended usage. Both the symmetric and the asymmetric gears are modeled and analyzed in APDL analysis software. The static structural analysis has been carried out to find the amount of reduction in the stresses and improvement in the load carrying capacity.

2. Modeling and Finite Element Analysis

Modeling is defined as creating the desired model using design software. The finite element analysis is carried out when the model is created. Ansys parametric design language (APDL) code has been generated for creating the two-dimensional gear model with the below assumptions

(i) The model is created by taking the plane strain condition
(ii) There is no backlash in between the gear and pinion
(iii) There is no friction exist in the contact model

Boundary conditions are applied in the model by fixing the gear radially in all directions and the torque is applied to the pinion. The EN 24 alloy steel with an elastic constant, E= 210 GPa and Poisson's ratio ν= 0.3 is used as a material in symmetric spur gear. WC-Fe metal matrix composite with an elastic constant, E= 330 GPa and Poisson's ratio ν= 0.26 is used as a material in asymmetric spur gear. The element used in this analysis is six nodded triangular 2D-PLANE 82 with two degrees of freedom on each node. Contact is made on surface to surface of pinion and gear. CONTA172 and TARG 169 are used as contact and target elements. The element size in the fillet region is 0.04 mm and the contact element edge length is 0.006 mm. Static structural analysis has been carried out on the gears using APDL. The bending stress analysis has been carried out at highest point of single tooth contact (HPSTC). The contact stress analysis has been carried out at pitch point. The von Mises stress analysis is also carried out for both spur gears.

3. Results and Discussion

3.1 Bending Stress

The examination of maximum bending stress at the HPSTC point reveals compelling insights into the performance of asymmetric composite spur gears compared to their symmetric counterparts. In the specific case discussed, the maximum bending stress for the asymmetric composite spur gear, from Figure 1 is measured at 132.211 MPa, notably lower than the corresponding 156.759 MPa bending stress observed in the symmetric spur gear, from Figure 2. This discrepancy highlights a critical advantage for the asymmetric design in terms of stress management. Bending stress is a pivotal parameter in gear design, exerting a direct impact on material requirements, durability, and overall system performance. The lower maximum bending stress exhibited by the asymmetric composite spur gear suggests that its design, potentially incorporating variations in tooth profile or material distribution, contributes to a more favorable stress distribution. This is particularly crucial at the root of the gear tooth, a location susceptible to fatigue failure, emphasizing the importance of stress minimization for ensuring prolonged gear life. The implications of the observed stress reduction at the root of the asymmetric composite gear tooth extend beyond mere numerical values. They signify improved structural integrity and hint at the potential for enhanced load-carrying capacity in asymmetric configuration. This outcome harmonizes with fundamental principles of gear design, which seek to optimize stress distribution to bolster the overall performance and reliability of gear systems.

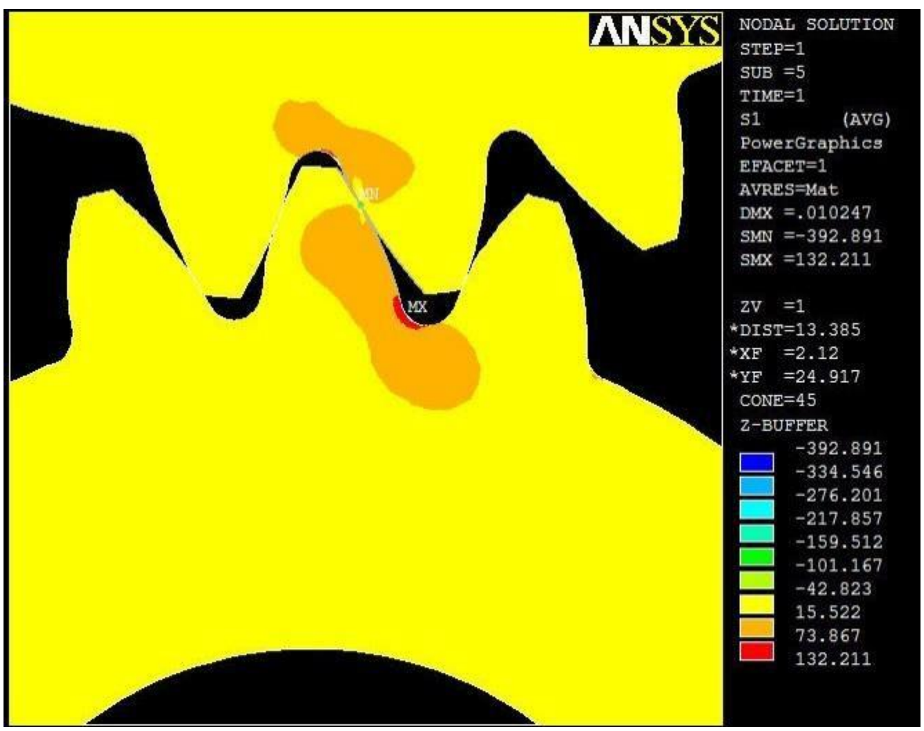

Figure 1. Bending stress of symmetric spur gear.

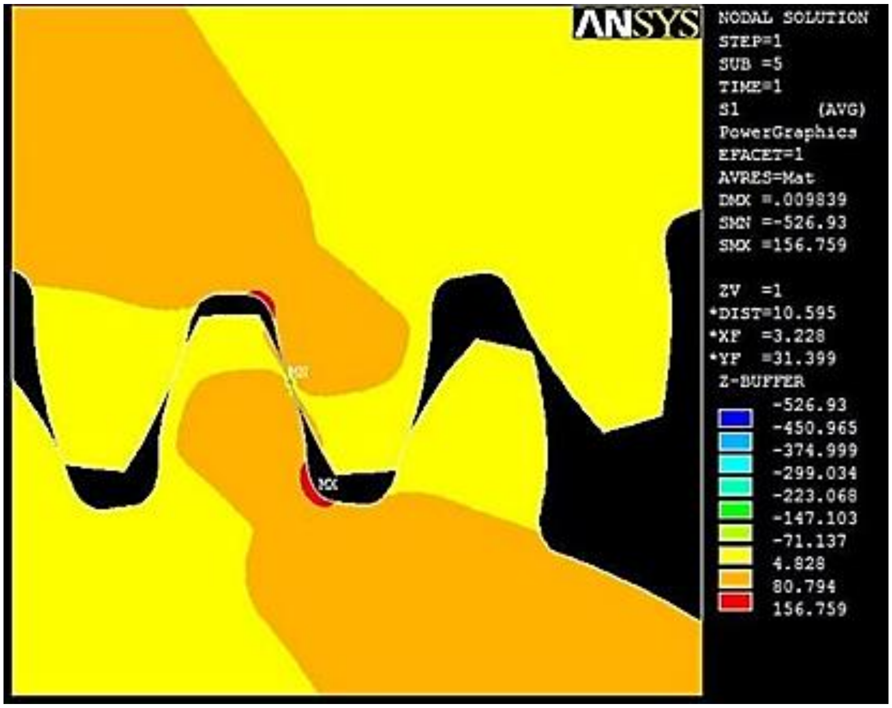

Figure 2. Bending stress of asymmetric spur gear.

3.2 Contact Stress

The observation that the maximum contact stress is obtained at the pitch point in the context of spur gears is a significant aspect of gear analysis. In the specific comparison discussed, the maximum contact stress for an asymmetric composite spur gear is measured at 764.460 MPa (Figure 3), which is notably lower than the corresponding contact stress of 896.727 MPa observed in a symmetric spur gear (Figure 4). This finding indicates that the asymmetric design contributes to a reduction in the maximum contact stress experienced by the gear teeth. The implications of this result are substantial and multifaceted. Contact stress is a critical parameter in gear design, influencing both the strength of the gear tooth and the propensity for pitting on the tooth profile. The reduction in maximum contact stress for the asymmetric composite spur gear suggests that its design, potentially involving variations in tooth profile or material distribution, contributes to a more favorable stress distribution at the pitch point. The connection between reducing contact stress and increasing the strength of the gear tooth is fundamental to gear design principles. Lower contact stress implies a reduced risk of material failure and improved resistance to wear, contributing to enhanced overall strength and durability of the gear tooth. Moreover, the correlation between reduced contact stress and minimized pitting on the tooth profile is crucial. Pitting, a form of surface fatigue, is often associated with high contact stresses and can lead to premature failure of the gear teeth. By mitigating contact stress, the asymmetric composite spur gear design offers a potential advantage in reducing the occurrence of pitting, thereby extending the operational life of the gear. Table 1 provides a comprehensive assessment of stress induced in symmetric and asymmetric spur gear. The comparison of maximum contact stress at the pitch point between asymmetric composite spur gears and symmetric spur gears highlights the advantageous stress characteristics of the asymmetric design. The lower contact stress in the asymmetric configuration not only contributes to increased strength of the gear tooth but also aligns with the goal of reducing pitting on the tooth profile. This result is integral to understanding how design variations can impact the mechanical performance and longevity of spur gears, providing valuable insights for gear designers and engineers.

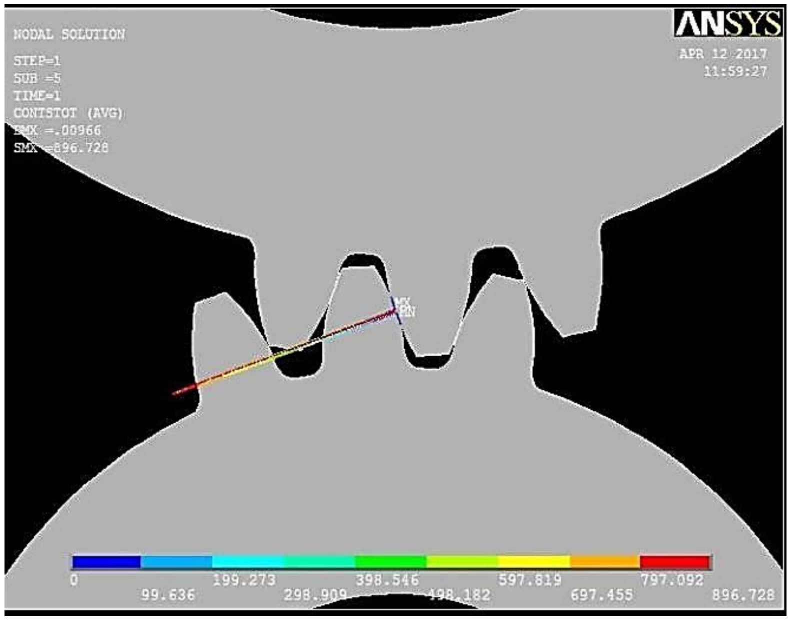

Figure 3. Contact stress of symmetric spur gear.

Figure 4. Contact stress of asymmetric spur gear.

Table 1. Comparison of stress induced in symmetric and asymmetric spur gear.

Type of gear	Material	Torque N-mm	Bending Stress N/mm^2	Contact Stress N/mm^2	Von Mises Stress N/mm^2
Symmetric spur gear	EN 24 Alloy Steel	59e3	156.759	896.727	523.342
Asymmetric spur gear	WC-Fe composite	59e3	132.211	764.460	460.508

3.3 von Mises Stress

The evaluation of von Mises stress is instrumental in determining the yield strength of a material, providing crucial insights into its ability to withstand deformation without permanent damage. In the specific comparison discussed, the von Mises stress analysis reveals that the maximum yield stress in an asymmetric composite gear is less than that produced in a symmetric spur gear. The induced von Mises stress in the asymmetric composite spur gear is measured at 460.508 MPa as per Figure 5, whereas the von Mises stress generated in the symmetric spur gear is higher, recorded at 523.342 MPa (Figure 6). The significance of this result lies in its implications for material behavior and structural integrity. Von Mises stress is a combined measure of the principal stresses and is particularly valuable in assessing complex loading conditions. The lower maximum yield stress observed in the asymmetric composite gear indicates that its design, possibly incorporating variations in material distribution or tooth profile, contributes to a more favorable stress distribution. Reducing the induced von Mises stress in the asymmetric composite spur gear is indicative of improved material performance and enhanced structural integrity. It suggests that the material in the asymmetric design is subjected to lower levels of stress, reducing the risk of yielding or permanent deformation. This is crucial for the longevity and reliability of gear systems, as lower von Mises stress implies a greater margin of safety against material failure. In connection with the given result, the lower maximum yield stress in the asymmetric composite gear aligns with the overarching theme of stress reduction observed in previous analyses, such as bending stress and contact stress. Collectively, these findings point towards the benefits of the asymmetric gear design in achieving a more favorable stress distribution across various critical points, contributing to increased strength, durability, and overall reliability of the gear system. In conclusion, the von Mises stress analysis provides valuable insights into the material behavior of asymmetric composite spur gears compared to symmetric spur gears. The lower maximum yield stress in the asymmetric design signifies a more robust and resilient material response, reinforcing the advantages of this design in terms of stress management and structural performance. This result contributes to a comprehensive understanding of how design variations impact the mechanical behavior of spur gears, providing essential information for engineers and designers in optimizing gear systems for enhanced performance and longevity.

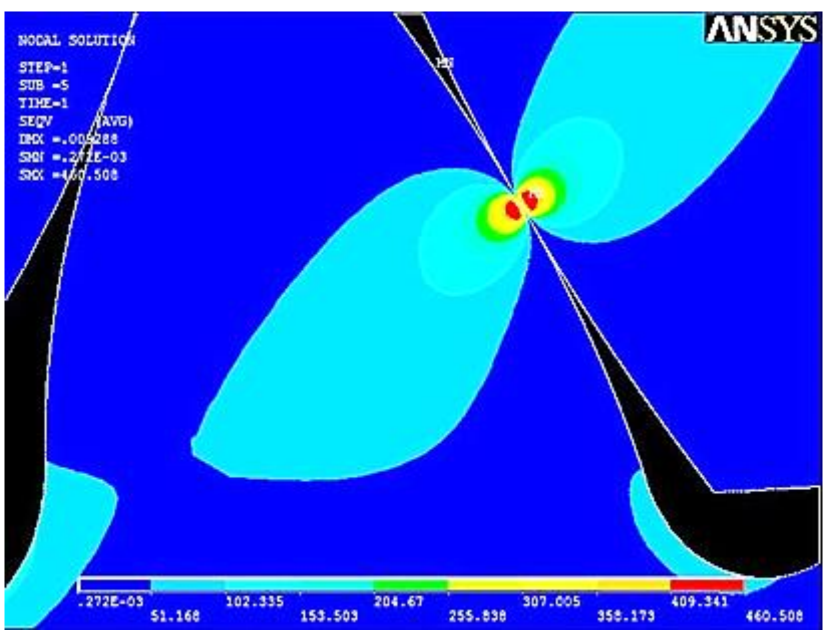

Figure 5. von Mises stress of asymmetric spur gear.

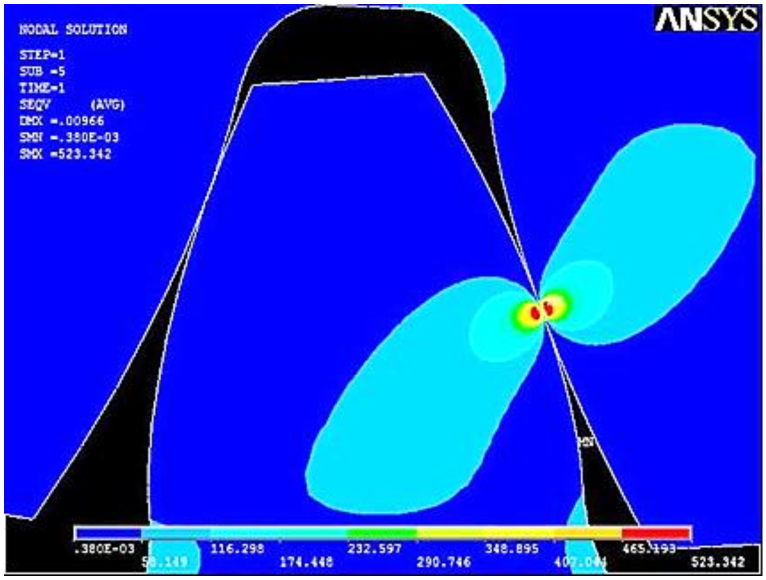

Figure 6. von Mises stress of symmetric spur gear.

4. Conclusion

The model has been designed for symmetric and asymmetric spur gear. The stress values obtained for the WC-Fe composite material is less compared to stress values of the EN 24 alloy steel material. The bending stress of asymmetric composite spur gear is 15% lesser than the conventional symmetric spur gear. The contact stress and the von Mises stress obtained for the asymmetric composite spur gear are 14.7% and 12% lesser than the conventional symmetric spur gear. Thus, the load carrying capacity is increased by using asymmetric composite spur gear.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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