International Research Journal of Education and Technology

Peer Reviewed Journal

ISSN 2581-7795

Static Structural Analysis of Spur Gear with Different Materials

Sanjay Amare, Prof. Ghanshyam Dhanera, Prof. Radheshyam Chherkee

M. E. Scholar Department of Mechanical Engineering, BM College of Technology, Indore (M.P.) India

N. Assistant Professor Department of Mechanical Engineering, BM College of Technology, Indore (M.P.) India

Department of Mechanical Engineering, BM College of Technology, Indore (M.P.) India

Abstract: This research focuses on the static analysis of a spur gear made from various materials. A spur gear with standard dimensions, supplied by a custom machine manufacturing company, was designed for the study. Four key properties—Von Mises stress, Cauchy stress, total deformation, and total strain—were analyzed using four materials: PLA, Ceramic ZrO2, Epoxy, and ABS. Static analysis results under a 1000 N load indicated that Ceramic ZrO2 was the most suitable material for the gear. Creo 3.0 software was used for modeling, while SimScale was employed for the analysis.

Key words: Spur gear, Creo 3.0, SimScale, material.

1. Introduction

Spur gears are the simplest type of gears and are primarily used to transmit rotary motion between parallel shafts. They are the preferred choice for most applications unless high speeds, heavy loads, or specific gear ratios necessitate alternative designs. Other gear types may be favored for quieter, low-vibration operations. Spur gears are straightforward in construction, easy to manufacture, cost-effective, and boast high efficiency and precision. They are widely employed in applications requiring high speed and load, such as in trains, clocks, household appliances, motorcycles, automobiles, railways, and aircraft. Additionally, they are commonly used in internal combustion engine gearboxes for producing small torques.

Gears often experience fluctuating loads, leading to the development of bending and compressive stresses. To ensure safe operation, it is crucial to analyze these stresses during gear design. Weight reduction is also a key consideration in gear design (Keerthi et al., 2016). In the present study, a spur gear was designed for a customized machine manufacturing firm in Ujjain (M.P.), based on the firm's specifications. The research investigated four properties—Von Mises stress, Cauchy stress, total deformation, and total strain—across four materials: PLA, Ceramic ZrO2, Epoxy, and ABS.

1.1 Objectives of the Research

Following are the objectives of present research work:

a) To evaluate the mechanical properties of gears fabricated from various materials.

b) To rank the gear materials based on their demonstrated properties.

2. Literature Review

Present section tells about the details of research contributions, and gaps in the literature,

2.1 Contributions of Researchers in the field of Spur Gears

Following points represent the survey of available literature in the field of spur gears.

- **Rahman (2024)**

The present research work discusses a method for modeling spur gears using parametric equations, which facilitates efficient design and optimization for static structural analysis. This approach is crucial for generating accurate CAD models that can be further analyzed using Finite Element Methods, thereby enhancing the reliability of structural assessments in gear design.

- **Chen (2024)**

The present research work discusses a novel punching forming process for spur gears, highlighting its advantages over traditional machining methods, which is crucial for understanding static structural analysis improvements in gear manufacturing. The study's finite element simulations and experimental validations provide insights into material behavior and process optimization, relevant for enhancing gear performance and longevity.

- **Yang (2023)**

The researcher discusses the impact of tooth tip modification on the mesh stiffness of spur gears, which is crucial for understanding static structural analysis. It highlights the relationship between mesh stiffness and gear performance, including noise and vibration, thus providing insights relevant to the static structural integrity of spur gears.

- **Czakó (2023)**

The research work discusses the static transmission error (STE) in spur gears, utilizing finite element analysis (FEM) to assess contact pressure and tooth root stress, highlighting the influence of shaft stiffness and boundary conditions on gear performance. This study contributes to the understanding of spur gear static structural analysis by comparing various gear types and providing insights into the effects of different loading conditions.

- **Rajesh et al. (2022)**

High contact ratio gears are used to minimize the stresses generated on the tooth surface. This research article represents an idea to enrich the contact strength of gear drive using novel high contact ratio spur gear.

- **Zeng et al. (2022)**

Focusing on the centrifugal force in high-speed working condition, this paper developed an analytical-FEM framework to integrate the centrifugal field into the mesh stiffness and nonlinear dynamics. The additional potential caused by centrifugal force is condensed in the mesh stiffness calculation. The gear torsion dynamic model is further extended to embody the internal dynamic effect in centrifugal field. Solutions of gear statics and dynamics are compared with existing models and experiments, and results demonstrate the reasonable accuracy of the present model.

- **Zhao et al. (2021)**

In present research work, considering the influence of roughness on the normal contact stiffness of gears, a fractal contact model suited for gear pair contact has been established.

- **Yilmaz et al. (2021)**

In this study, the effect of rim thickness of hybrid gears on the root stress, joint stress, tooth stiffness, natural frequency, and dynamic behavior are examined numerically.

- **Zheng et al. (2021)**

This study focuses on the wear performance of the gear generated by modified cutter. Numerical results show that the wear resistance can be enhanced through proper cutter modification.

- **Demet & Ersoyoğlu (2021)**

In this study, the fatigue performances of symmetrical and asymmetrical spur gears were analyzed by performing single tooth bending fatigue tests. The gears tested were determined to be symmetrical spur gears with a 20°/20° pressure angle, asymmetrical spur gears with a 20°/22° pressure angle, and asymmetrical spur gears with a 20°/25° pressure angle. It was observed that the formation of tooth flank damage negatively affected the fatigue performance.

- **Lin et al. (2021)**

In the present research work, distributed cumulative wear and wear at various test stages are quantitatively evaluated. The method is experimentally validated and agrees with the previous simulation.

- **Zhang et al. (2020)**

The use of 3D printing to manufacture nylon polymer gears is evaluated in this paper. More specifically, Nylon spur gears were 3D printed using Nylon 618, Nylon 645, alloy 910 filaments, together with Onyx and Markforged nylon proprietary materials, with wear rate tests performed on a custom-built gear wear test rig. The results showed that Nylon 618 provided the best wear performance among the 5 different 3D printing materials tested.

- **Pleguezuelos et al. (2020)**

This paper presents a study on the influence on the quasi-static transmission error of symmetric long profile modifications on high contact ratio spur gears.

- **Karpat et al. (2020)**

In this study, single tooth stiffness of involute spur gear was measured experimentally. A special test rig for this purpose was designed, and an experimental technique was proposed to investigate the effects of drive side pressure angle on the stiffness. The validation process of this study was performed using the finite element method. The experiments were repeated in ANSYS Workbench, and the elastic deformations were calculated. Experimental and numerical results were found to be generally consistent. Results showed that, the single tooth stiffness increase nearly 38% with the increase in drive side pressure angle from 20° to 35°. Single tooth stiffness of gear types manufactured by non-traditional methods, including additive manufacturing and forged bimetallic gears, can be investigated experimentally with this technique.

- **Chen et al. (2019)**

The complex gear foundation types and the crack propagation paths are considered in the proposed method, and the effects of various foundation types, crack propagation paths and crack lengths on the mesh stiffness are analyzed

- **Feng et al. (2019)**

Gear wear introduces geometric deviations in gear teeth and alters the load distribution across the tooth surface. Wear also increases the gear transmission error, generally resulting in increased vibration, noise and dynamic loads. This altered loading in turn promotes wear, forming a feedback loop between gear surface wear and vibration. Having the capability to monitor and predict the gear wear process would bring enormous benefits in cost and safety to a wide range of industries, but there are currently no reliable, effective and efficient tools to do so. This paper develops such tools using vibration-based methods.

- **Doğan & Karpat (2019)**

Gears are one of the most important power transmission elements in every area of the industry. Because of its importance, the gear design must be carefully performed. Unfortunately, due to the changing of the boundary conditions, gears are exposed to failures such as cracks, pitting, tooth missing etc. during the operation. Thus the gear diagnostic and monitoring become a very critical phenomenon for the gearboxes. A dynamic transmission error based numerical fault detection model is proposed.

- **Singh and Singh (2018)**

This study investigates the potential of three different thermoplastic materials viz. Acrylonitrile Butadiene Styrene (ABS), High Density Polyethylene and Polyoxymethylene to be used in plastic gearing applications.

- **Singh et al. (2018)**

This article presents a comprehensive review of the research on polymer spur gears operating under low (0–8 Nm) and moderate (>8 and ≤17 Nm) loading conditions. Different polymers and polymer composites used till date for the fabrication of such gears are included along with different operating conditions.

- **Diez-Ibarbia et al. (2018)**

In this proposal, the effect of the friction coefficient on the efficiency of spur gears with tip reliefs was analysed. For this purpose, the efficiency values using an average friction coefficient along the mesh cycle were compared with those obtained implementing an enhanced friction coefficient formulation, which is based on elastohydrodynamic lubrication fundamentals. In this manner, it can be established the differences between both formulations in the efficiency and friction coefficient values, as well as the advantages of using this enhanced friction coefficient with respect to formulations implemented in traditional approaches of efficiency calculation. In addition to studying the impact of the friction coefficient choice on efficiency, the profile modifications influence on the friction coefficient and efficiency was also assessed.

- **Simon *et al.* (2017)**

According to the researchers a very important feature of high quality gears is a low noise emission in all operating conditions. Micro-geometry of the gear is of relevance for the vibration excitation in the tooth contact and significantly affected by the manufacturing process, especially the finishing operations. Besides known process related effects, uncontrolled variations such as inaccuracies in the speed synchronization of different axes or vibrations influence the surface structure of the tooth flanks. In the research work a detailed simulation of the production process is presented, providing crucial information about characteristic process properties and enabling investigations on the impact of manufacturing process on gear mesh acoustics.

- **Dirk *et al.* (2017)**

Researchers tell that forming processes are generally characterized by a high degree of material utilization as well as short process times and, consequently, a decent economic efficiency. Considering their application in the manufacturing of large spur gears, forming processes offer a significantly attractive characteristic for the production of essential gearing components commonly used in wind turbines or marine engines. Furthermore, the hot forming process can be defined as an incremental forming process which enables the use of relatively low forming forces and results in a more compact design of the used machines. These conveniences are utilized in terms of roll forming with round tools to form gears and threads in a competitive way. Based on experiences gained over many years of researching rolling technologies, a cross-rolling process characterized by round tools with outer gearings was elaborated to realize a hot forming process for gear rolling of large spur gears at the Fraunhofer IWU Chemnitz. Based on the already researched forming of smaller dimensioned gears, rolling trials utilizing new hot-forming machinery - including defined inductive heating process before rolling - to realize large gears with outer diameters of up to 1000 millimeters were conducted. In terms of realizing this ambition, the derivation of the designated machine parameters for rolling large gears in real-life dimensions can be defined as a crucial factor. Consequently, the experimental research was followed by a mathematical analyzation of the forming forces, momentum as well as the necessary steps to determine the best possible scaling factors for the work pieces.

2.2 Gaps in the Literature

The survey of the available literature revealed the following gaps:
a) Limited research explores the use of different materials for gear modeling.
b) Limited research provides a ranking of materials used in gear manufacturing.

Based on these gaps, the objectives of the proposed research have been formulated.

3. Problem Identification and Problem Definition

Present section about problem identification and problem definition, the details of which are presented in upcoming sections.

3.1 Problem Identification

On the basis of investigated gaps in the research, it has been found that there is an utmost need of analysis of spur gear with different materials.

2.2 Problem Definition

For the present research work, a gear needed by a customized machine making firm was targeted, for which static structural analysis was requested by the firm, under a load, with four different materials, and four mechanical properties. On the basis of the requirements put by the firm, the research problem was defined as follows:

Static Structural Analysis of Spur Gear with Different Materials

4. Solution Methodology

Present section explains about different investigated properties in the research work as well as the details of software used for the purpose of modeling and simulation work.

3.1 Investigated properties in the Research Work

Following properties were investigated in the present research work

a) Von misses Stresses

Von Misses stress is a value used to determine if a given material will yield or fracture. It is mostly used for ductile materials, such as metals. The von Misses yield criterion states that if the von Misses stress of a material under load is equal or greater than the yield limit of the same material under simple tension then the material will yield.

b) Cauchy Stresses

Cauchy stress refers to the current configuration of the system, which means, it is a measure of force per unit area acting on a surface in the current configuration.

c) Total Deformation

It is the deformation in the body considering the deformations along all the axes.

d) Total Strain

It is defined as the summation to all the strains generated in the body, considering both the elastic and plastic stages.

3.2 Software used in the Research Work

The code used for the purpose of modeling was Creo 3.0, which is one of the renounced software in the field of modeling provided by PTC Corp, USA..

The software used for conducting static analysis was Simscale. Simscale SimScale is a computer-aided engineering (CAE) software product based on cloud computing. SimScale was developed by SimScale GmbH and allows computational fluid dynamics, finite element analysis and thermal simulations. The backend of the platform uses open source codes:

a) FEA: Code_Aster and CalculiX

b) CFD: OpenFOAM

The cloud-based platform of SimScale allows users to run more simulations, and in turn iterate more design changes, compared to traditional local computer-based systems.

5. Case Study

Present section tells about the details of model formulation and data needed for solving the research problem. The research work was based on the static analysis of a spur gear for a customized machine manufacturing firm in Ujjain (M.P.).

5.1 Model Formulation

As the first step of the research, the model of the gear was constructed in Creo software, with the help of dimensions of gear obtained from the firm, as follows:

a) Outside diameter of gear = 200 mm

b) No. of teeth (Z) = 12

c) Pitch circle diameter (PCD) = 178 mm

d) Base Circle diameter = 158 mm

e) Addendum = 11 mm

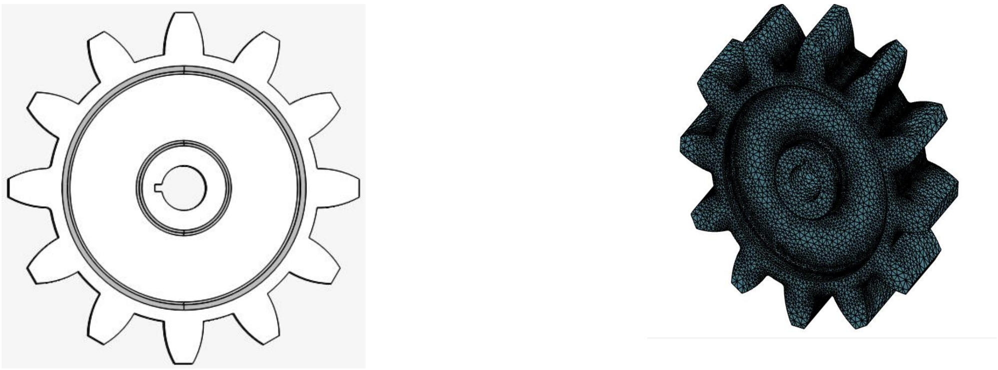
f) Deddendum = 14 mm

g) Deddendum circle diameter = 150 mm

h) Fillet Radius = 2.9 mm

i) Face Width = (b) = 50 mm

Figure 5.1 shows the mode of the spur gear.



(a) (b)

Figure 5.1: Model and Mesh of the Gear

5.2 Solution of the Model

As the first step of solving the model, meshed model of the targeted item was created in simscale software, the details of which are presented as follows:

Table 5.1: Details of Mesh

S. No	Entity	Details
1	Element type	Default
2	No. of nodes	86.2k
3	No. of cells	4263.2k

In next step, the meshed mode was solved using static analysis procedure in the simscale software. For this following boundary conditions were used, as desired by the firm:

- Load = 1000 N

- Boundary condition type: Surface load
- Support: Fixed at the Center.

For this purpose, following material properties were used for the materials, provided by the firm.

Table 5.2: Mechanical Properties of Materials

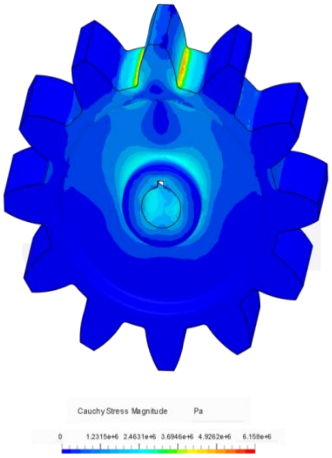
S. No	Mechanical Property	Unit	Materials			
			Epoxy	Ceramic ZrO_2	PLA	ABS
1.	Young's modulus	Pa	2.5e+9	2.1e+11	3.5e+9	1.8e+9
2.	Poisson's ratio	-	0.3	0.3	0.36	0.35
3.	Density	Kg/m^3	1400	6000	1250	1200

6. Results and Discussion

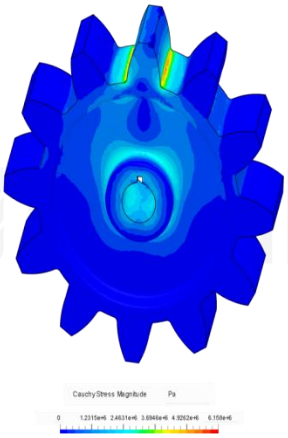
Present section tells about the details of results obtained and discussion made about the results obtained, the details of which are presented in upcoming sub-sections.

6.1 Results

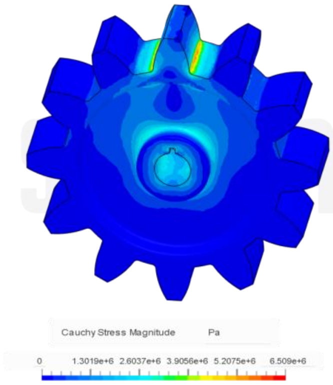
Figure 6.1 shows the results of Cauchy stresses for different materials.



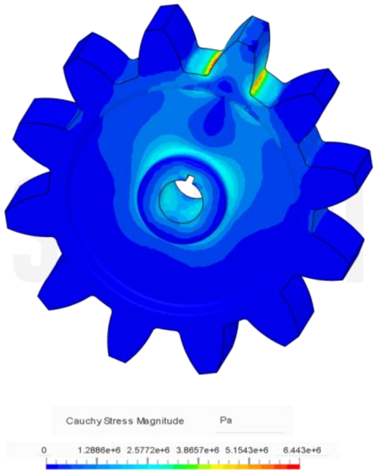
a) Epoxy



b) Ceramic ZrO_2



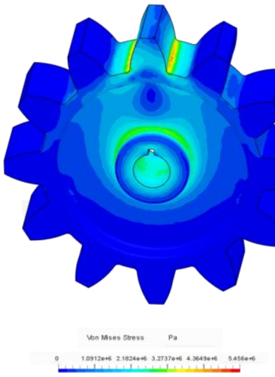
c) PLA



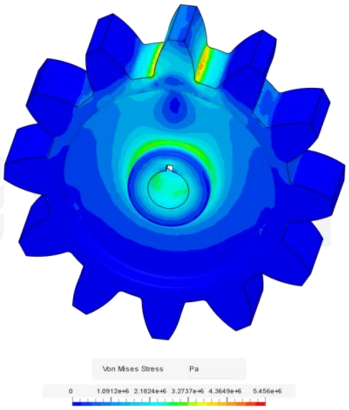
d) ABS

Figure 6.1: Results of Cauchy Stresses

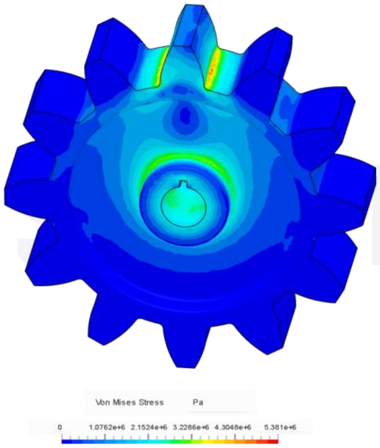
Figure 6.2 shows the results of Von misses stresses for different materials.



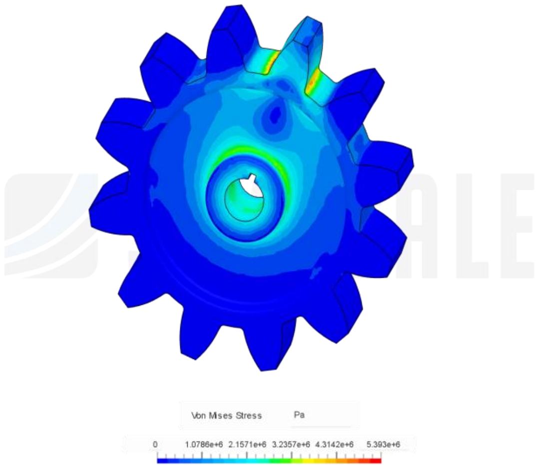
a) Epoxy



b) Ceramic ZrO_2



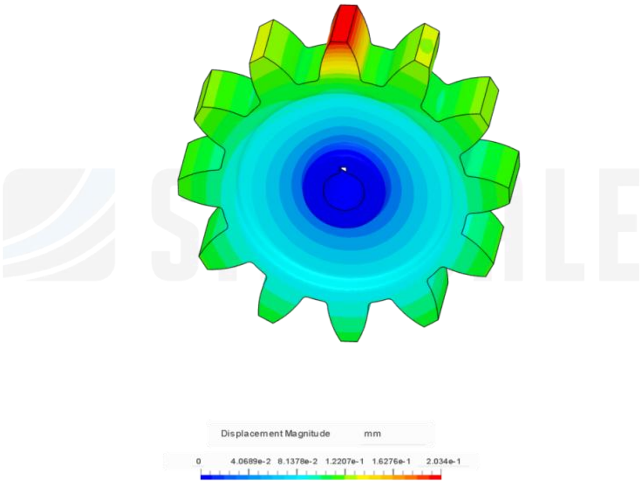
c) PLA



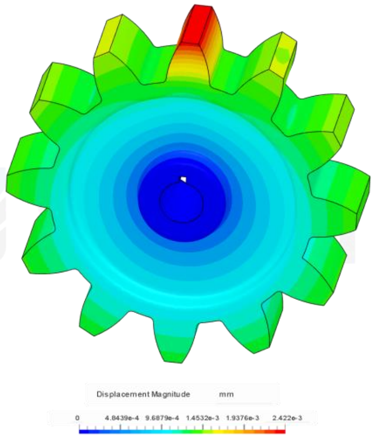
d) ABS

Figure 6.2: Results of Von Misses Stresses

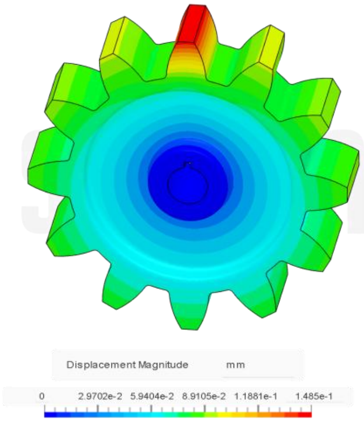
Figure 6.3 shows the results of displacement for different materials.



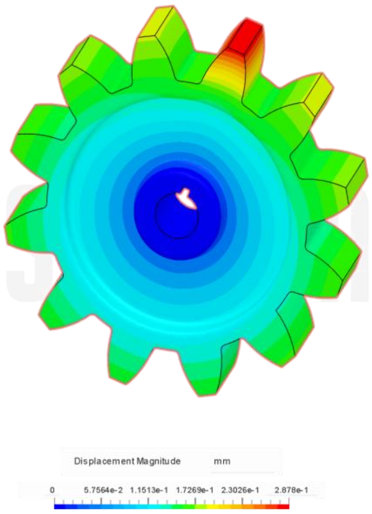
a) Epoxy



b) Ceramic ZrO_2



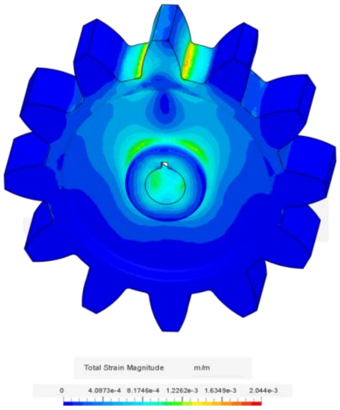
c) PLA



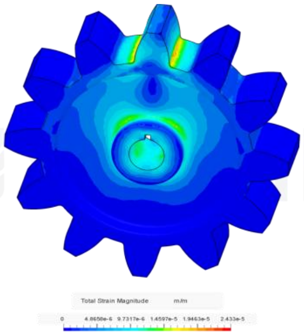
d) ABS

Figure 6.3: Results of Displacement

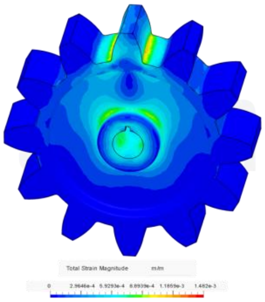
Figure 6.4 shows the results of total strain magnitude for different materials.



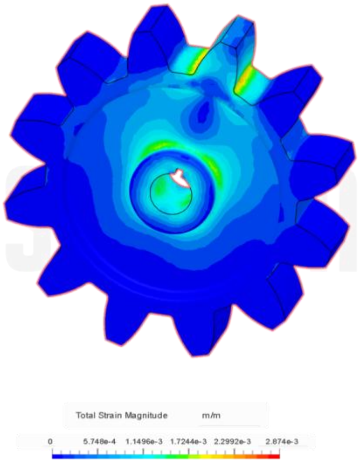
a) Epoxy



b) Ceramic ZrO_2



c) PLA



d) ABS

Figure 6.4: Results of Total Strain

Table 6.1 shows the summary of simulation results.

Table 6.1: Simulation Results of Materials

S. No	Materials	Investigated Properties			
		Cauchy Stress Magnitude (Pa)	**Von misses Stresses (Pa)**	**Displacement (mm)**	**Total Strain (m/m)**
1.	Epoxy	6.158e+6	5.456e+6	2.034e-1	2.044e-3
2.	Ceramic ZrO_2	6.158e+6	5.456e+6	2.422e-3	2.433e-5
3.	PLA	6.509e+6	5.381e+6	1.485e-1	1.482e-3
4.	ABS	6.443e+6	5.393e+6	2.878e-1	2.874e-3

6.2 Discussion

Figure 6.5 to Figure 6.6 shows the graphical representations of results.

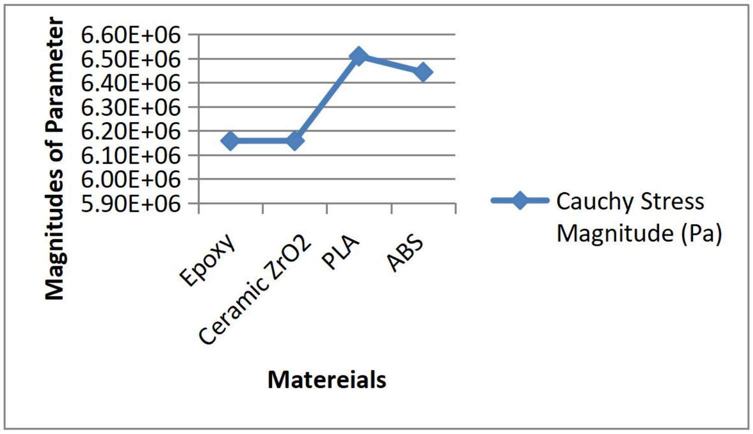


Figure 6.5: Cauchy Stresses of Materials

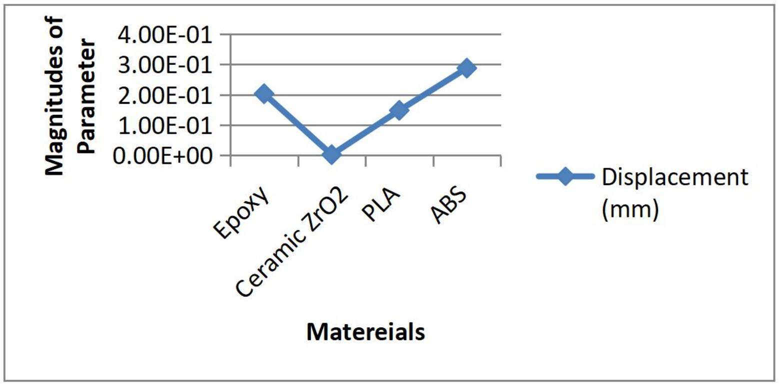


Figure 6.6: Displacement of Materials

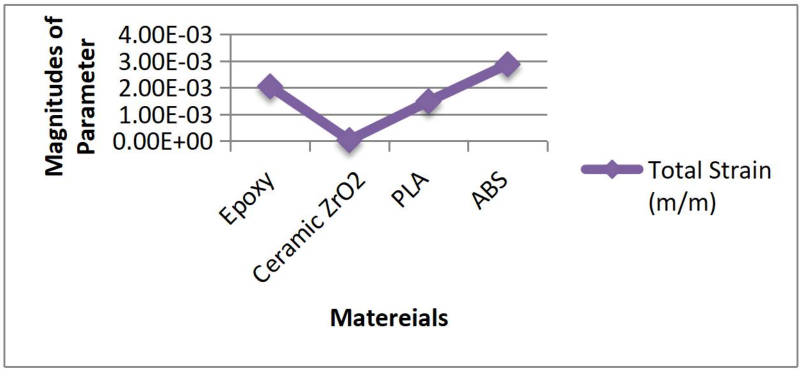


Figure 6.7: Total Strains of Materials

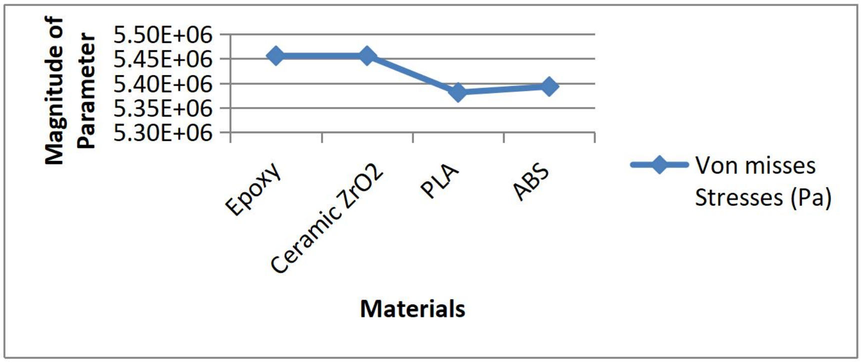


Figure 6.8: Von Misses Stresses of Materials

Table 6.2 shows the rankings of materials on different criteria.

Table 6.2: Rankings of Materials on Different Criteria

S. No	Materials	Cauchy Stress Magnitude (Pa)	Rank	Von mises Stresses (Pa)	Rank	Displacement (mm)	Rank	Total Strain (m/m)	Rank
1.	Epoxy	6.158e+6	1	5.456e+6	3	2.034e-1	3	2.044e-3	3
2.	Ceramic ZrO_2	6.158e+6	1	5.456e+6	3	2.422e-3	1	2.433e-5	1
3.	PLA	6.509e+6	3	5.381e+6	1	1.485e-1	2	1.482e-3	2
4.	ABS	6.443e+6	2	5.393e+6	2	2.878e-1	4	2.874e-3	4

Figures 6.5 to 6.8 as well as Table 6.2 present the overall picture of scores of materials on different criteria for the purpose of obtaining ranks. Both the table and figures show that for the criteria Cauchy Stress Magnitude, materials Epoxy and Ceramic ZrO_2 both score rank 1, with the score of 6.158e+6 Pa, whereas the materials ABS and PLA, acquire ranks 2 and 3with the scores 6.443e+6 Pa and 6.09e+6 Pa, respectively.

For the criteria, Von-mises stresses, material PLA shows the stress of 5.381e+6 Pa and appears at rank 1, whereas the materials ABS, Epoxy and Ceramic ZrO_2 show the stresses of 5.393e+6 Pa, 5.456e+6 Pa, and score the ranks 2 and 3, respectively.

For the displacement criteria, the material Ceramic ZrO_2 shows the strain value of 2.422e-3 mm and appears at rank 1, where the materials PLA, Epoxy and ABS score 1.485e-1mm, 2.034e-1 mm, and 2.878e-1mm, and obtain the ranks 2, 3, and 4, respectively.

For the criteria, total strain, material ZrO_2, again scores rank 1 with 2.433e-5 m/m, where as the materials, PLA, Epoxy and ABS obtain the ranks, 2, 3 and 4 with the total strain values of 1.482e-3 m/m, 2.044e-3 m/m, and 2.874e-3 m/m, respectively.

On the basis of above results one can find that the material Ceramic ZrO_2 scores rank 1, three times, which makes him eligible for the ranking. In the similar manners, material Epoxy scores rank 3, as it appears on this rank from three criteria. Proceeding further, it can be found that the material PLA scores rank 2 because it scores this rank two times plus rank 1, one time. Lastly, the material ABS may be placed at the rank 4, as it scores this rank two times and rank 2 two times. Table 6.3 shows the overall rankings of the materials.

Table 6.3: Overall Rankings of the Materials

S. No	Materials	Overall Ranking of Materials
1.	Epoxy	3
2.	Ceramic ZrO_2	1
3.	PLA	2
4.	ABS	4

7. Conclusion, Limitations and Future Scope of the Research

Present section tells about the conclusion, limitations and future scope of the research, the details of which are presented in upcoming sub sections.

7.1 Conclusion

Present research work is devoted to the selection of a gear material for the design of a machine, and involves four different types of materials, namely, ABS, ZrO_2 ceramic, Epoxy and PLA, and three mechanical properties, namely, Von misses stresses, total deformation and total equivalent strain. In order to select the best material for the application, static analysis was done on SimScale, and rankings of materials for different properties were investigated. Finally, overall rankings of materials were investigated. Following points represent the conclusion of the research work:

a) Material Ceramic ZrO_2 is considered as the best material for the application;
b) Material PLA is considered as the second best option;
c) Material Epoxy is considered as the third best option for the gear manufacture.

7.2 Limitations and Future Scope of the Research

Following points represent the limitations of the research

a) Present research work is based on limited number of materials
b) The research work is also limited by the number of properties investigated

Following points represent the future scope of the research

a) A detailed research work may be initiated considering a broader set of materials
b) An extensive research work, involving a greater set of properties, may also be called.

References

- Chen, K., Huangfu, Y., Ma, H., Xu, Z., Li, X., & Wen, B. (2019). Calculation of mesh stiffness of spur gears considering complex foundation types and crack propagation paths. *Mechanical Systems and Signal Processing*, *130*, 273-292.
- Chen, Z., Guo, Z., Fang, B., Gao, L., Su, G., & Liu, B. (2024). Simulation study of the punching forming process and die wear of spur gears. The International Journal of Advanced Manufacturing Technology, 131(9-10), 4635-4648. https://doi.org/10.1007/s00170-024-13297-1
- Czakó, A., Řehák, K., Prokop, A., Rekem, J., Láštic, D., & Trochta, M. (2023). Static transmission error measurement of various gear-shaft systems by finite element analysis.

Journal of Measurements in Engineering, 12(1), 183-198. https://doi.org/10.21595/jme.2023.23843

- Demet, S. M., & Ersoyoğlu, A. S. (2021). An analysis of the effect of pressure angle change on bending fatigue performance in asymmetrical spur gears. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, *235*(9), 2142-2150.
- Diez-Ibarbia, A., Fernandez-del-Rincon, A., De-Juan, A., Iglesias, M., Garcia, P., & Viadero, F. (2018). Frictional power losses on spur gears with tip reliefs. The friction coefficient role. *Mechanism and Machine Theory*, *121*, 15-27.
- Dirk Landgrebe, Andreas Sterzing, Mike Lahl, Matthias Milbrandt, Anne Manuela Taubert, Hot forming of large spur gears, Procedia Engineering, Volume 207, 2017, Pages 615-620.
- Doğan, O., & Karpat, F. (2019). Crack detection for spur gears with asymmetric teeth based on the dynamic transmission error. *Mechanism and Machine Theory*, *133*, 417-431.
- Feng, K., Borghesani, P., Smith, W. A., Randall, R. B., Chin, Z. Y., Ren, J., & Peng, Z. (2019). Vibration-based updating of wear prediction for spur gears. *Wear*, *426*, 1410-1415.
- Karpat, F., Yuce, C., & Doğan, O. (2020). Experimental measurement and numerical validation of single tooth stiffness for involute spur gears. *Measurement*, *150*, 107043.
- Lin, J., Teng, C., Bergstedt, E., Li, H., Shi, Z., & Olofsson, U. (2021). A quantitatively distributed wear-measurement method for spur gears during micro-pitting and pitting tests. *Tribology International*, *157*, 106839.
- Pleguezuelos, M., Sánchez, M. B., & Pedrero, J. I. (2020). Control of transmission error of high contact ratio spur gears with symmetric profile modifications. *Mechanism and Machine Theory*, *149*, 103839.
- Rahman, A. and Kumar, A. (2024). Geometry modeling of a spur gear using parametric equation &amp; global variables... https://doi.org/10.21203/rs.3.rs-4263821/v1
- Rajesh, S., Marimuthu, P., & Dinesh Babu, P. (2022). Optimization of contact stress for the high contact ratio spur gears achieved through novel hob cutter. Forschung im Ingenieurwesen, 1-9.
- Simon Kimme, Ruben Bauer, Welf-GuntramDrossel, Matthias Putz, Simulation of Error-

prone Continuous Generating Production Processes of Helical Gears and the Influence on the Vibration Excitation in Gear Mesh, Procedia CIRP, Volume 62, 2017, Pages 256-261.

- Singh, A. K., Siddhartha, & Singh, P. K. (2018). Polymer spur gears behaviors under different loading conditions: A review. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, *232*(2), 210-228.
- Singh, P. K., & Singh, A. K. (2018). An investigation on the thermal and wear behavior of polymer based spur gears. *Tribology International*, *118*, 264-272.
- Yang, H., Yang, D., Shi, W., & Xu, M. (2023). Nonlinear dynamic modeling and analysis of mesh stiffness of the spur gear pair considering tooth tip modification.. https://doi.org/10.21203/rs.3.rs-3437856/v1
- Yılmaz, T. G., Doğan, O., & Karpat, F. (2021). A numerical investigation on the hybrid spur gears: Stress and dynamic analysis. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 0954406220982007.
- Zhang, Y., Purssell, C., Mao, K., & Leigh, S. (2020). A physical investigation of wear and thermal characteristics of 3D printed nylon spur gears. *Tribology International*, *141*, 105953.
- Zhao, Z., Han, H., Wang, P., Ma, H., Zhang, S., & Yang, Y. (2021). An improved model for meshing characteristics analysis of spur gears considering fractal surface contact and friction. Mechanism and Machine Theory, 158, 104219.
- Zheng, F., Zhang, J., Yao, L., & Tan, R. (2021). Investigation on the wear of spur gears generated by modified cutter. *Friction*, *9*(2), 288-300.
- Zheng, X., Luo, W., Hu, Y., He, Z., & Wang, S. (2022). Study on the mesh stiffness and nonlinear dynamics accounting for centrifugal effect of high-speed spur gears. Mechanism and Machine Theory, 170, 104686.