Comparative analysis using finite element method for straight bevel gears made of Steel and PA 66

Análisis comparativo mediante elementos finitos para engranajes cónicos rectos para Acero y PA 66

DOI: https://dx.doi.org/10.17981/ingecuc.21.1.2025.15

Scientific Research Article

Date Received: 03/03/2022, Date Accepted:11/05/2022.

Luis Javier Fuentes-Martínez
Universidad de Córdoba. Montería, Colombia
lfuentesmartinez@correo.unicordoba.edu.co

Juan Ramon Hernández-Méndez
Universidad de Córdoba. Montería, Colombia
jhernandezmendez@correo.unicordoba.edu.co

Stiven Andrés Peralta-Jorge
Universidad de Córdoba. Montería, Colombia
speraltajorge95@correo.unicordoba.edu.co

Jesús David Rhenals-Julio
Universidad de Córdoba. Montería, Colombia
jesusrhenalsj@correo.unicordoba.edu.co

Miguel Ángel Lancheros-Montiel
Universidad de Córdoba. Montería, Colombia
miguellancherosm@correo.unicordoba.edu.co

Válery José Lancheros-Suárez
Universidad de Córdoba. Montería, Colombia
vlancheros@correo.unicordoba.edu.co

To cite this paper
L. Fuentes-Martínez, J. Hernández-Méndez, S. Peralta-Jorge, J. Rhenals-Julio, M. Lancheros-Montiel & V. Lancheros-Suárez "Comparative Analysis Using Finite Element Method for Straight Bevel Gears Made of Steel and PA 66," INGE CUC, vol. 21, no. 1, 206 - 2015. 2025. DOI: https://dx.doi.org/10.17981/ingecuc.21.1.2025.15

Resumen

Introducción: La búsqueda de materiales con un alto rendimiento en el uso de engranajes cónicos de dientes rectos, ha dado lugar a la implementación de materiales polímeros, los cuales brindan excelentes características dependiendo las condiciones de trabajo para las cuales se construye, reduciendo costos en cuanto a su fabricación, y que podrían brindar características que los aceros no pueden, como su baja densidad, tiempo de fabricación, entre otras.
Objetivo: Comparar el rendimiento de la implementación de PA66 en engranajes cónicos de dientes rectos en lugar de aceros como Acero AISI 1020.
Metodología: Se analizaron dos engranajes cónicos de dientes rectos con dimensiones idénticas, pero usando dos tipos de materiales, constituido por un acero y un polímero, con buenas propiedades teóricas para un buen desempeño en su funcionamiento. El análisis de los engranajes se realizó mediante el uso de elementos finitos (FEA) en ANSYS 2022 R1 student, para estudio de deformaciones, tensión elástica equivalente tensiones equivalentes y energía de deformación.
Resultados: Cuando los engranajes están construidos con PA 66. los valores de deformaciones son mayores en comparación a los del acero AISI 1020, esto se comprobó mediante las tensiones elásticas equivalentes, esfuerzos equivalentes y tensiones de equivalentes (Von mises). A consecuencia de eso el PA 66 posea mayor energía de tensión que el acero estudiado.
Conclusiones: Después de analizar los resultados obtenidos mediante la simulación de FEA mediante ANSYS R1 student, se pudo identificar que para condiciones de altas velocidades y altas temperaturas, es adecuado usar el engranajes en acero como AISI 1020, pero a condiciones de bajas y medias velocidades, se recomienda el uso de PA 66 por su bajo costo, son más silenciosos, y fácil de crear, además, se recomienda realizar un estudio térmico a los engranajes o revisiones de artículos con ese tema en relación, dado que un factor que afecta el rendimiento de los engranajes en especial de los polímeros es la temperatura, al igual, se puede realizar una investigación de polímeros compuestos cuyas propiedades mecánicas para el uso en engranajes estén mejoradas y comprar estos con los diseñados en aceros, en iguales condiciones y dimensionamiento.

Palabras clave: Engranajes; FEM; esfuerzos; deformaciones.

Abstract

Introduction: The search for high-performance materials in the use of straight bevel gears has led to the implementation of polymer materials, which offer excellent characteristics depending on the working conditions for which they are designed. These materials reduce manufacturing costs and can provide properties that steels cannot, such as low density, shorter manufacturing time, among others.
Objective: To compare the performance of PA66 in straight bevel gears against steels like AISI 1020 steel.
Methodology: Two straight bevel gears with identical dimensions were analyzed, using two types of materials: one made of steel and the other of polymer, both with theoretically good properties for optimal performance. The gear analysis was conducted using the finite element method (FEA) in ANSYS 2022 R1 Student Edition, focusing on deformation, equivalent elastic stress, equivalent stresses, and strain energy.
Results: When gears are made of PA66, deformation values are higher compared to those made of AISI 1020 steel. This was confirmed through equivalent elastic stresses, equivalent efforts, and Von Mises stresses. As a result, PA66 exhibits higher strain energy than the studied steel.
Conclusions: After analyzing the results obtained through FEA simulations in ANSYS R1 Student Edition, it was identified that for conditions of high speeds and temperatures, steel gears such as AISI 1020 are more suitable. However, for low to medium-speed conditions, PA66 is recommended due to its lower cost, quieter operation, and ease of manufacturing. Additionally, a thermal study on the gears or a review of related articles is recommended, as temperature significantly impacts gear performance, especially for polymers. Further research into composite polymers with enhanced mechanical properties for gear applications could also be conducted to compare them with steel gears under identical conditions and dimensions.

Keywords: Gears; FEM; Stress; Deformations

INTRODUCTION

Gears are motion transmission mechanisms that operate through the friction generated between toothed wheels, where the pinion is the smaller wheel. The ongoing development of polymers and the enhancement of their properties have brought significant changes to industry and engineering. Many metals have been replaced with polymers due to their lower cost and performance advantages. Notable among these changes is the creation of gears using various polymers tailored to meet specific needs, offering properties like self-lubrication, reduced noise, and lightweight design [1].

Given this, many designers seek viable alternatives for gear design. To this end, different simulations using polymers are conducted to evaluate their lifespan and surface temperature. Various materials, including bio-based PA 6.10, POM, and PA66, were analyzed and compared in terms of performance [2]. Additionally, working temperature is a critical factor for polymer gears. Exceeding the acceptable temperature can lead to gear failures, such as reduced polymer fatigue life, decreased mechanical properties, and changes in behavior, as increasing temperature significantly affects viscosity [2], [3].

Further analysis of polymer composite gears, such as those reinforced with carbon fiber and cured in an autoclave, revealed their performance and fatigue life [3]. Comparisons between POM-PA66 and POM-PA66 GF30 TF15 highlighted that load conditions have the most significant influence on gear life. In finite-life fatigue resistance, even small changes in load conditions can significantly impact the lifespan of observed polymer gear combinations. The use of composite polymers (e.g., glass fiber-reinforced PA66) ensures appropriate friction conditions, including PTFE and silicone lubricants [4]. Analysis shows that if gear use demands resistance to wear and temperature, PA66 is preferable [1], [4].

In straight bevel gears, material selection significantly influences design outcomes, especially regarding quality and cost. A major issue with lightweight load gears is their high transmission error. Theoretically, the transmission error of a design reaches its minimum value when combining these two errors leads to nonlinear phenomena related to tooth contact loss [5]. Additionally, the tooth height and width in these gears vary depending on the reference point, complicating force calculations compared to straight gears. Load distribution along the gear operation is also uneven, requiring finer meshing in finite element analysis [6].

Cracks in teeth can propagate in various scenarios, depending on factors such as material properties, microstructure, tooth geometry, crack geometry, load distribution, load magnitude, and loading rate. Tooth surface wear is a common failure mode, defined as the progressive material loss at contact surfaces due to rolling and sliding motions. This wear can increase transmission errors, power loss, noise levels, and vibration, ultimately affecting load distribution and contact stresses [7].

In terms of normal stresses, those generated in the pinion are higher in absolute value than those in the gear. Similarly, the pinion's normal deformations exceed those in the gear. Increasing loads raises normal deformations in the interacting teeth of the pinion and gear [8]. Contact stress is greater at the tooth tip and heel, making the tooth ends more prone to damage. In frequently operating straight bevel gear drives, misalignment errors are always present, directly affecting gear performance and transmission quality [9]. Moreover, increasing the driving gear's tooth count results in higher normal deformation when both toothed surfaces engage. Normal elastic stress is also directly proportional to the gear tooth count [10].

During machining, the material's internal stress near the gear cutting area is greater than in areas further away [11]. To achieve realistic results when predicting gear behavior, the finite element method (FEM) was implemented. FEM is a numerical analysis technique that offers approximate solutions to various engineering problems. Its versatility and flexibility make it an essential tool for designers in engineering and other fields. Analytical solutions provide mathematical expressions to calculate unknown quantities at any location in a body, valid for finite points. For problems involving complex material properties and boundary conditions, FEM proves more accurate in identifying critical sections [3].

FEM also benefits thermal analysis, providing data across the mesh region at different temperatures throughout the gear. It demonstrates higher accuracy in temperature variations compared to the Hu and Sun methods [13]. However, fault detection for asymmetric tooth profiles is more challenging than for symmetric profiles due to smaller variations in mesh stiffness over time, leading to minor changes in dynamic transmission error and indicators [14].

METHODOLOGY

The primary objective of this article is to establish comparison guidelines for straight bevel gears by analyzing two different materials: AISI 1020 steel and PA66. For this purpose, the Finite Element Method (FEM) was employed using ANSYS 2022 R1. This software combines the power of advanced simulation tools with project management functionalities. ANSYS is a structural analysis software designed to efficiently solve complex engineering problems. Its FEM analysis tools provide the capability to simulate all structural aspects of a product [15].

Steps for Simulation in ANSYS 2022 R1

The ANSYS R1 Student software was accessed, and a structural analysis tool was selected. Subsequently, the piece was imported into the software from SolidWorks.

The material type corresponding to the gears was defined.

In the structural analysis, the option to edit the mesh was selected. The material data for the simulation was entered, assembly constraints were added, and a torsional force was applied to the pinion.

The mesh and its respective refinement for tooth contact in the gears were created. The mesh essentially divides the entire model into small cells, where equations are solved in each cell, providing the most accurate solution and improving its quality [16].

The following parameters were used for meshing:

Show	
Display Style	Use geometry settings
Display Style	Default values
Default values	
Physics Preference	Mechanical
Element Order	Program controlled
Element Size	0.465 mm
Sizing	
Use adaptive size	Yes
Resolution	Default (2)
Mesh defeat	Yes
Feature size	Default
Span angle center	Coarse
Bounding box diagonal	59.841 mm
Average surface area	9.6934 mm^2
Sizing	
Target element quality	Default (5.e-002)
Smoothing	High
Mesh metric	None
Inflation	
Refinement	
Scope	
Scope method	Geometry selection
Geometry	4 faces
Geometry	
Geometry Suppressed	No
Refinement	2

Finally, the simulation was carried out in the software, and the generated calculations were saved in PDF format, while the images were saved in PNG format.

Materials

The materials used for the gears were AISI 1020 steel and PA66, both of which are widely used in engineering. The properties of these materials are described in Table 1.

TABLE 1. MECHANICAL PROPERTIES

Property	AISI 1020 Steel	PA66	Units
Mass density	7.85E-06	1.14E-06	kg/m³
Bulk modulus	1.67E+05	3000	MPa
Shear modulus	76923	574.47	MPa
Thermal expansion coefficient	1.20E-05	0.00013	1/°C
Poisson‘s ratio	0.3	0.41	
Young‘s modulus	2.00E+05	1620	MPa

Fuente: Ansys for Students 2022 R2

For the simulation of the gear in ANSYS R1 Student Edition, the same data was used, differing only in the materials.

TABLE 2. GEAR DATA

DATA	
Pinion Gear	12 teeth
Wheel Gear	30 teeth
Module	1 mm
Pinion Diameter	12 mm
Wheel Diameter	30 mm
Cone Distance	16.1554944 mm

In Fig. 1, a high-quality mesh was used, with mesh refinement applied to the contact surface contours of the gear teeth. This meshing was applied to both types of gear materials.

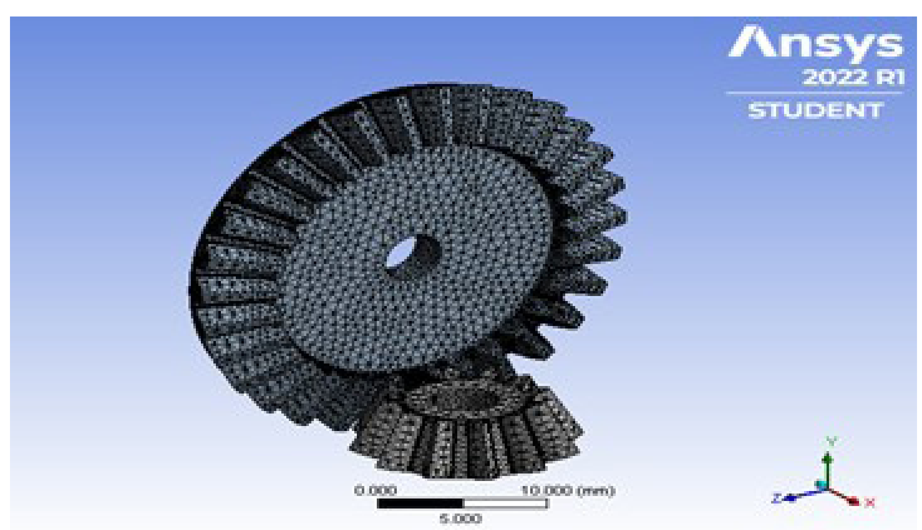


Fig 1. Mesh creation

In Fig. 2, the mesh refinement applied to the gear tooth contours is shown, ensuring more accurate data collection during the interaction between the teeth.

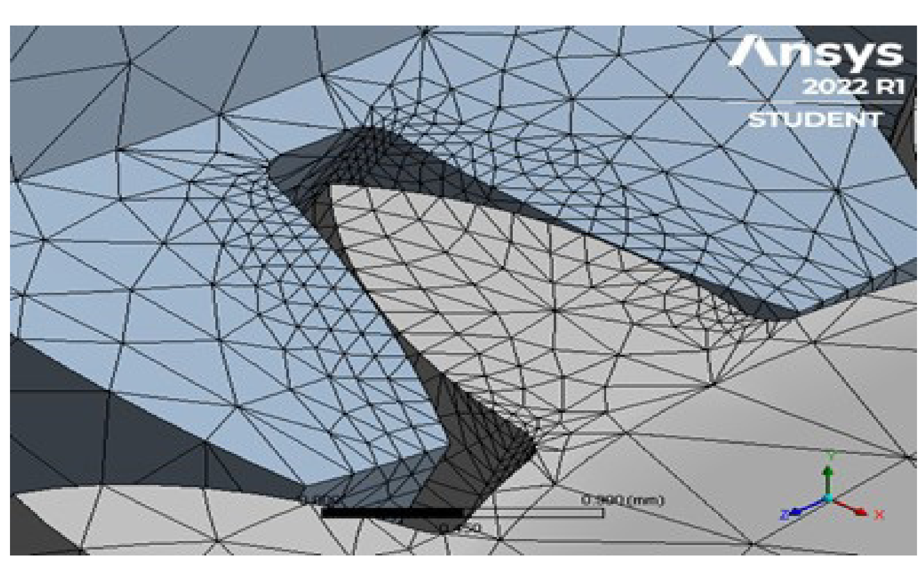


Fig 2. Mesh refinement in contact areas of the gear teeth

For the pinion rotation simulation, a torque of 1 N/mm was applied to the pinion. This parameter was used for both AISI 1020 steel and PA66 gears.

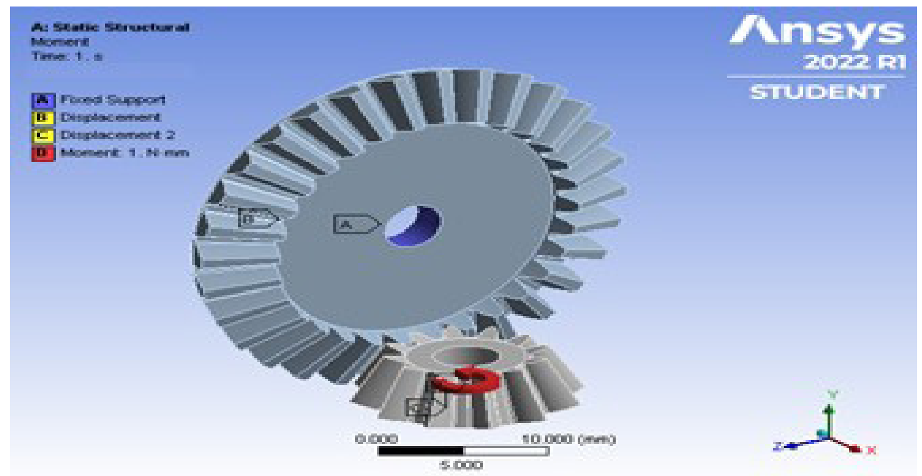


Fig 3. Respective loads on the gear

RESULTS AND DISCUSSIONS

Results

Through the gear simulation for different materials under identical stress and dimensional conditions, the results obtained were consistent with theoretical expectations. These include analyses of deformation, equivalent elastic deformation, deformation energy, and equivalent stress (Von Mises), as shown in Figs. 4, 6, 8, and 10.

Meanwhile, Figs. 5, 7, 9, and 11 provide a closer view of the contact area between the teeth in the analyses mentioned above.

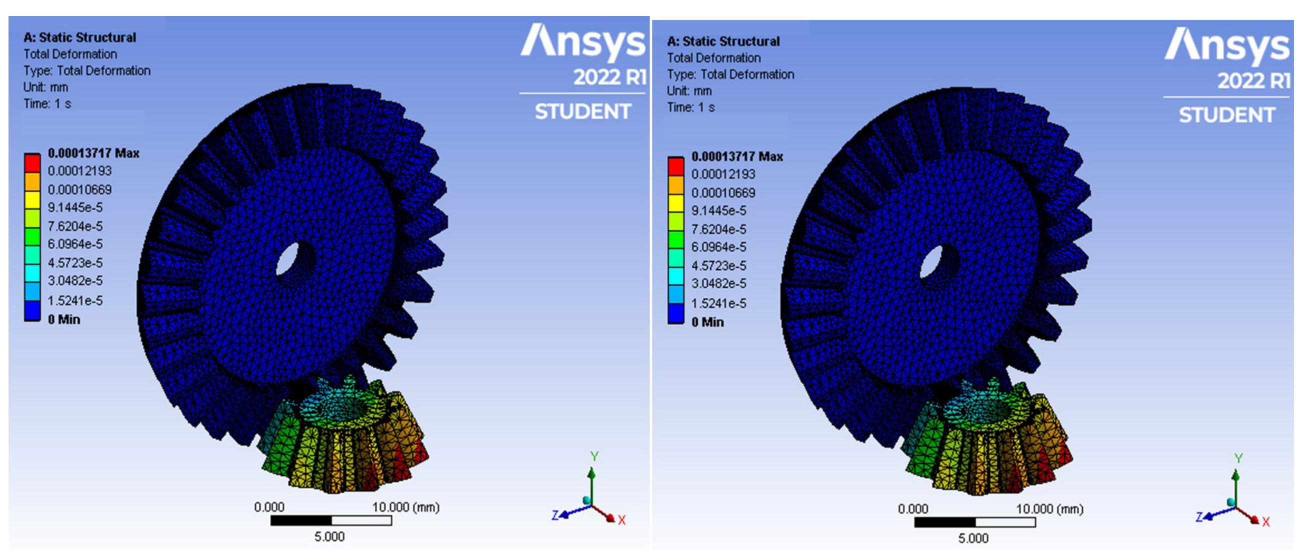


Fig 4. Total deformations, a) AISI 1020 steel, b) PA66

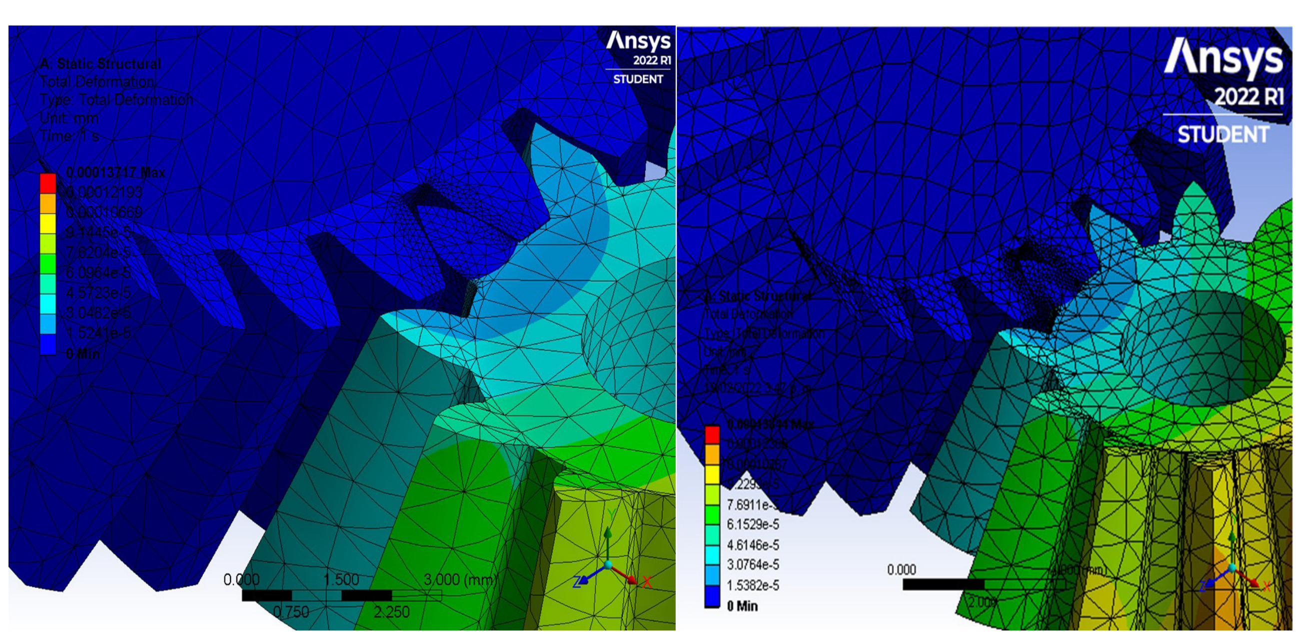


Fig 5. Deformations in the contact area of the gear teeth, a) AISI 1020 steel, b) PA66

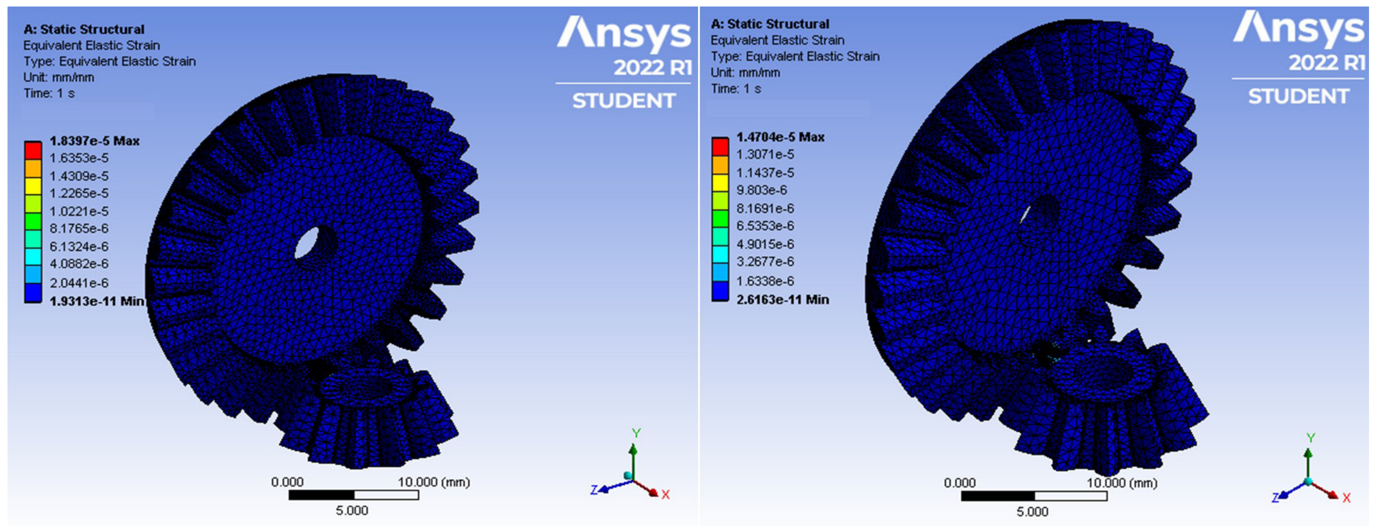


Fig 6. Equivalent elastic deformation, a) AISI 1020 steel, b) PA66

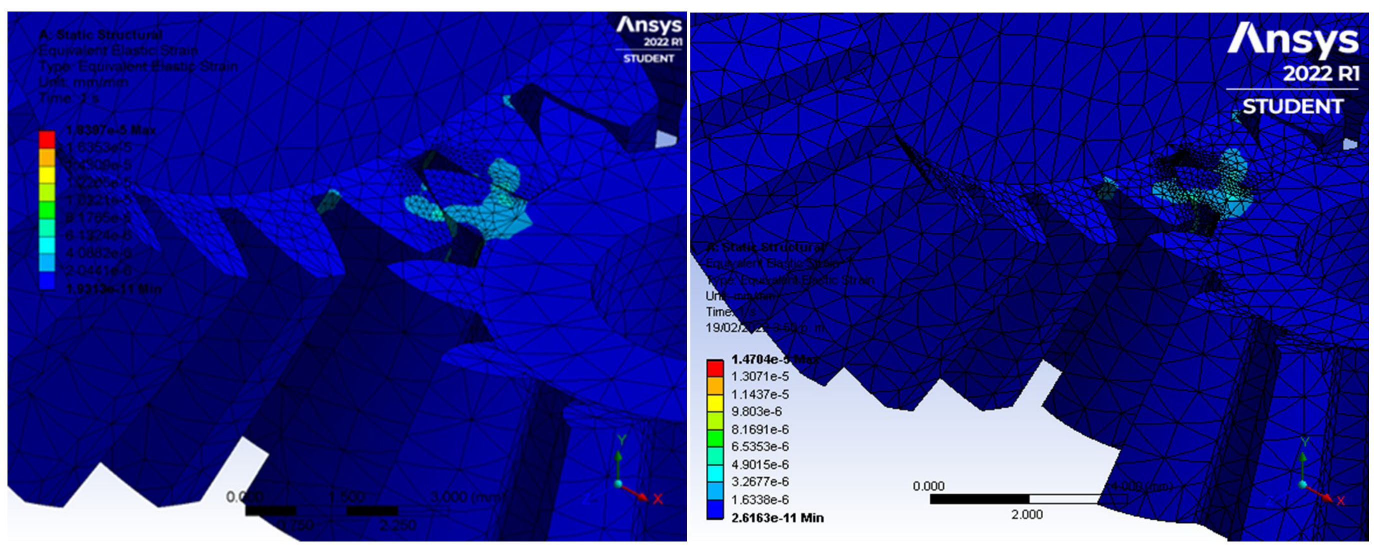


Fig 7. Equivalent elastic deformation in the contact area of the gear teeth, a) AISI 1020 steel, b) PA66

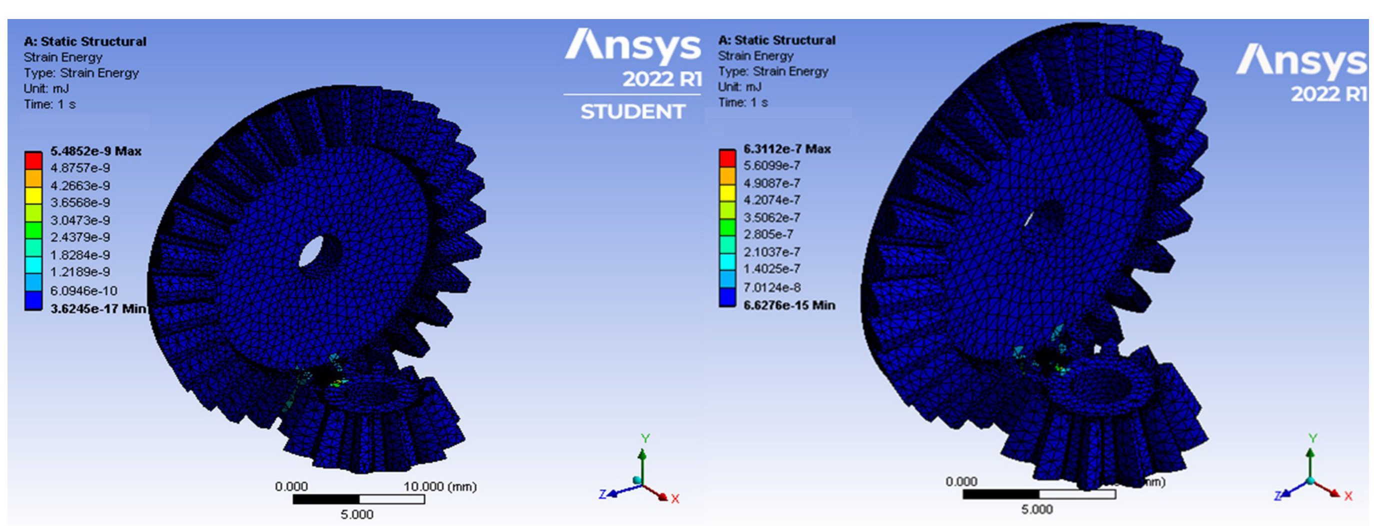


Fig 8. Strain energy, a) AISI 1020 steel, b) PA66

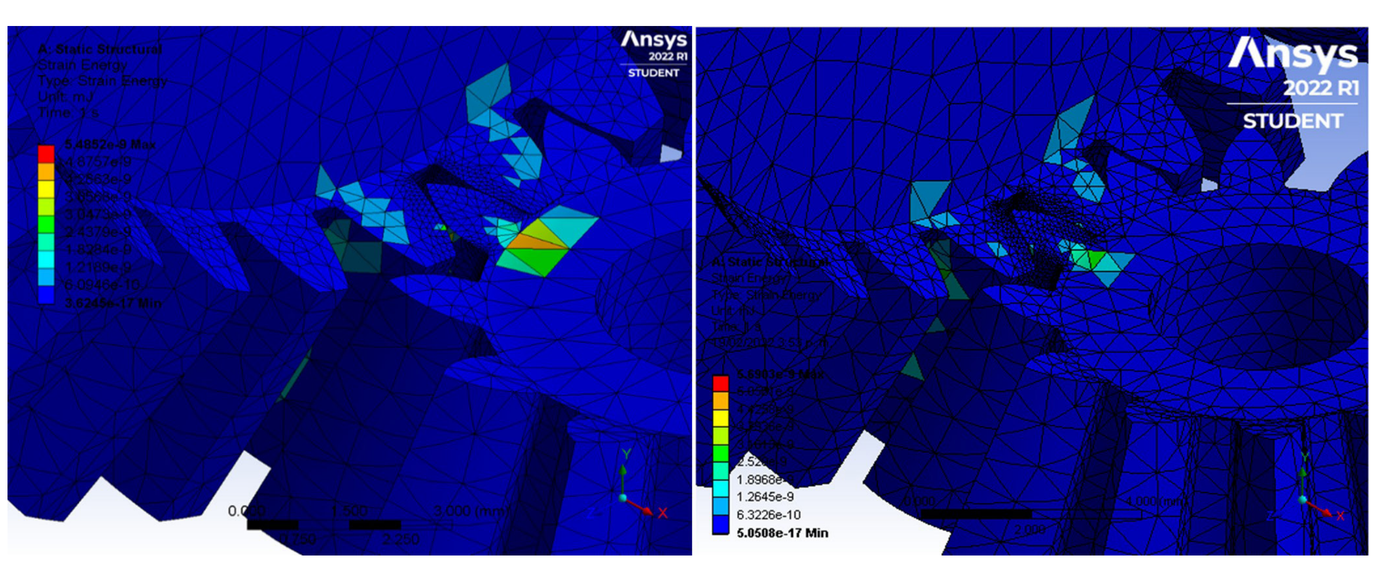


Fig 9. Strain energy in the contact area of the gearteeth, a) AISI 1020 steel, b) PA66

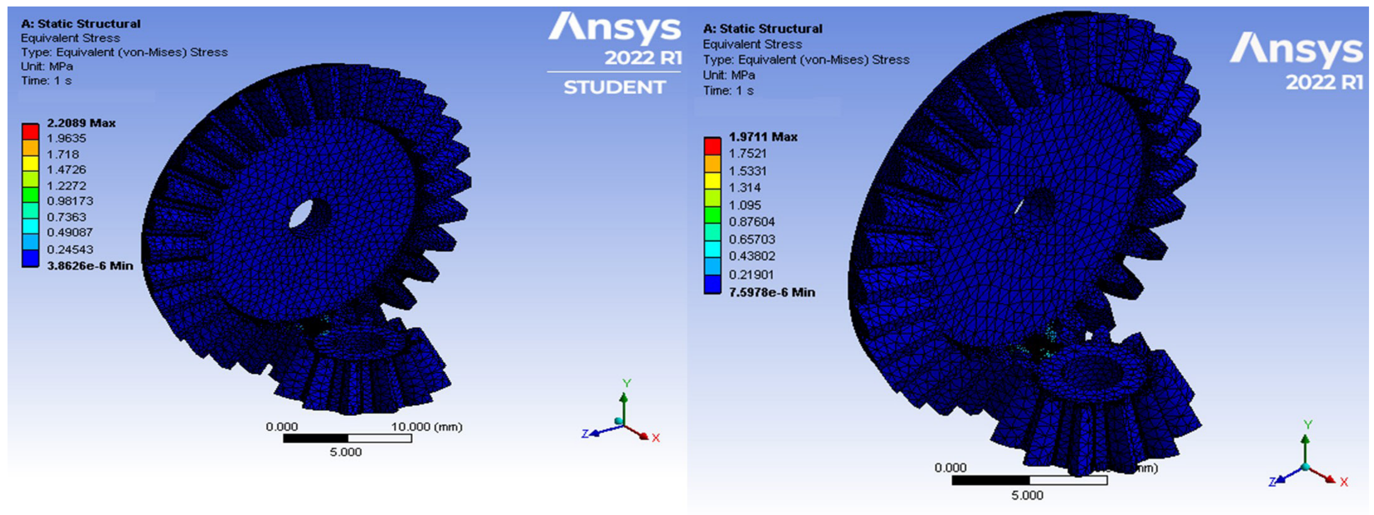


Fig 10. Equivalent stress (Von Mises), a) AISI 1020 steel, b) PA66

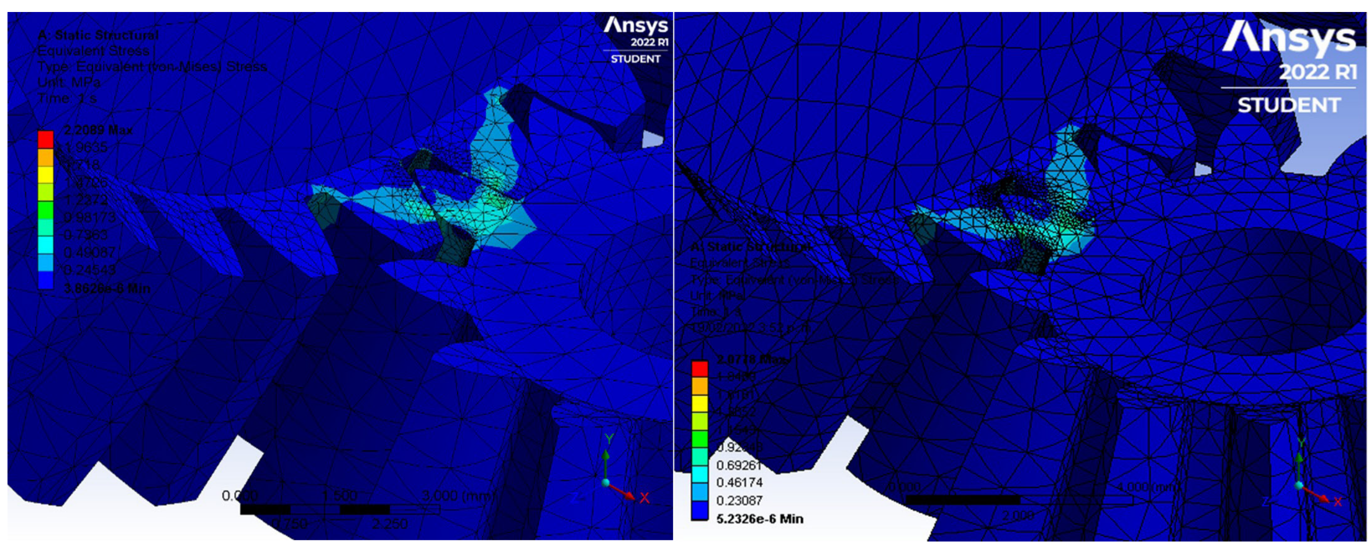


Fig 11. Equivalent stress (Von Mises) in the contact area of the gear teeth, a) AISI 1020 steel, b) PA66

In Table 3, a summary of the maximum values obtained during the structural analysis of AISI 1020 steel and PA66 is presented.

TABLE 3. STRUCTURAL ANALYSIS RESULTS

Maximums	PA66	AISI 1020	Units
Total Deformations	0.016648	0.00013717	mm
Equivalent Elastic Strain	0.0016672	0.000018397	mm/mm
Equivalent Stress	1.9711	2.2089	MPa
Deformation Energy	6.311E-07	5.4852E-09	mJ

Using the data from Table 3, four diagrams were created to more clearly illustrate the differences in structural performance.

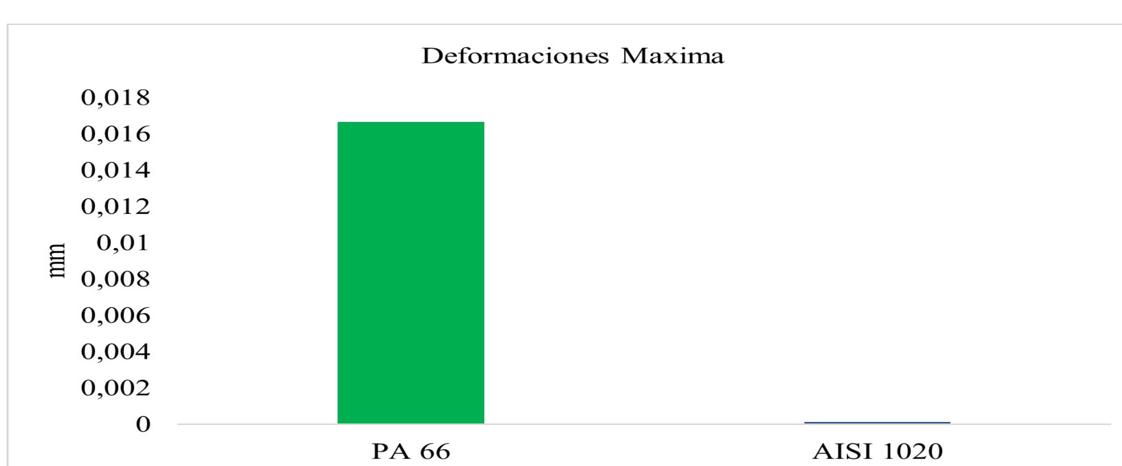
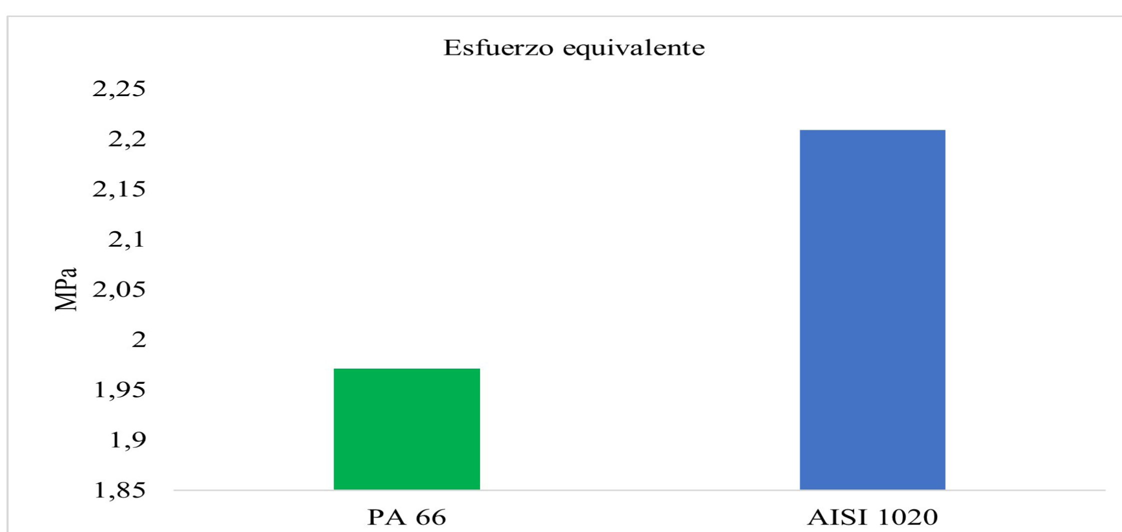


Fig9. Comparison of maximum deformation

Fig 10. Comparison of maximum stress.

Fig 11. Maximum strain energy.

Fig. 12. Comparison of maximum equivalent stress (von Mises).



Discussions

As observed in Fig. 4 and Fig. 5, due to the plastic zone exhibited by these materials, PA66, being a thermoplastic, has relatively low deformation resistance compared to AISI 1020 steel. This leads to significantly higher deformations in PA66, as shown more clearly in Fig. 9, where the maximum deformation for steel is 0.00013717 mm, while for PA66, it is 0.016648 mm. Under the specified working conditions, AISI 1020 steel is undoubtedly more suitable for applications requiring minimal deformation.

From Fig. 6 and Fig. 7, it can be noted that the Young's modulus of PA66 is much lower than that of AISI 1020 steel. This results in much larger unit deformations for PA66 compared to steel. Furthermore, the stiffness modulus of PA66 is significantly lower, leading to greater deformations before reaching the material's breaking point, as seen in Fig. 10.

As shown in Fig. 8 and Fig. 9, polymers have a larger plastic zone than steels. In this particular case, when a torsion is applied to gears made of AISI 1020 steel and PA66, the steel accumulates more internal energy from external forces (torsion). These maximum deformations are illustrated in Fig. 11, where the deformation energy for PA66 is 6.311E-07 mJ, while for steel it is 5.4852E-09 mJ.

From Fig. 10 and Fig. 11, it is evident that steel, specifically AISI 1020, has greater resistance to shear stresses. This is due to the forces interacting with the teeth of the straight bevel gear, resulting in higher yield stress for steel, as shown in Fig. 12, where the maximum stress for AISI 1020 steel is 1.9711 MPa, while for PA66, it is 2.2089 MPa.

Based on the FEA simulation, PA66 is not a suitable material for tasks requiring high stress under working conditions (high operating speeds), such as those for gears made from AISI 1020 steel.

CONCLUSIONS

For total deformations, it is observed that in both graphs, the minimum value is found in areas where displacement is caused by contact between the tooth surfaces, remaining within the displacement limit range. However, in the external areas of the pinion teeth, critical zones are identified that could result in irreversible damage to the design.

From the structural analysis comparisons, it can be confirmed that PA66 gears have a significant disadvantage in terms of stress resistance compared to AISI 1020 steel gears. However, the cost of the latter is much higher than that of gears made with PA66. Additionally, PA66 gears are easier to manufacture thanks to 3D printing, have lower inertia, are resistant to many corrosive environments, are quieter, and often require little to no lubrication compared to AISI 1020 steel gears.

Nonetheless, it is recommended for future work to conduct thermodynamic analyses on these gears, as polymers are significantly affected by working temperature. Furthermore, comparative analyses between AISI 1020 steel and other materials commonly used in the industry with composite polymers could be conducted, as their mechanical properties have been improved to meet more rigorous stress parameters.

It is also important to note that the study of straight bevel gears has been less explored compared to other types of gears, such as helical bevel gears. This is due to their decreased application, as they require more specific conditions for implementation. Consequently, articles related to these gears are scarce and often too outdated to be used as references.

Based on the above, it is not recommended for designers to use PA66 instead of AISI 1020 steel for high-stress gear applications (high speeds). However, for low to medium-speed applications, polymers like PA66 are recommended, An example includes pinions for concrete mixer drums.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

V. Lancheros-Suárez: Conceptualization, Methodology, Fund Acquisition. M. Lancheros-Montiel: Validation, Supervision, Writing - Revision and Editing. J. Rhenals-Julio: Research, Software (ANSYS), Formal Analysis, Writing - Original Draft. L. Fuentes-Martínez: Research, Data Curation, Formal Analysis, Visualization, Software (ANSYS). J. Hernández-Méndez: Data Curation, Visualization, Validation, Writing - Review and Editing. S. Peralta-Jorge: Software (ANSYS), Formal Analysis, Writing - Original Draft.

FUNDING

This research was funded by the University of Córdoba (Colombia) through the SIMEC research group. The research was supported and advised by engineers from the Department of Mechanical Engineering, University of Córdoba.

ACKNOWLEDGMENTS

The authors extend their gratitude to the University of Córdoba, Montería campus, for funding this project.

REFERENCES

[1] M. Jain and S. Patil, “Comparative analysis of surface characteristics of Nylon based polymer gears manufactured by different techniques,” *Materials Today: Proceedings*, Feb. 2022, doi: 10.1016/j.matpr.2022.02.050.

[2] D. Zorko, I. Demšar, and J. Tavčar, "An investigation on the potential of bio-based polymers for use in polymer gear transmissions," *Polymer Testing*, vol. 93, Jan. 2021, doi: 10.1016/j.polymertesting.2020.106994.

[3] D. Zorko, J. Tavčar, M. Bizjak, R. Šturm, and Z. Bergant, "High cycle fatigue behaviour of autoclave-cured woven carbon fibre-reinforced polymer composite gears," *Polymer Testing*, vol. 102, Oct. 2021, doi: 10.1016/j.polymertesting.2021.107339.

[4] M. Hriberšek and S. Kulovec, "Study of the glass fibres and internal lubricants influence in a polyamide 66 matrix on the wear evolution of polyacetal and polyamide 66 based gears in a meshing process," *Engineering Failure Analysis*, vol. 134, p. 106071, Apr. 2022, doi: 10.1016/j.engfailanal.2022.106071.

[5] M. Buzzoni, G. D'Elia, E. Mucchi, and G. Dalpiaz, "A vibration-based method for contact pattern assessment in straight bevel gears," *Mechanical Systems and Signal Processing*, vol. 120, pp. 693–707, Apr. 2019, doi: 10.1016/j.ymssp.2018.10.002.

[6] X.-F. Gou, G.-Y. Li, and L.-Y. Zhu, "Dynamic characteristics of a straight bevel gear drive system considering multi-state meshing and time-varying parameters," *Mechanism and Machine Theory*, vol. 171, p. 104779, 2022, doi: https://doi.org/10.1016/j.mechmachtheory.2022.104779.

[7] O. D. Mohammed and M. Rantatalo, "Gear fault models and dynamics-based modelling for gear fault detection – A review," *Engineering Failure Analysis*, vol. 117. Elsevier Ltd, Nov. 01, 2020. doi: 10.1016/j.engfailanal.2020.104798.

[8] S. Bodzás, "Computer-aided design and loaded tooth contact analyses of bevel gear pair having straight teeth by different loaded torques," *Mechanics and Industry*, vol. 21, no. 1, 2020, doi: 10.1051/meca/2019076.

[9] M. Chen, X. Xiong, and W. Zhuang, "Design and simulation of meshing performance of modified straight bevel gears," *Metals*, vol. 11, no. 1, pp. 1–22, Jan. 2021, doi: 10.3390/met11010033.

[10] S. Bodzás, "Tooth contact analysis of straight bevel gears in the function of the modification of number of teeth of the driving gear," *Australian Journal of Mechanical Engineering*, 2019, doi: 10.1080/14484846.2019.1654964.

[11] B. Wang et al., "Residual stress and deformation analysis in machining split straight bevel gears," *Strojniski Vestnik/Journal of Mechanical Engineering*, vol. 67, no. 3, pp. 114–122, 2021, doi: 10.5545/sv-jme.2020.7064.

[12] M. Phyoe Thu and N. Lin Min, "Stress Analysis on Spur Gears Using ANSYS Workbench 16.0," 2018. [Online]. Available: www.ijsea.com208

[13] Z. Sun, S. Chen, Z. Hu, X. Tao, and Y. Chen, "Analytical models for thermal deformation and mesh stiffness of spur gears under steady temperature field," *Engineering Failure Analysis*, vol. 133, Mar. 2022, doi: 10.1016/j.engfailanal.2021.105972.

[14] O. Doğan and F. Karpat, "Crack detection for spur gears with asymmetric teeth based on the dynamic transmission error," *Mechanism and Machine Theory*, vol. 133, pp. 417–431, Mar. 2019, doi: 10.1016/j.mechmachtheory.2018.11.026.

[15] A. Justin, A. Prince, A. S. Reddy, K. Nagateja, and B. Tech, "Design and Analysis of A Spur Gear with Composite Material Nagineni Nikhil Chowdary." [Online]. Available: www.ijert.org

[16] S. Ghosh, R. Ghosh, B. Patel, T. Srivastava, and R. Nath Barman, "Article ID: IJMET_07_06_015 Rabindra Nath Barman, Structural Analysis of Spur Gear Using Ansys Workbench 14.5," *International Journal of Mechanical Engineering and Technology*, vol. 7, no. 6, pp. 132–141, [Online]. Available: http://www.iaeme.com/IJMET/index.asp132http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=7&IType=6JournalImpactFactor