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Optimizing Weight in Gear Wheels with Different Filling Geometries

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Abstract: Gears are important machine elements widely used in industry. A mechanism can consist of only two gears, while in more complex systems, gears of different sizes and numbers are used. However, the use of a large number of gears can increase the weight and cost of the machine. The production methods developed with today's technology allow for the easy production of all kinds of geometries. In this study, in order to minimize the weight of spur gears, triangular, square and hexagonal shaped infill geometries were applied to the gear body. Designs with different edge lengths and infill thicknesses were modeled with SolidWorks software and finite element analysis was performed in ANSYS software. As a result of the analyses, it was determined that the square profile design offered the lightest solution. When compared to the unfilled design, a 63.65% reduction in weight was achieved.

Farklı Dolgu Geometrilerine Sahip Dişli Çarklarda Ağırlığın Optimize Edilmesi

Anahtar Kelimeler
Düz Dişli Çarklar,
Gövde Tasarımı,
3D Modelleme,
Sayısal Analiz

Öz: Dişli çarklar, endüstride yaygın olarak kullanılan önemli makine elemanlarıdır. Bir mekanizma yalnızca iki dişli çarktan oluşabileceği gibi, daha karmaşık sistemlerde farklı boyutlarda ve sayılarda dişliler kullanılmaktadır. Ancak, fazla sayıda dişli çarkın kullanımı makine ağırlığını ve maliyetini artırabilmektedir. Günümüz teknolojisiyle gelişen üretim yöntemleri, her türlü geometrinin kolayca üretilmesine olanak tanımaktadır. Bu çalışmada, düz dişli çarkların ağırlığını minimuma indirmek amacıyla, çark gövdesine üçgen, kare ve altıgen şekillerinde dolgu geometrileri uygulanmıştır. Farklı kenar uzunlukları ve dolgu kalınlıklarına sahip tasarımlar, SolidWorks yazılımı ile modellenmiş ve ANSYS yazılımında sonlu elemanlar analizi gerçekleştirilmiştir. Analizler sonucunda, kare profilli tasarımın en hafif çözüm sunduğu belirlenmiştir. Dolgusuz tasarımla karşılaştırıldığında, ağırlıkta %63,65 oranında bir azalma elde edilmiştir.

1. INTRODUCTION

Gear systems play a crucial role in power transmission and regulating mechanical motion. Widely used across industries such as manufacturing, automotive, and aerospace, these systems are continuously optimized for performance, durability, and energy efficiency. In recent years, topology optimization has emerged as a prominent method in gear design. This approach is recognized as a powerful tool for reducing structural weight and enhancing mechanical performance [1-3].

Studies on the potential of topology optimization in gear design demonstrate its ability to balance lightweight and durability. Ramadani et al. [4] explored the feasibility of using this method to design low-vibration, lightweight gear bodies. Patel and colleagues [5] highlighted that topology optimization could significantly reduce weight while improving energy efficiency in automotive applications.

Asymmetric tooth designs in gear systems have gained attention as an alternative method to enhance mechanical performance. Kapelevich [6] emphasized that such designs increase tooth strength, thereby extending operational life. Similarly, Song and Kim [7] investigated the impact of asymmetric tooth geometries on vibration reduction.

Material selection and heat treatment techniques have also been comprehensively examined for their effects on the performance of gear systems. Sharma et al. [8] demonstrated the positive impact of heat treatment on durability, while Doğan and Kamer [9] emphasized that additive manufacturing methods enable the production of optimized gear designs with reduced material usage. Additive manufacturing also facilitates the creation of complex geometries.

The integration of lattice structures has been identified as a significant innovation for lightweight and high-strength gear designs. Kara and Altun [10] noted that these structures are effective in reducing weight. Additionally, Maiti et al. [11] examined the impact of composite materials on lightweight gear systems, highlighting their advantages in vibration control and durability, which support modern design approaches.

Understanding and controlling the vibration behavior of gear systems is crucial for overall performance. Li et al. [12] analyzed how vibration characteristics can be optimized through material choices. Furthermore, studies on lubrication techniques to minimize energy losses in gear systems are noteworthy. Xu and Zhang [13] reported the positive effects of innovative lubrication solutions on energy efficiency.

Moreover, artificial intelligence and machine learning methods have ushered in a new era in gear design. Wang and Chen [14] demonstrated how these methods could be employed to rapidly generate optimized designs. It is anticipated that these technologies will play a significant role in the design of more complex systems in the future.

2. MATERIAL AND METHOD

In the study, the material to be used in gear designs was first determined. For this purpose, Polyamide (PA), a polymer material frequently used in engineering applications and easily producible through additive manufacturing, was selected. To obtain the mechanical properties of the material, a Type IV tensile test specimen was designed according to the ASTM D638 (ASTM, 2014) standard [9].

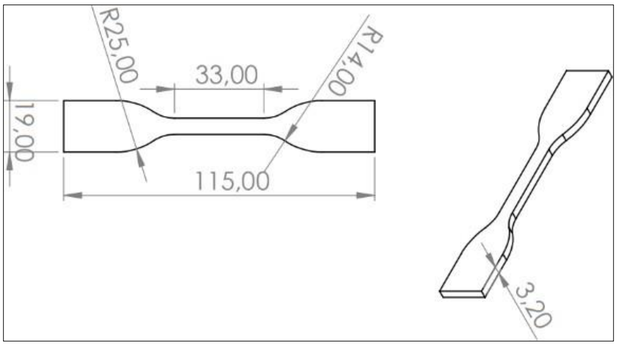

Figure 1. Tensile test specimens

To obtain the mechanical properties of the Polyamide material, a Polyamide filament from Flashforge was procured. The designed test specimen was produced using the FDM method. An industrial 3D printer, the CoreMax600 Pro, was used for the production of the test specimens. The specimens were tested using the Shimadzu AGS-X tensile testing machine available at our university. The tensile test was conducted on the specimens using the Shimadzu AGS-X tensile testing machine with a 10 kN load capacity, maintaining a grip distance of 65 mm. The tests were carried out at a tensile speed of 5 mm/min until the specimens experienced failure. Five Polyamide (PA-Nylon) specimens were subjected to testing, and their mechanical properties were compared after the tensile tests.

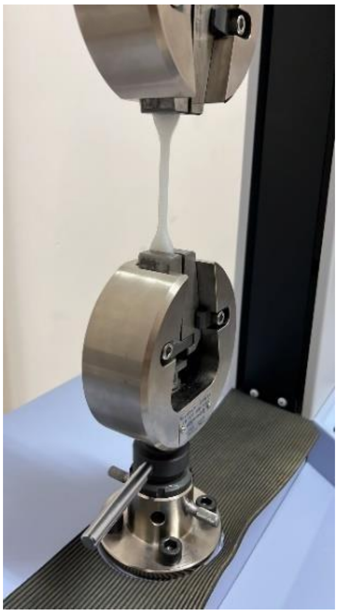

Figure 2. Tensile testing setup

Table1. Test results

Number	Yield Strength (Mpa)	Young's Modulus (Mpa)
1	87,621	2540,129
2	93,503	2744,989
3	83,899	2459,031
4	79,552	2502,065
5	85,166	2635,595
Average	**85,9482**	**2576,3618**

2.1. Modeling of Gear Wheels

In the subsequent phase of the study, individual gear models were created using SolidWorks. The solid models were then analyzed using the finite element analysis (FEA) software ANSYS Workbench. The CAD model of the spur gear involved in this study was created with the following design parameters:

- *Module (m): 4 mm*
- *Number of teeth (z): 25*
- *Pressure angle (α): 20°*
- *Gear width: 20 mm*
- *Shaft diameter: 20 mm*

During the design process of the gear wheels, the Equations dialog box in SolidWorks was used. The equations that define the geometric dimensions of the gear were imported into SolidWorks, and these parameters were applied to model the gear accurately.

The gear's tooth profile was designed as an involute profile. To generate this profile, involute profile equations were entered into the curve drawing command in SolidWorks, enabling the creation of the precise tooth profile.

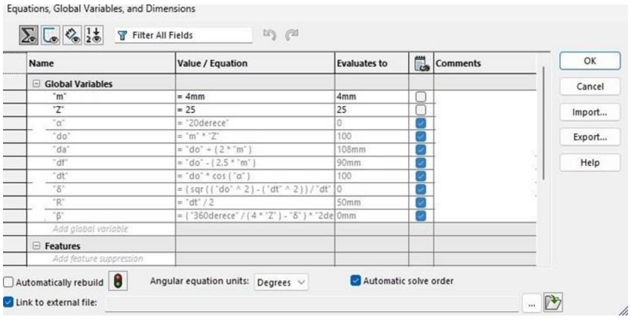

Figure 3. Equation Used in Solidworks

Subsequently, the gear model was created in SolidWorks using these equations throughout all stages of the design.

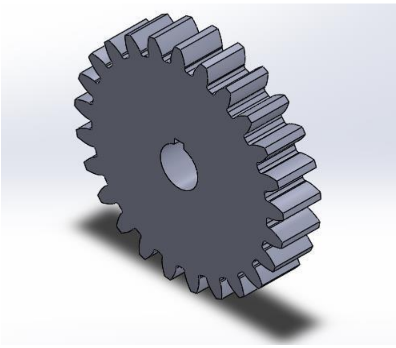
Figure 4. Model of Spur Gear

In the study, triangular, hexagonal, and square geometries were utilized for the gear designs. The designs were made in such a way that there were no gaps in the gear body, with 4 different edge lengths and 4 different fill thicknesses for each geometry. For the hexagonal geometry, a total of 16 gear designs were created using edge lengths of 6 mm, 8 mm, 10 mm, and 12 mm, and fill thicknesses of 1.5 mm, 2 mm, 2.5 mm, and 3 mm. As an example, visual representations of gears with the same thicknesses but different edge lengths are provided.

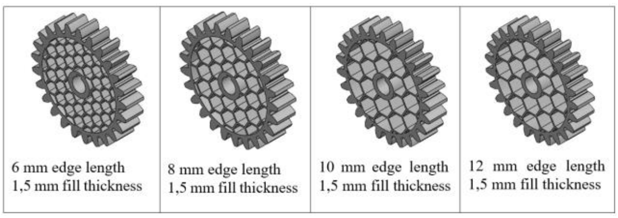

Figure 5. Hexagonally Geared Designs

For the square geometry, a total of 16 gear designs were created using edge lengths of 10, 12, 14, and 16 mm, and fill thicknesses of 1.5, 2, 2.5, and 3 mm. Visual representations of gears with the same thicknesses but different edge lengths are provided as examples.

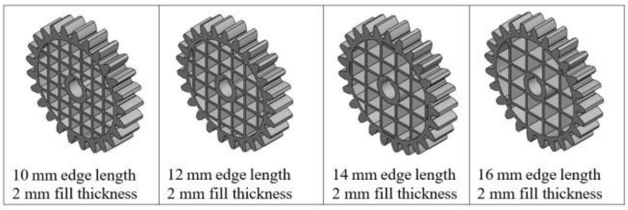

Figure 6. Square Geometry Gear Designs

For the triangular geometry, a total of 16 gear designs were created using edge lengths of 12, 14, 16, and 18 mm, and fill thicknesses of 1.5, 2, 2.5, and 3 mm.

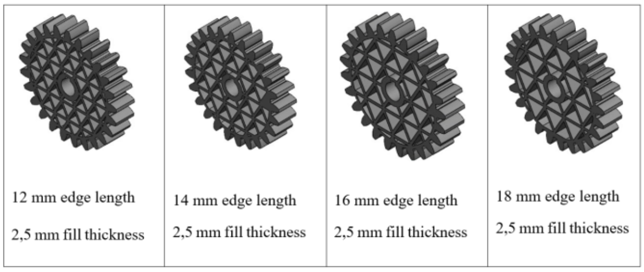

Figure 7. Triangle Geometry Gear Designs

2.2. Finite Elements Analysis

In the analysis phase, the analysis of a standard spur gear, which had not undergone any material removal, was first performed. Subsequently, analyses of the specially designed spur gear models were conducted in the static-structural mode of ANSYS Workbench 2020 R1.

Initially, the designs were created in SolidWorks. The designed gear models were then imported into ANSYS. For the solid models introduced into ANSYS, Polyamide (PA), the most commonly used material in gear manufacturing, was assigned, taking into account both cost considerations and material preference.

As another step in the finite element analysis, meshing was performed. The mesh applied to the gear models significantly impacts the analysis results. Initially, a default mesh was applied, and the sizing command was used to improve the mesh quality. After completing the meshing process, boundary conditions were defined. The gear wheels were fixed at the shaft hole, and loading was applied to the tooth profile, as shown in Figure 8.

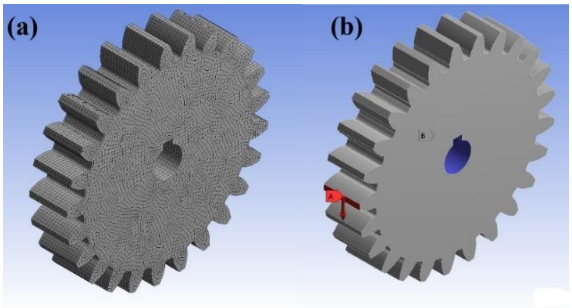

Figure 8. Finite Element Model of the Gear: (a) Mesh Structure and (b) Boundary Conditions

In the analyses performed, forces of 250N, 500N, 750N, 1000N, and 1250N were applied incrementally to the samples. The force at which yield stress was reached was considered as the failure load.

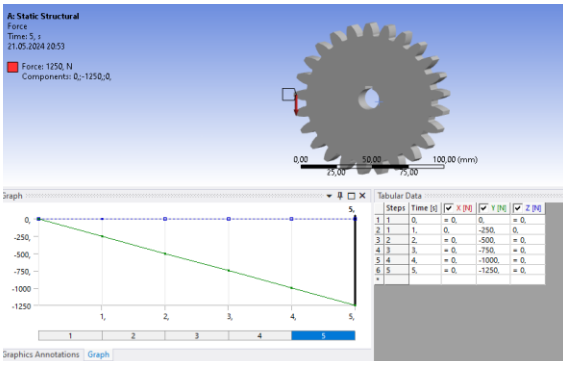

Figure 9. Applied Loads in the Finite Element Model

The same boundary conditions were applied to all gear models, and stress analyses under load were performed. The Von-Mises maximum stress values from the stress analyses were used as the basis for evaluation.

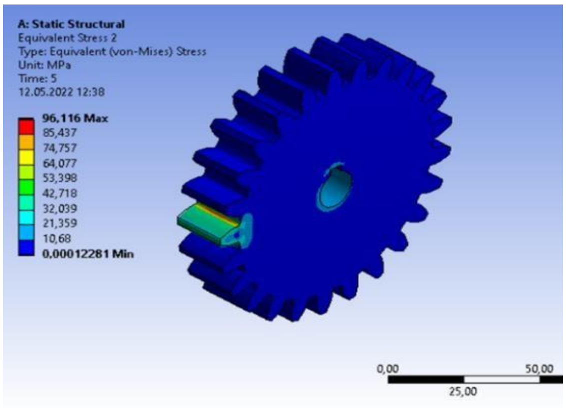

Figure 10. Von-Mises Stress Distribution of the Untreated Spur Gear

In Figure 10, the stresses resulting from the applied loads on the spur gear are shown step by step. As expected, the yield stress was reached at the tooth root and along the line. The force at which yield stress was achieved was considered the failure load. Yield stress was reached at step 4.5, with the applied force being 1125 N. Thus, the untreated spur gear reached yield stress at 1125 N.

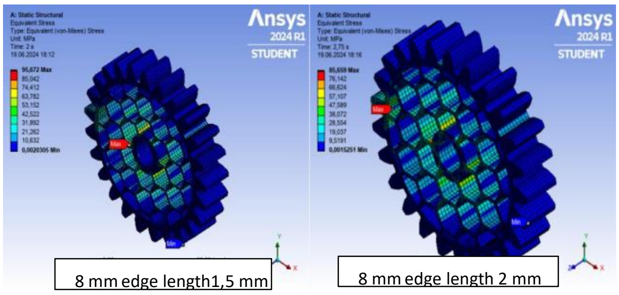

Figure 11. Von-Mises Stress Distribution of Hexagonal Geometry Gears with 8 mm Edge Length and 1.5 mm and 2 mm Fill Thicknesses

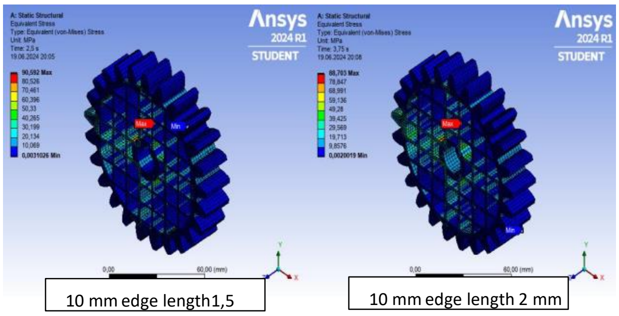

Figure 12. Von-Mises Stress Distribution of the Square Geometry Gear with 10 mm Edge Length and 1.5 mm and 2 mm Fill Thicknesses

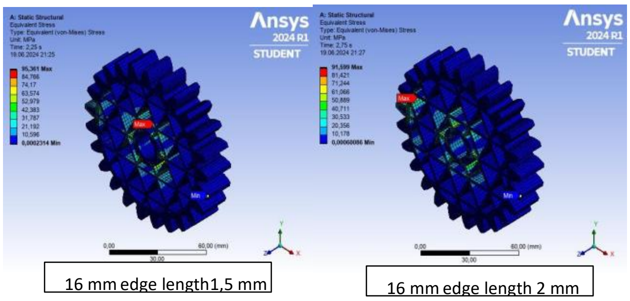

Figure 13. Von-Mises Stress Distribution of the Triangular Geometry Gear with 16 mm Edge Length and 1.5 mm and 2 mm Fill Thicknesses

In the designed gears, it is desired that the maximum stress always occurs at the tooth root for each loading condition. For the triangular geometry, this condition is achieved with a fill thickness between 1.5 mm and 2 mm. At 1.5 mm thickness, the maximum stress appears on the body and in different regions of the geometry and edge lengths. This stress distribution indicates that these areas may fail under operating conditions. However, when the thickness is increased to 2 mm, it is observed that the body is safe, and the maximum stress shifts to the tooth root (Figures 11-13).

3. RESULTS AND DISCUSSION

Initially, designs were created for gears with triangular, square, and hexagonal geometries on the gear body, using 4 different edge lengths and 4 different fill thicknesses. Stress analyses of the designed gears were conducted using the ANSYS program to evaluate their performance under load.

The analysis showed that in fully filled spur gears, the maximum stress occurred at the tooth **root**, which is typical for spur gear designs. For gears where material was removed from the body, it was observed that the stresses increased as the material was removed toward the **center** of the gear. The material removal process continued until the stresses were reduced to a level below the yield stress**,** thus achieving the goal of reaching the optimal weight without compromising the strength of the gear. The weights of the designs were obtained using SolidWorks and compared with the weight of the untreated spur gear to assess the effectiveness of the material reduction.

During the gear selection process, the gears where the maximum stresses were concentrated at the tooth root under loading conditions were considered optimal. Gears where maximum stresses appeared on the gear body were excluded from consideration, as these areas would likely be more prone to failure or damage during operation. This careful approach ensured that only the designs with the most reliable stress distribution and optimal performance were chosen for further evaluation.

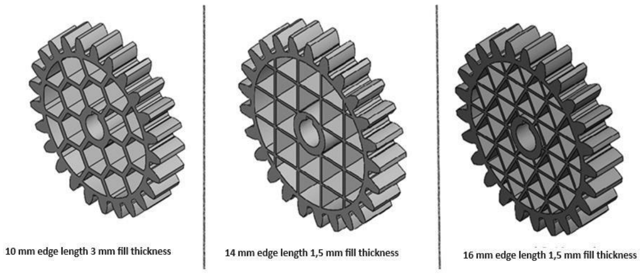

Figure 14. Optimum Gears for All Geometries

Among all the designs and weights, the lightest gear was achieved with the square geometry. This gear represented a significant weight reduction of 63.65%, marking a groundbreaking achievement in the literature for such a substantial weight reduction.

The use of lightweight gears offers several advantages in mechanical systems. First, reducing the weight of the gears helps decrease the overall weight of the system, leading to improved energy efficiency. As the weight decreases, the friction and energy losses in the system are also minimized. This not only leads to energy savings but also improves the balance and stability of mechanical systems, enabling machines to operate with greater precision and efficiency. Additionally, lightweight gears are easier to handle and assemble, simplifying the logistics and labor involved in manufacturing and maintaining the system.

With the continuous advancement in technology, further reductions in gear weight can be achieved by exploring different gear geometries and incorporating artificial neural networks into the design process. These innovations hold great potential for optimizing gear performance, enhancing energy savings, and reducing material usage, contributing to the development of more sustainable and efficient mechanical systems.

Acknowledgements

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