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# The Influence of Infill Patterns on Tooth Root Rigidity by Additive Gear Manufacturing

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**Abstract**

In this study, we present an analysis of the infill patterns of 3D-printed gears with the aim of optimizing their load- capacity. During the investigation, we developed custom infill patterns, taking into account the influence of the direction of forces which occur under service. These patterns were compared with the Gyroid infill, which is the most commonly recommended in the literature. The examined gears were cylindrical involute gears, and the mass of the part was used as a reference parameter during the printing process.

A unique infill pattern was designed and combined with the Gyroid infill, then compared to the conventional Gyroid infill structure. The load-bearing capacity of different infill structures was determined by applying a simple static load test. Three gears were printed for each infill pattern, and three individual static load-bearing tests were performed on each gear.

Since plastic gears were used in this study, the central bore of the gears was modified. This modification was necessary because, if a simple keyway solution had been applied, the gears could have rotated on the shaft due to the applied torque. To prevent this, the central bore was replaced with a hexagonal design.

**Keywords:** *gear, infill pattern, load-bearing capacity, static load test, involute.*

## 1. Introduction

Nowadays, the processing and recycling of plastics are gaining increasing attention, especially from the perspective of sustainable manufacturing. One of the most widespread plastic processing methods is injection molding, which is readily used in the automotive industry, packaging industry, and in the production of electronic devices. The advantage of injection molding is rapid and economical mass production; however, it has a significant disadvantage, namely the high upfront cost of the tool. In contrast, additive manufacturing technologies – especially FDM (Fused Deposition Modelling) – have gained increasing popularity in recent years, as they minimize waste through layer-by-layer material construction and provide opportunities for the rapid production of components with unique and complex geometry.

With the development of FDM technology, an increasingly wide range of materials has become available, including carbon fiber and glass fiber reinforced polymers, which improve mechanical properties and wear resistance. In the present research, we used the FFF (Fused Filament Fabrication) additive technology. Since most gears used in household appliances are made of plastic, along with cost-effectiveness, reduced service life must be taken into account, mainly due to operation at high rotation speeds and wear resulting from material properties [9]. Replacing these gears is often cumbersome, as product catalogs in many cases do not contain standard dimensions, making individual replacement difficult.

In the case of FFF technology printed gears, the appropriate infill pattern and optimal printing parameters are crucial for mechanical performance. During our research, we compared the effect of different infill patterns on the load-bearing capacity of gears.

## 2. Design of the General Tooth Profile and 3D Model

At the beginning of the research, we determined that we would apply the most widespread tooth profile, the involute profile, since we intended to investigate involute cylindrical gears [4].

To create the 3D model, the first step is to develop the tooth profile and the corresponding root curve. Both the profile and the root curve are created in the Mathcad environment. The following parameters were used to development the tooth profile [4, 5]:

- modul: $m = 5$ mm,
- specific tooth addendum height: $h_0 = 1$,
- specific backlash: $c_0 = 0.25$,
- number of teeth: $z_1 = 17$,
- tooth height: $a = (h_0 + c_0)m = 6.25$ mm,
- gear width: $b = 20$ mm.

Arc segments of equal length were used to construct the gear tooth profile to achieve a more precise geometry. The root curve was not determined using the standard formula $\rho_{0f} = 0.38$ m [6] but rather based on literature [7] striving for a more robust root design. With this approach, our aim was to optimize the load distribution and increase the service life of the gear. However, in the present research, we will not delve into a detailed analysis of this.

The root and tooth profile are illustrated in Fig. 1.

The 3D model was developed in the Autodesk Inventor environment, using the profile points exported from Mathcad. To create the model, we applied specific Autodesk Inventor commands such as Extrude, Circular Pattern, Mirror, etc. [8]. The geometry created this way ensured precise tooth profile reconstruction, which is essential for further simulations and manufacturing processes. The model can be seen in Fig. 2.

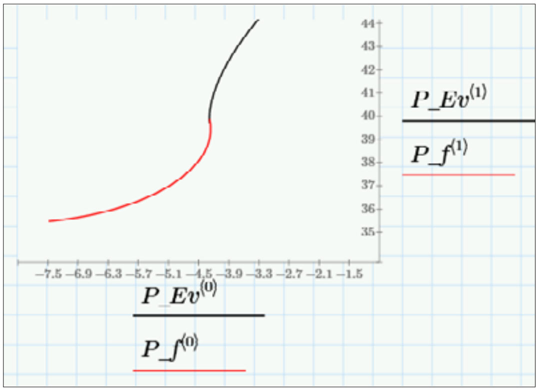


**Fig. 1.** *Involute profile with specialized root curve.*

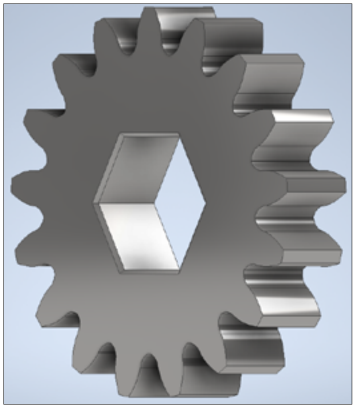

**Fig. 2.** *The Inventor model of the applied involute cylindrical gear.*

## 3. Development of specialized patterns

### 3.1. Levoid infill pattern

All patterns were created in the Autodesk Inventor environment, and in each case the model was developed by modifying the existing gear model. During the design of the patterns, special attention was paid to the precise setting of geometric parameters to ensure they meet the desired mechanical properties. The wall thickness was set to 0.8 [mm] in all cases, as this thickness provides the appropriate balance between mechanical strength and material usage, while minimizing the disadvantages arising from excessive material consumption.

The supports, were designed by taking into account the symmetry line of the tooth. Additionaly, we designed 0.8 [mm] wide supports along the line connecting the intersection point of the root curve radii and the gear axis. These supports ensure that the gear structure does not deform during printing, and the component maintains its shape even under maximum load.

The Levoid infill (resembling leaf venation (Fig. 3) was created by designing additional support elements at a 75° angle to the tooth's axis of symmetry. The width of these supports was 0.4 mm in all cases to provide sufficient stability while minimizing material usage. The distance between the supports was determined to be 1 mm, as this distance ensures that the printed pattern is strong enough but does not excessively strain the material. The arrangement and dimensioning of the support elements are crucial in ensuring the strength and long service life of the printed components.

Since we were working with plastic gears, we modified the central bore of the gears. This was necessary because in the case of a simple keyway fixing, the gears could have rotated on the shaft due to the applied torque. To prevent this, we designed the central bore with a hexagonal shape, thereby ensuring more secure torque transmission (Fig. 4).

### 3.2. Hybrid Levoid infill

In this case, we combined the Levoid and conventional Gyroid infills to optimize the mechanical performance and material usage of the gears. The infill of the teeth was Levoid, as this pattern is presumed to be suitable for ensuring long-term load-bearing capacity and achieving the necessary stability. However, the core of the gear was designed with 30% Gyroid infill (Fig. 5), as the Gyroid structure is ideal for weight reduction and maintaining structural integrity while providing the desired mechanical properties.

We apply the Gyroid infill within a circle of 71.264 [mm] diameter to maintain the external wall thickness at 0.8 [mm] in all cases. This approach ensures that the outer layer of the gear is strong enough to withstand the forces occurring during operation, while the internal structure remains lighter. The Gyroid infill is a complex geometric pattern, and its development using analytical methods is a very complicated task. Therefore we used the slicing software, which automatically generated the appropriate fill pattern for 3D printing..

We illustrate the sliced hybrid Levoid model in Fig. 6. This combined infill structure enables the gear to potentially achieve optimal mechanical properties in both regions: the load-bearing capacity and wear resistance of the teeth could presumably be improved thanks to the Leaf infill, while the central part of the gear would remain lighter and more flexible, yet retain the required strength due to the Gyroid infill.

### 3.3. Conventional Gyroid infill

We created a version with entirely Gyroid infill for comparison purposes. The aim was to examine the effect of infill methods on structural strength, weight savings, and manufacturing processes.

Additionally, in this case we applied a 30% Gyroid infill within a circle of 71.264 [mm] diameter, ensuring the preservation of the 0.8 [mm] external wall.

For the internal structure of the teeth, we applied a denser, 56% Gyroid infill. The purpose of this was to ensure that the mass of the subsequently created gears matched, regardless of which infill structure we used. This method allowed gears with different geometries to have similar dynamic and static properties.

The complete Gyroid infill model is illustrated in Fig.7. The exact formation of the infill was created by the slicer program, which automatically generated the Gyroid structure taking into account the given density parameters and geometric constraints. This approach not only simplified the design process but also ensured uniform material distribution during manufacturing and optimization of mechanical performance.

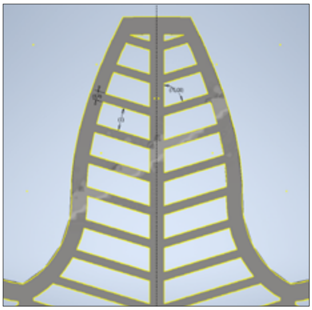

**Fig. 3.** *Levoid infill pattern.*

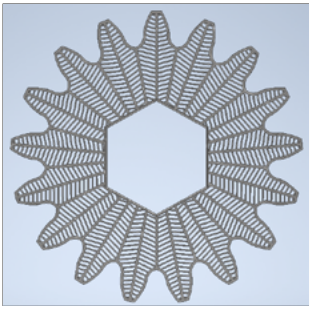

**Fig. 4.** *100% Levoid infill.*

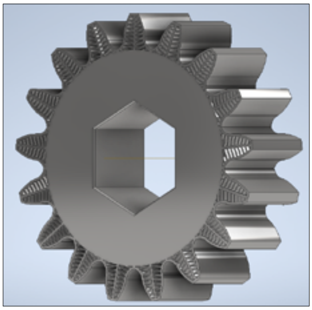

**Fig. 5.** *Hybrid Levoid infill.*

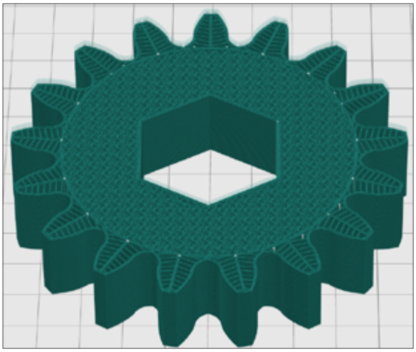

**Fig. 6.** *Hybrid Levoid infill: sliced model.*

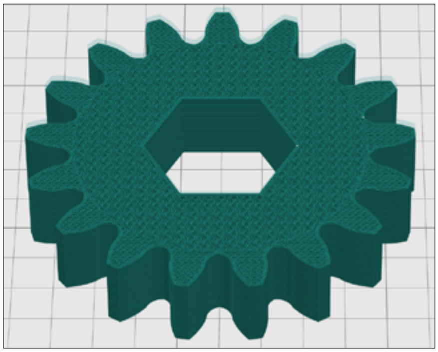

**Fig. 7.** *Conventional Gyroid sliced model.*

## 4. Manufacturing of gears using additive technology

For printing the gears, we used a bed slinger, Sovol SV07 type 3D printer operating with Klipper firmware. This printer allows for higher speed and more precise printing, which is crucial for ensuring the accurate geometry of the gears.

The used filament was AzureFilm black, matte coloured HS (High Speed) PLA. This material was specifically optimized for high-speed printing, with low shrinkage and excellent inter-layer adhesion. The matte surface is not only aesthetically advantageous but also helps reduce the visibility of the printing layers.

During the printing process, we did not use the printer's own slicing program (Sovol Cura), but rather OrcaSlicer software, which offers more advanced setting options and provides more precise control. The printing speed was set to 150 mm/s, which provided fast and efficient extrusion in accordance with the characteristics of HS PLA without compromising the adhesion between layers [9].

The settings were specifically adjusted to study the effect of the infill pattern on load-bearing capacity. For this purpose:

- We limited the number of walls to 2, minimizing the perimeter layer thickness.
- We did not apply top and bottom solid layers, so the infill structure remained directly visible and analyzable.
- The bed temperature was set to 60°C to ensure proper adhesion of the first layer and reduce the risk of deformation (warping) [9].
- The nozzle temperature was 210°C, which is optimal for proper melting and uniform extrusion of HS PLA [9];
- When designing the gears, we used mass as a reference, thereby ensuring balance and comparability between different constructions.

With these settings, the printing was fast and efficient, while ensuring the mechanical integrity and dimensional accuracy of the gears. The applied parameters enabled more accurate examination of the effects of the infill pattern, which contributed to the optimization of design and manufacturing processes.

For each printed gear, we aimed to have the mass of the gears as close as possible. The lightest gear weighed 56.395 grams, while the heaviest was 57.450 grams. This means that the difference between the masses, or the range of dispersion, was 1.055 grams. This difference can be attributed to minor variations in the printing process, such as unevenness in extrusion, temperature fluctuations, and adhesion characteristics of individual layers.

The mass constraint allowed us to ensure that the comparison of individual samples was not influenced by weight difference, allowing us to exclusively examine the effects of the infill pattern. Based on the results, it can be concluded that the printing process is acceptable from the experiment's perspective, as the mass differences remained minimal.

Regarding the printing time, the results show that there is only a minimal difference between printing times, indicating that the printing processes run reliably and uniformly. The standard deviation of the printing time for the three models is only 8 minutes.

## 5. Static loading tests and results

We prepared three specimens with each of the three proposed infills to generate sufficient measurement data. The manufacturing of each sample occurred under identical parameters, thus ensuring comparability and consistency of the printing process. We performed 3 measurements on each specimen, on 3 different teeth.

The static tests were conducted on a conventional TOS-250 type lathe, which provided adequate stability and precision for the experiments. A 250 mm long, 32 mm hexagonal bar was placed in the chuck of the lathe, serving as the central bore of each gear.

A 10 mm diameter cylinder was placed in the tool holder of the lathe, which was adjusted to fit into the gear tooth space. This setup enabled direct loading of the teeth and precise measurement of deformations.

A Sealey 1/2" SQ Drive Digital Torque Adapter with an accuracy of ±2% was mounted on the free end of the hexagonal bar. A ratchet wrench was connected to the torque meter, with which we gradually increased the load while monitoring the deformation of the gears and the failure torque. During the test quasi-steady state condition was maintained.

The purpose of the measurement was to obtain accurate data on the load-bearing capacity and mechanical behaviour of gears with different infill structures. The data thus obtained provide assistance in optimizing gear geometries and evaluating the practical applicability of 3D printed gears.

The measured values were summarized in the following tables.

**1. Table.** *Levoid infill*

| | 1. pcs (Nm) | 2. pcs (Nm) | 3. pcs (Nm) |
|---|---|---|---|
| 1. | 28.6 | 33.5 | 26.2 |
| 2. | 24.1 | 23.7 | 30.4 |
| 3. | 24.6 | 40.7 | 35.6 |

**2. Table.** *Hybrid Levoid infill*

| | 1. pcs (Nm) | 2. pcs (Nm) | 3. pcs (Nm) |
|---|---|---|---|
| 1. | 24.3 | 49 | 46.9 |
| 2. | 26 | 48.6 | 47.1 |
| 3. | 35 | 55.7 | 48.3 |

**3. Table.** *Conventional Gyroid infill*

| | 1. pcs (Nm) | 2. pcs (Nm) | 3. pcs (Nm) |
|---|---|---|---|
| 1. | 37.7 | 49.5 | 58.2 |
| 2. | 53.8 | 56.4 | – |
| 3. | 61 | 57.2 | – |

## 6. Conclusions

Our investigations confirmed that the geometry of the chosen pattern does not randomly determine the load-bearing capacity of the gears, but rather stems from the kinematics of the machine elements' operation. This is a particularly important aspect during design, as the mechanical properties and service life of gears can be optimized by selecting the appropriate infill structure.

During the destructive tests, we observed that every failure occurred at a critical displacement below the tooth root, which correlated with the alternation of the infill pattern. This indicates that the transitional zones of the material structure may be weaker, therefore increased attention should be paid to the homogeneity of the infill pattern during design.

In the case of conventional Gyroid infill, significant spikes can be observed in the measured values. This can be attributed to the fact that the slicer program randomly forms the infill, thus the arrangement of the infill may differ for each tooth. Consequently, the load-bearing capacity of gears made with such infill is not constant and is unstable, which makes this infill pattern unreliable in industrial applications.

For the Hybrid Levoid infill, the measured data suggest that the structure's load-bearing capacity is more stable than that of the simple Levoid infill, and approaches the level of conventional Gyroid infill. The measurement results show a smaller distribution, which suggests that the hybrid structure helps in more uniform distribution of the load. This indicates that hybridization can optimize the mechanical behaviour of gears, reducing stress peaks at critical loading points.

The measurement results show that the load-bearing capacity of conventional Gyroid infill is better than that of the Levoid infill pattern we developed. From the measured data, it can also be observed that the simple Levoid infill has a weaker load-bearing capacity, which is also evident from the lower average torque values.

Our results highlight that in gear design, not only the tooth profile and material selection but also the internal infill pattern play a key role in achieving optimal mechanical performance.

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