

A Comparative Study of the Involute Profile, Pitch Deviation and Surface Roughness of Spur Gears Manufactured by 3D Printing and by Injection Molding [†]

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Abstract

This article presents a comparative study of the geometric accuracy of spur gears manufactured by additive manufacturing (3D printing) and by injection molding. Gears were produced from two engineering plastics—POM (polyoxymethylene) for injection molding and carbon fiber-reinforced polyamide for 3D printing. The study evaluates three key parameters: deviation from the involute profile, single-pitch deviation, and surface roughness (Ra). Gears with identical geometric parameters (module 3 mm) were produced using both methods, allowing direct comparison between the resulting products under identical design conditions. Profile measurements were performed using a coordinate measuring machine (CMM) according to ISO 1328-1:2013. The surface roughness of gear teeth is a key parameter that determines operability, efficiency, and wear resistance. Smoother surfaces reduce friction and wear, leading to lower operational losses, higher efficiency, and longer service life. High roughness may lead to local stress points, increased noise levels, and vibrations during operation, which are especially critical for high-speed and heavily loaded gears. The obtained data serve as a basis for an objective evaluation of the applicability of additive manufacturing and injection molding for producing gears with different requirements for geometric accuracy, as well as for formulating guidelines for selecting an appropriate manufacturing technology depending on the specific application.

Keywords: 3D-printed gears; injection-molded gears; involute profile deviation; pitch deviations



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1. Introduction

The transmission of continuous rotary motion from one link to another is most commonly achieved through a gear mechanism [1]. It consists of two gears, which form a closed kinematic pair, and a stationary frame. The advantages of gears include the ability to transmit both large and small amounts of power, high efficiency, the provision of a constant transmission ratio, and great durability. There are various classifications of gears—according to the arrangement of their axes, the longitudinal shape of the teeth, the orientation of the teeth, and the tooth profile. In engineering practice, the most commonly

used are cylindrical gears with straight teeth and an involute working profile, as they are the simplest to manufacture and operate.

To ensure efficient operation during the meshing process and maintain a constant transmission ratio, the teeth of meshing gears should be conjugate. Consequently, the profile of a tooth on one gear must correspond precisely to the profile of a tooth on the opposing gear.

In mechanical engineering and transmission systems, involute gears are the most prevalent type of gear [2]. The defining feature of the involute tooth profile is that the teeth make contact along the involute curve, ensuring a consistent speed transmission between the gears in mesh. This results in smooth torque transfer and minimized friction. Proper meshing depends on the gear module and pressure angle. An involute gear's profile consists of two symmetrical involute segments, an arc of the addendum circle, a transition curve, and an arc of the dedendum circle. The parts of the profile that engage during meshing are the working sections—Figure 1.

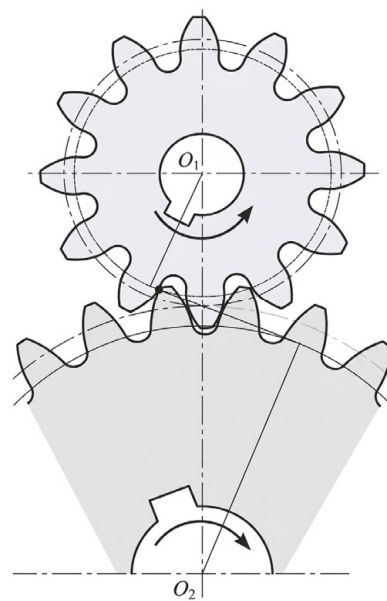


Figure 1. Gear meshing.

The choice of material for gears depends on the load, the required precision, and the manufacturing method. Steel is most commonly used, but in modern mechanical engineering, plastics are increasingly being utilized. Plastics are suitable for low speeds, light loads, and corrosive environments.

The microgeometry of surfaces plays an important role in the wear resistance, the nature of both moving and stationary joints, and the strength of the components [3]. Parts with more surface irregularities wear out more rapidly, and strength is reduced due to the presence of stress concentrators. Surface roughness is a key parameter for gears because it affects both wear and the accuracy of the transmission—it contributes to the even distribution of torque and the stability of speed. Controlling roughness is particularly important for highly loaded and high-speed transmissions.

Polymer gears are increasingly used to replace metal gears in power transmission, but their accuracy and wear behavior depend strongly on material, geometry, temperature, and manufacturing route. Three-dimensional-printed gears add further complexity through anisotropy and process-parameter effects.

Although extensive research has shown that carbon fiber-reinforced polymers can substantially improve mechanical and tribological performance through increased stiffness,

strength, hardness, and reduced friction and wear, their application in additively manufactured gears remains insufficiently investigated. Most existing studies focus on bulk material characterization rather than evaluating the dimensional quality and functional suitability of 3D-printed gears. As a result, there is limited understanding of whether such materials can provide an effective alternative to conventionally manufactured gears. This study therefore investigates the involute profile accuracy, pitch deviation, and surface roughness of 3D-printed and injection-molded gears in order to assess the feasibility of using reinforced polymer gears produced by additive manufacturing in industrial applications.

2. Materials and Methods

When choosing plastic for the production of gears, reliability, wear resistance, and the efficiency of the gear mechanism are taken into account. The main factors are:

- Mechanical properties;
- Heat resistance;
- Friction coefficients;
- Chemical resistance;
- Production and economic factors.

For the purposes of this article, engineering plastics have been selected—POM for injection molding and polyamide for 3D printing. It should be noted that different materials were used for each process, which may influence the results independently of the manufacturing method.

POM is a high-strength engineering thermoplastic widely used for gears and precision mechanical components. It is characterized by excellent mechanical strength, high impact resistance, and good wear resistance, making it suitable for applications with moderate loads. The material has a low coefficient of friction and partially self-lubricating properties, allowing it to operate without additional lubrication and reducing noise and vibration in gears. POM demonstrates good dimensional stability, minimal thermal expansion, and an operating temperature range from $-40\text{ }^{\circ}\text{C}$ to $+100\text{ }^{\circ}\text{C}$. It is chemically resistant to water, oils, and weak solutions of acids and bases, but it has low UV resistance. POM is easily processed by injection molding, extrusion, and machining while maintaining dimensional accuracy. The combination of these properties makes it a preferred material for light to moderately loaded gears, especially in electronic and household applications, office equipment, and automotive systems.

Polyamide is a widely used thermoplastic for gears, known for its high strength, wear resistance, and good impact resistance [4]. It has a relatively low coefficient of friction, allowing for partially self-lubricating operation and reducing noise and vibration. Polyamide is hygroscopic, which means it absorbs moisture from the environment, potentially altering its dimensions and mechanical properties. Its operating temperature range is approximately $-40\text{ }^{\circ}\text{C}$ to $100\text{ }^{\circ}\text{C}$. It is resistant to oils and many chemicals, is easily processed by injection molding and extrusion, and maintains good dimensional accuracy with proper processing. Polyamide is preferred for light and moderately loaded gears where a combination of strength, wear resistance, and low noise is required.

In order to facilitate a comprehensive comparative analysis between additive and conventional manufacturing methodologies, the specific fabrication settings for the 3D-printed specimens must be precisely defined and documented. The subsequent table delineates the comprehensive array of 3D printing parameters utilized during the production of the experimental gear samples, designated as Z_3 and Z_4 . These additive processing variables were meticulously selected to optimize the structural integrity and geometric fidelity of the involute profiles, thereby ensuring a robust basis for evaluation against the benchmark injection-molded components, referred to as Z_1 and Z_2 . By explicitly defining these param-

eters the study provides the necessary technical transparency to evaluate how individual additive manufacturing constraints influence the resulting pitch and profile deviations in contrast to the traditional molding process used for the first two specimens. The 3D-printed parameters are provided in Table 1.

Table 1. Three-dimensional printing parameters.

3D Printing Parameters	Value
3D printing speed	360 mm/s
Extruding temperature Z ₃	260 °C
Bed temperature	105 °C
Layer height	0.12 mm
Infill	15%
3D printing duration	56 min

The 3D printing speed of 360 mm/s was selected to reflect an industrial production context where productivity (manufacturing speed) is balanced against functional accuracy. This study does not aim to achieve the highest possible surface quality or dimensional accuracy, but rather to evaluate whether 3D-printed gears produced at industrially relevant speeds can serve as an alternative to injection-molded gears for low-load applications. The effect of this parameter on surface roughness ($R_a = 12.75 \mu\text{m}$) is explicitly discussed in Section 3.

For the purpose of this study, four gear samples with a module of 3 mm were examined. Two of them are 3D printed, and two are manufactured by injection molding. The chosen module is one of the most commonly used for plastic gears. A drawing of the gears is shown in the following Figure 2 and a picture of the molded gear is shown in Figure 3. Gear wheel design. (A-A): cross-sectional view of the gear; (B): detailed view (magnified scale) of a single gear tooth profile.

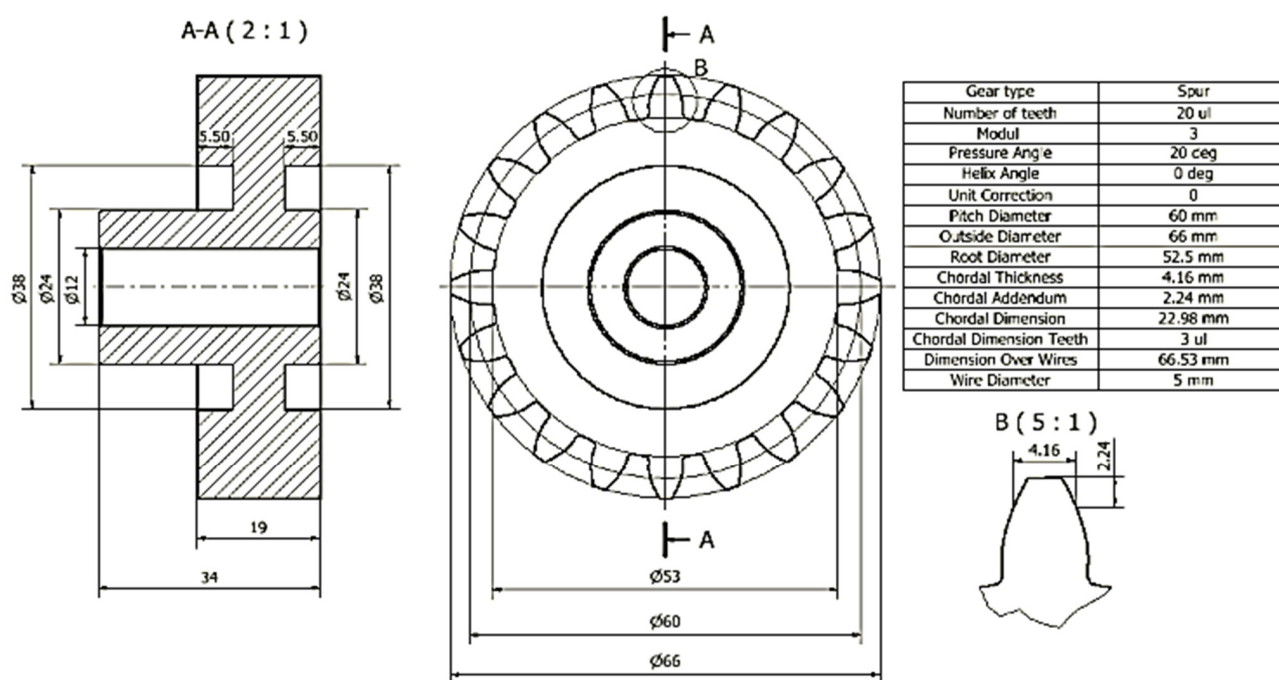


Figure 2. Drawing of the gears.



Figure 3. Injection-molded gear.

To determine the involute profile deviation, measurements were taken along the involute section of the sample teeth. A Hexagon 4.5.4 SF 3D coordinate measuring machine (CMM) was used for the measurements. To ensure accurate and reliable experimental results, the recommendations presented in the following standards were implemented in the measurement laboratory: ISO 5725-1-1994(E) [5] and ISO-IEC-17025-2017-IAS [6] (Figure 4).

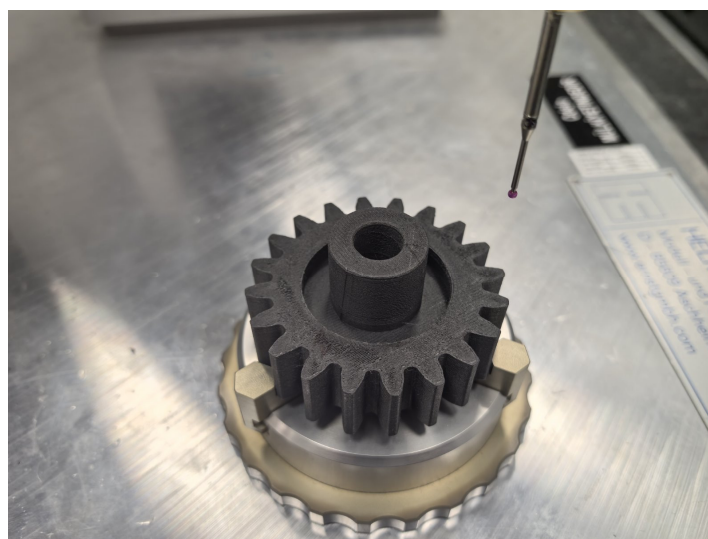


Figure 4. Three-dimensional-printed gear measurement set up on CMM.

To determine the form deviation of the involute gear section, 3D models containing CAD data of the ‘ideal’ involute profile were developed through parametric definition of the gear’s geometric characteristics [7]. The coordinate measuring machine compares the data points captured from the gear under test against the 3D model, providing information regarding the coordinates of each measured point and its respective deviation from the theoretical model [8].

According to ISO 1328-1:2013 [9], the profile evaluation length of the tooth L_a starts from the profile control diameter d_{cf} and ends at 95% of the diameter d_a , which is at a distance equal to the size of the chamfer at the tooth tip— h_k (Figure 5).

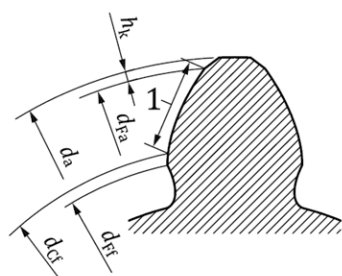


Figure 5. The length of the measured tooth profile L_a in accordance with the ISO 1328-1:2013 standard.

The length of path of contact— g_a is defined from the start of active profile diameter d_{Nf} to the diameter of the tip profile d_{Fa} or to the point where contact stops due to undercut of the tooth can be observed.

The deviation from the pitch f_p , or single-pitch deviation, of the samples is measured for each tooth of the gear under consideration, and according to the aforementioned standard, the value of the deviation is taken as the modulus of the maximum error (Figure 6) and Formula (1).

$$f_p = \max |f_{pi}|. \quad (1)$$

where f_{pi} —pitch error for the i -th tooth, P_{tM} —theoretical pitch value of the gear.

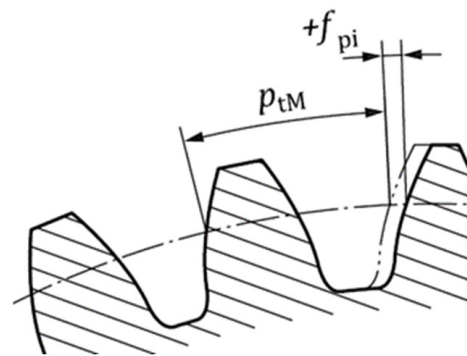


Figure 6. Single-pitch deviation according to ISO 1328-1:2013 standard.

3. Results and Discussion

The total profile deviation of four investigated plastic gears was quantified and compared based on standard involute profile evaluation [10]. For each gear the total tooth profile deviation (F_α) was determined using a CMM measuring system, following approaches similar to those reported for plastic gears and small-module gears in prior work. The measurement procedure was designed to minimize installation and positioning errors by reconstructing the workpiece coordinate system from measured tooth data, as recommended in recent profile deviation evaluation methods.

Plots of the total profile deviation are presented in accordance with the ISO 1328-1:2013 standard (Figure 7). The injection-molded samples are referred to as Z1 and Z2, while the 3D-printed samples are designated as Z3 and Z4.

The experimental values for total profile deviation and individual single-pitch deviation for each gear sample are summarized in Table 2.

Table 2. Measurement results for total profile and single-pitch deviation.

Gear Sample	F_α (μm)	f_p (μm)
Z ₁	128	0.68
Z ₂	59	0.61
Z ₃	126	0.53
Z ₄	104	0.56

The measurement reports generated by the gear inspection system are shown in Figure 8a–d.

Table 3 presents the deviation values at specific measurement points for the four gear samples, along with their locations on the tooth profile expressed by diameter and roll length (L_a).

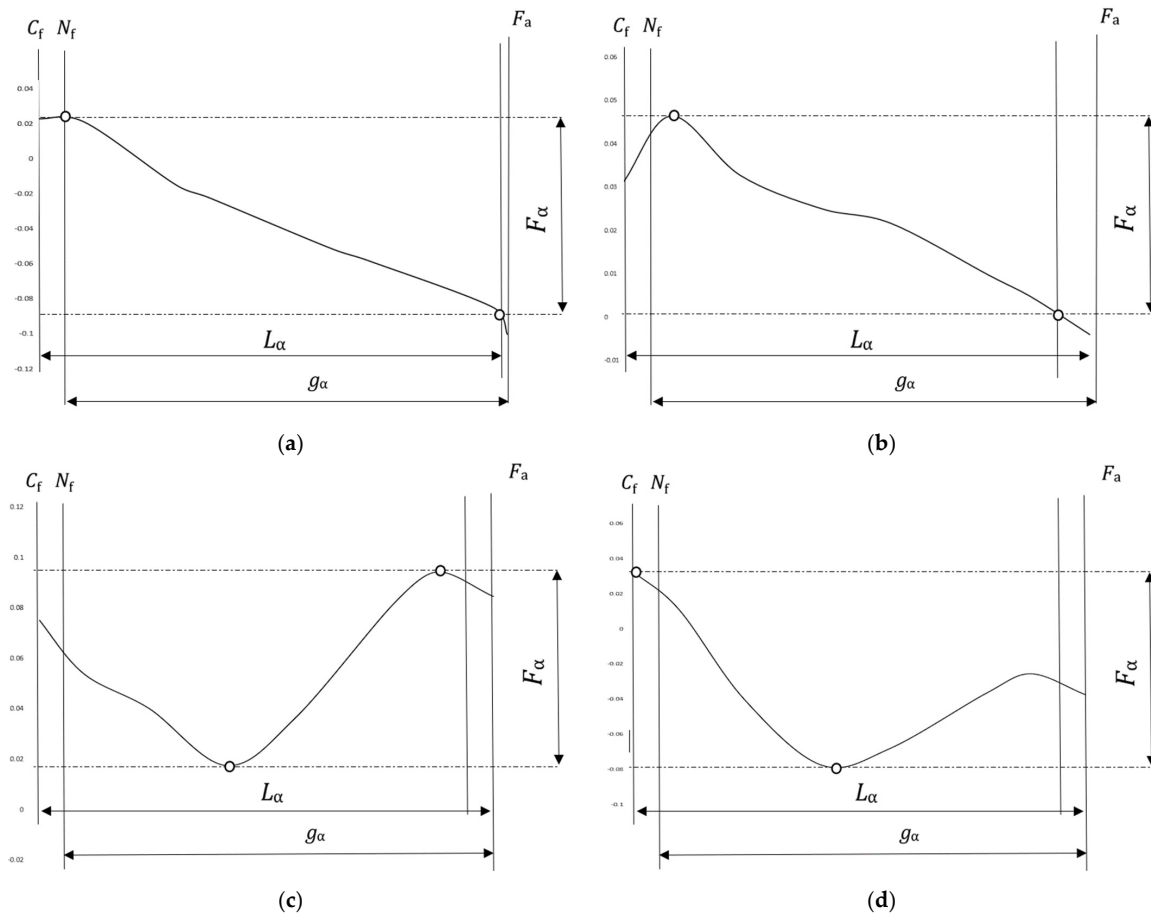


Figure 7. Total profile deviation: (a) Injection-molded gear sample Z1; (b) Injection-molded gear sample Z2; (c) 3D-printed gear sample Z3; (d) 3D-printed gear sample Z4.

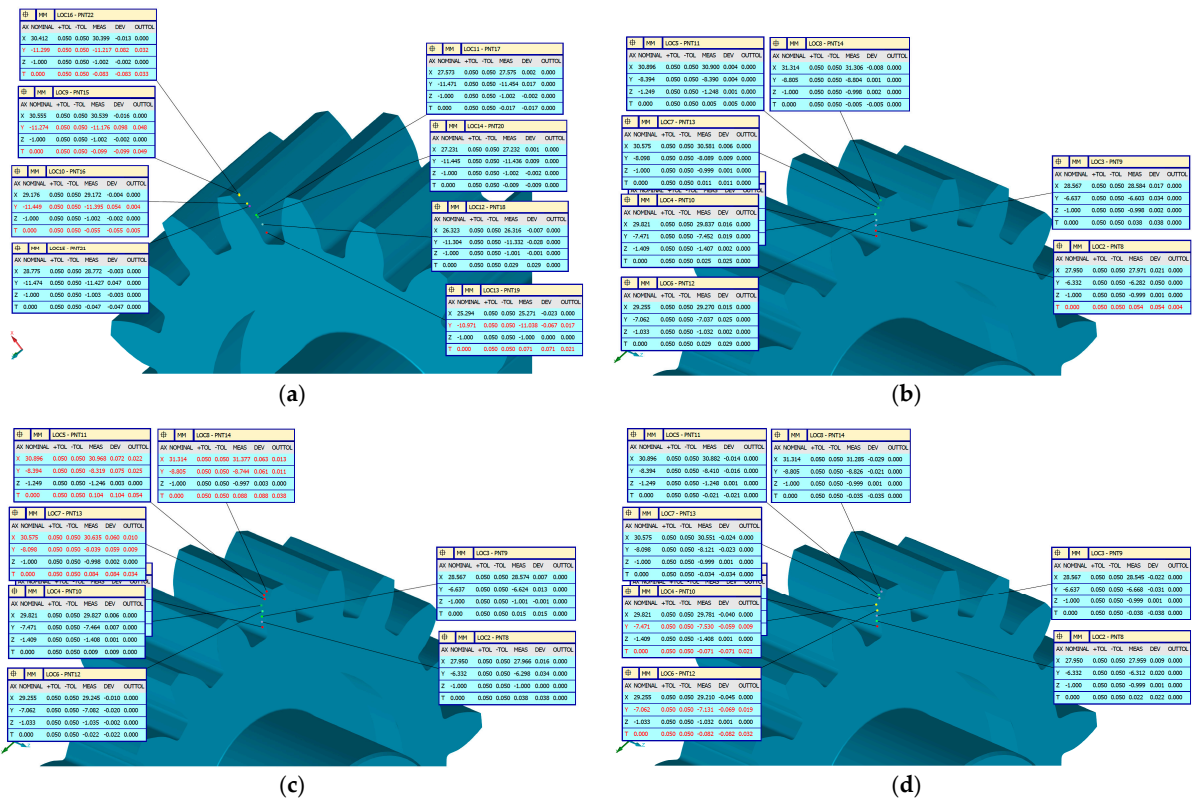


Figure 8. CMM report for tested gears: (a) Z1; (b) Z2; (c) Z3; (d) Z4.

Table 3. Measured points and their deviation.

Gear Sample	Diameter (mm)	L_a (mm)	Deviation (mm)
Z_1	57.305	0.4655	0.029
	59.072	1.3773	−0.009
	59.719	1.7181	−0.017
	61.916	2.903	−0.047
	62.637	3.3012	−0.055
	64.806	4.5269	−0.083
	65.040	4.6616	−0.099
Z_2	57.341	0.4838	0.054
	58.675	1.17	0.038
	60.214	1.981	0.029
	61.507	2.679	0.025
	63.275	3.657	0.011
	64.038	4.0882	0.005
	65.044	4.6639	−0.005
Z_3	57.342	0.484	0.038
	58.671	1.168	0.015
	60.187	1.966	−0.022
	61.507	2.679	0.009
	63.363	3.7068	0.084
	64.142	4.1473	0.104
	65.157	4.7292	0.088
Z_4	57.342	0.4843	0.022
	58.641	1.1524	−0.038
	60.141	1.9424	−0.082
	61.439	2.6421	−0.071
	63.226	3.63	−0.034
	64.034	4.0859	−0.021
	65.013	4.6461	−0.035

Differences in F_α among the four samples were used to assess the repeatability of the molding and to identify systematic versus tooth-to-tooth variation in the profile. Upon closer inspection, the profile deviation plots for the injection-molded gears exhibit a distinct slope (inclination) compared to the 3D-printed samples [11]. This indicates a pressure angle deviation unique to the molding process. This phenomenon is likely attributable to differential shrinkage during the solidification of the polymer or slight geometric offsets in the mold cavity itself.

Notably, the 3D-printed samples demonstrated slightly superior pitch accuracy in comparison to the injection-molded gears [12]. This enhancement can be attributed to the high indexing precision inherent in the additive manufacturing system, as well as the absence of non-uniform shrinkage typically induced by the flow dynamics and gate locations associated with injection molding [13].

The surface roughness was measured using the R_a parameter (Figure 9), defined as the arithmetic mean of the absolute ordinate values of the profile deviations from the mean line over a given evaluation length. The measurement is expressed in micrometers and characterizes the fine surface irregularities. The measurement results are presented in Table 4.



Figure 9. Surface roughness measurements.

Table 4. Surface roughness (Ra) measurements for 3D-printed and injection-molded gears.

No	3D-Printed (μm)	Injection-Molded (μm)
1	12.8	1.44
2	13.36	0.66
3	12.08	0.8

The measured average roughness values (Ra) show a significant difference between the two manufacturing methods: $12.75 \mu\text{m}$ for the 3D-printed parts and $0.96 \mu\text{m}$ for the injection-molded ones.

In FDM, the material is built up layer by layer, which leads to the characteristic staircase effect [14]. Each layer has a thickness on the order of $100\text{--}300 \mu\text{m}$, and the boundaries between layers form micro-edges. Additionally, vibrations of the moving print head and uneven cooling of the material introduce periodic errors and localized deformations [15]. In injection molding, the molten polymer is injected under high pressure ($500\text{--}1500 \text{ bar}$) into a steel mold with a mirror-like surface ($R_a < 0.2 \mu\text{m}$). The material flows and completely fills the surface micro-geometry of the mold, resulting after cooling, in an almost exact copy of the smooth surface.

The significant difference ($13.3\times$) places the two processes in distinct surface finish classes. The injection-molded gears ($R_a = 0.96 \mu\text{m}$) fall into class N7 (semi-finish to fine surface), which is typical for precision-machined metals or high-quality plastics. The 3D-printed gears ($R_a = 12.75 \mu\text{m}$) correspond to class N9–N10 (rough surface), comparable to a rough as-cast surface.

During gear operation, roughness directly affects tribological characteristics. The high Ra values ($12.75 \mu\text{m}$) lead to increased friction between the teeth, which translates into mechanical power losses, increased heat generation, as well as noise and vibration generation [16,17]. This leads to premature gear failure and a shortened service life. Conversely, the injection-molded gears with $R_a = 0.96 \mu\text{m}$ provide significantly lower friction, minimal heat generation, quiet operation, and long durability compared to 3D-printed gears. They are suitable for precision mechanisms such as servo drives, robotics, and clockwork mechanisms. The 3D-printed gears are generally suitable for prototypes, rapid functional tests, or low-load applications.

The results of the present study are consistent with recent findings on additively manufactured polymer gears, which report that modern 3D printing technologies are capable of producing complex gear geometries with dimensional accuracy and surface quality sufficient for low-load precision mechanical applications. However, these studies also indicate that the overall mechanical and functional performance of 3D-printed gears generally remains below that of injection-molded counterparts [18,19].

A significant number of studies made in relation to the mechanical properties of carbon fiber-reinforced polyethylene (UHMWPE and HDPE) show large increases in stiffness, strength, hardness, and typically substantial reductions in friction and wear. Performance depends on fiber content, fiber length/size, surface treatment, and use of coupling agents or solid-lubricant fillers such as graphite [20–22].

The findings of the present study align with recent research indicating that advances in additive manufacturing have enabled the production of polymer gears with dimensional accuracy suitable for low-load and precision mechanical applications, although their overall functional performance remains dependent on material selection and operating conditions. In parallel, studies on carbon fiber-reinforced polyethylene systems have demonstrated notable improvements in stiffness, strength, hardness, and tribological behavior, including reduced friction and wear compared with unreinforced polymers. These improvements have been linked to enhanced load transfer mechanisms and modified surface interactions. In this context, the present results suggest that 3D-printed gears manufactured from carbon fiber-reinforced polyamide have the potential to serve as an alternative to injection-molded gears in selected industrial applications. Nevertheless, additional studies involving larger sample sets are required to improve statistical confidence and to investigate the effect of increased surface roughness on meshing behavior, wear development, and overall gear performance during operation.

The use of different materials (POM for injection molding vs. carbon fiber-reinforced polyamide for additive manufacturing) introduces a confounding variable in this study. It is therefore impossible to isolate the effects of the manufacturing process from the material-specific responses regarding dimensional accuracy and surface characteristics. The results should be interpreted as an evaluation of representative manufacturing–material combinations rather than as a direct process-to-process assessment.

4. Conclusions

Based on the experimental results of this comparative study, the following conclusions can be drawn:

Surface roughness: The injection-molded gears exhibit a significantly lower average surface roughness ($R_a = 0.96 \mu\text{m}$) compared to the 3D-printed gears ($R_a = 12.75 \mu\text{m}$). This 13.3-fold difference is attributed to the replication of the mirror-like mold surface in injection molding versus the staircase effect inherent to the layer-by-layer FDM process.

Surface finish classification: According to ISO 21920-1:2021, the injection-molded gears fall into class N7 (semi-finish to fine surface), while the 3D-printed gears correspond to class N9–N10 (rough surface), comparable to a rough as-cast surface [23].

Total profile deviation ($F\alpha$): The injection-molded sample Z2 achieved the lowest total profile deviation ($59 \mu\text{m}$), demonstrating the potential of injection molding for high geometric accuracy. However, sample Z1 showed the highest deviation ($128 \mu\text{m}$), indicating process variability. The 3D-printed samples exhibited consistent $F\alpha$ values (110 – $124 \mu\text{m}$).

Pitch accuracy (f_p): The 3D-printed gears demonstrated slightly superior single-pitch deviation (0.53 – $0.56 \mu\text{m}$) compared to the injection-molded gears (0.61 – $0.68 \mu\text{m}$). This suggests higher indexing precision in the additive manufacturing system, as well as the absence of non-uniform shrinkage typically induced by flow dynamics in injection molding.

Pressure angle deviation: The distinct slope observed in the profile deviation plots of injection-molded gears indicates a pressure angle deviation unique to the molding process, likely attributable to differential shrinkage during polymer solidification or geometric offsets in the mold cavity.

Application suitability: Injection-molded gears are suitable for precision mechanisms requiring low friction, minimal heat generation, quiet operation, and long durability—such

as servo drives, robotics, and clockwork mechanisms. Three-dimensional-printed gears are generally suitable for prototypes, rapid functional tests, or low-load applications where extended service life is not critical.

Future work: Further investigations should focus on using identical materials for both manufacturing processes to isolate the effect of the manufacturing method from material properties, as well as optimizing 3D printing parameters (e.g., lower printing speed) to improve surface quality.

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