INVESTIGATING THE GEOMETRIC ACCURACY OF PRINTED GEARS AND IMPROVING THEIR ACCURACY

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Abstract

3D printing technology has completely changed the manufacturing processes concept because of its tremendous benefits over conventional methods. 3D printing offers an advantageous method for producing complex components economically, as it rapidly prototyping, lowers the material waste, increases the component strength and design flexibility which gives the designers the ability to modify the parts production easily. In different sectors, 3D printed gears have become a feasible substitute for noncrucial applications, like automotive and medical. The lightweight, adaptable design, unnecessary use of expensive tooling in the production processes and simpler to accommodate in confined areas, have made them ideal for low-volume applications. In this article, a series of experiments are presented to explain the shape deviations experienced in printed gears. We will demonstrate the nature of the relationship between the shape deviation and the module which is a characteristic dimension of the gear. The pitch inaccuracy (the chordal thickness at the pitch circle), gear span and gear runout will be investigated through these experiments. These investigations aim to ensure that 3D-printed gears, after specially defined geometric modifications, meet industry standards in terms of precision and endurance, promoting broader use in multiple industrial sectors.

Keywords: 3D-printed gears, gear span, gear runout, chordal thickness, pitch circle.

1. Introduction:

Additive manufacturing, utilizing 3D-printing, is revolutionizing production in sectors like automotive, aerospace, robotics, and medical. It offers cost-effective, rapid prototyping, waste reduction, and high-strength components, while controlling the printing parameters, build plate temperature and humidity for dimensional stability. The following academic articles indicate that many researchers have employed this technology in their studies.

In 3D-printed gears, PLA with reduced infill ratios demonstrates superior dimensional accuracy relative to nylon, which shows greater deviations but fewer roundness defects and improved concentricity, making PLA more effective in minimizing dimensional errors [1]. In the context of ABS gears, build plate temperature is the primary factor in reducing shrinkage, surpassing other variables such as layer thickness, nozzle temperature, print speed, and infill density [2]. A comparison of vertically and horizontally printed ABS gears with a horizontally printed PA gear revealed that the horizontally printed ABS gear exhibited superior dimensional accuracy, characterized by diminished rotational errors and profile deviations. The PA gear exhibited significant shrinkage. Effective management of temperature and humidity is crucial, and the horizontal ABS gear may meet ISO accuracy standards, despite challenges related to profile tolerance [3]. While increasing the print speed and layer thickness results in precise tooth geometries with smooth surfaces and dense structures, underscoring the importance of digital modeling in low-power applications [4]. High emissivity in darker-colored enhances shrinkage due to greater heat absorption relative to white components, hence enhancing the quality of FDM parts in a cost-effective manner [5]. Furthermore, part shrinkage in FDM diminishes with increased internal diameters, signifying enhanced dimensional stability, whereas external diameters exhibit negligible shrinkage, and elevated infill percentages mitigate shrinkage for components with same internal diameters [6]. The gear design requires precise CAD models, though working quickly, CAD software spline approximations lose accuracy with larger gear module sizes, making an equation-based method effective for producing high-quality gears [7].

2. Methodology:

This part illustrates the examination of the dimensional accuracy of the tooth pitch and employs an experimental methodology to assess the impact of shrinkage on additively manufactured spur gears. The process involves gear design and manufacturing via FDM, dimensional measurement, and comparison with nominal CAD specifications.

Spur gears were modeled in accordance with standards by using NX software. Later, the designed gears were exported in STL format, sliced using UltiMaker CURA software, then manufactured using UltiMaker[3] 3D-printer with tough PLA material, then the results came out with several measurements using the KEYENCE VHX-6000 microscope. In order to study the shrinkage phenomena properties, printing parameters such as infill density 100%, nozzle temperature 210.0 °C, print speed 45.0 mm/s, nozzle diameter 0.4 mm, layer height 0.1 mm, and build plate temperature 60.0 °C, kept constant during the manufacturing processes.

The gear was designed with the help of the involute curve technique, as shown in the standard equations below, (d_b) refers to the base circle diameter and (φ) is a variable angle starts from zero and located between the generated line (which is always tangent to the base circle) and the positive x-axis, so with different (φ) angle, a new position of the tangent line is created, finally the involute curve is created as shown in Figure 1. Subsequently, there is no need for the z-coordinate as the modelling is in the x,y plane. For various module dimensions the [teeth number of the gear were 18, base profile angle was 20° and the bore diameter was 15 mm], during the designing process, all the mentioned parameters were kept constant. Figure 2 shows the 3D model of the involute curve using NX CAD.

$$x = \frac{d_b}{2} [\sin(\varphi) - \varphi \cos(\varphi)] \tag{2.1}$$

$$y = \frac{d_b}{2} [\cos(\varphi) + \varphi \sin(\varphi)] \tag{2.2}$$

$$z = 0 \tag{2.3}$$

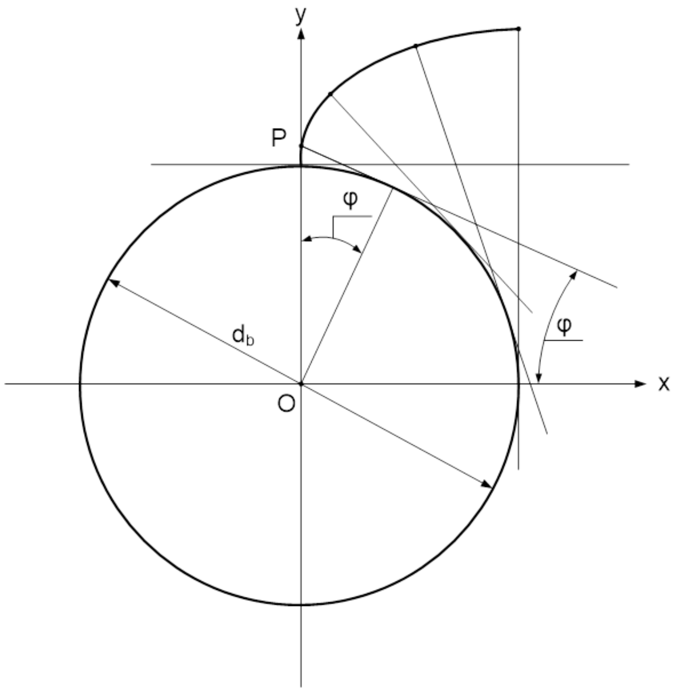


Figure 1. Involute curve creation [8].

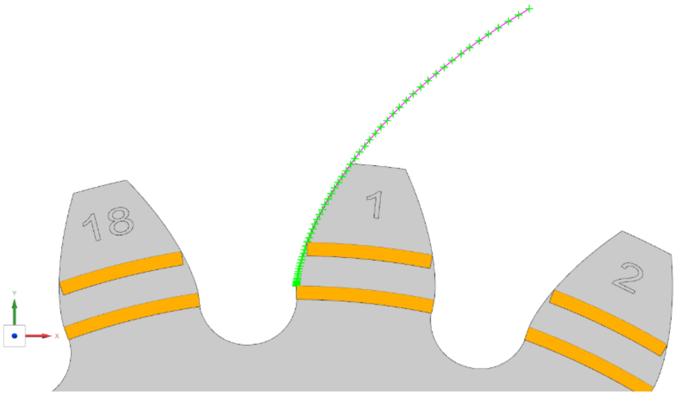


Figure 2. Creating the involute curve using NX.

A reference markings were included into the gear design as printed surface features, as shown in Figure 3, these included indicators for tooth numbering, the pitch circle, the base circle, and an x y coordinate system, allowing for easier alignment and dimensions measurement using the microscope across all samples.

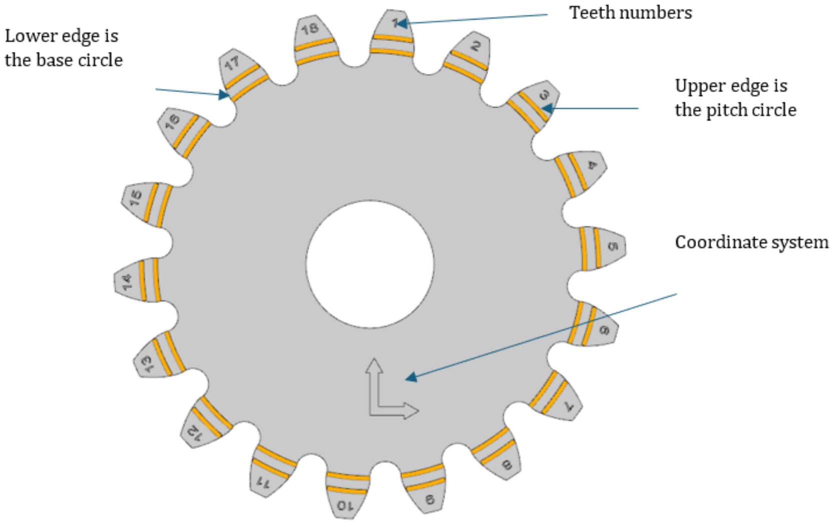


Figure 3. CAD model of the designed spur gear.

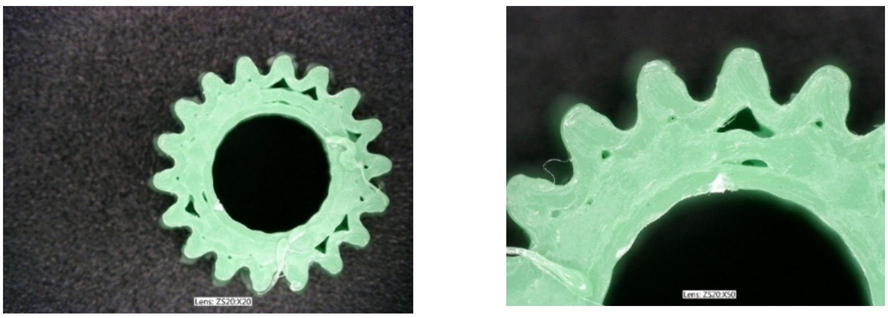
3. Results

a) Chordal thickness

In order to determine the shrinkage rate and the pitch deviation occurred to the gear tooth; the deviations were analyzed and measured using Excel. The spur gear model was printed using the nominal CAD dimensions as shown in Figure 4.

Figure 4. 3D-printed spur gears.

Due to the big shrinkage and deformation, modules (0.5, 1.0 and 1.5 mm) were ignored from the measurement, because of several faults in the printed gears as noted in Figure 5, there were difficulties in measuring their dimensions.



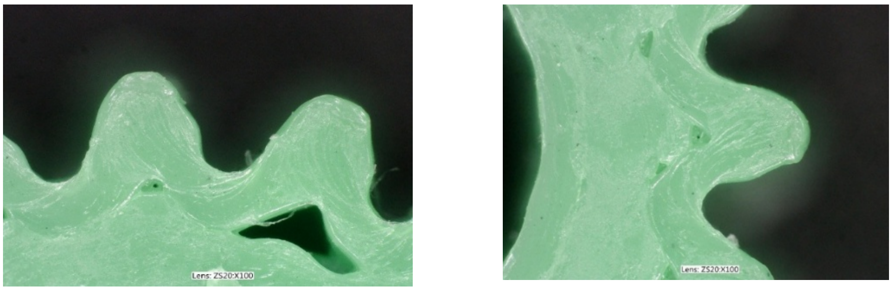


Figure 5. Defected 3D-printed gears extracted from KEYENCE VHX-6000 microscope with different rates of magnification.

The printed measurements as explain in Figure 6, gives almost smooth gear profile, the given results were concentrated on the pitch circle error for each module, shown below in Table 1, the negative sign indicates that the printed gear is smaller than nominal CAD dimensions, however, all the 18 teeth are obvious that they are close to the teeth average which mean somehow the accuracy is exist as a primary print, as they are expressed in Figure 7, Figure 8 and Figure 9 below.

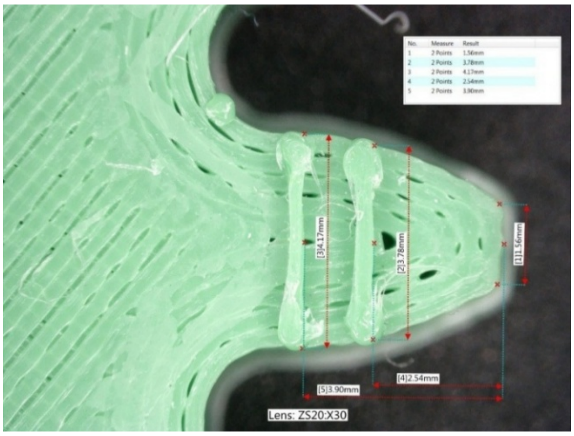


Figure 6. First print of the spur gear.

Table 1. First print results (pitch circle).

Module (mm)	Average error (%)
2.0	-3.97%
2.5	-4.63%
3.0	-3.07%

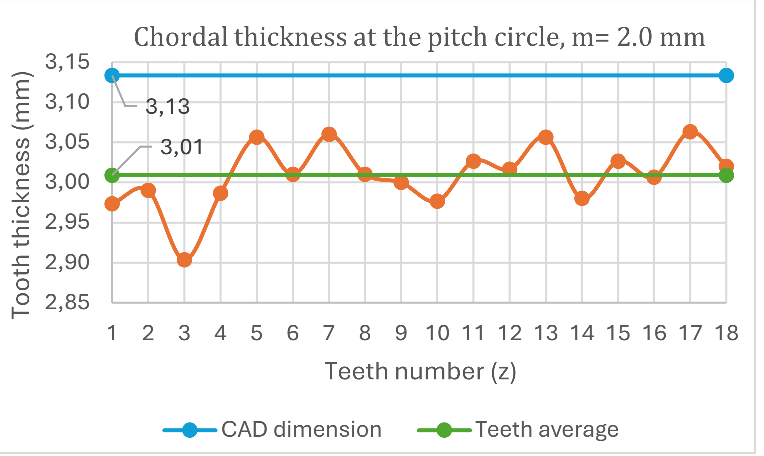


Figure 7. Chordal thickness at the pitch circle, m= 2.0 mm (-0.12 mm between blue & green lines)

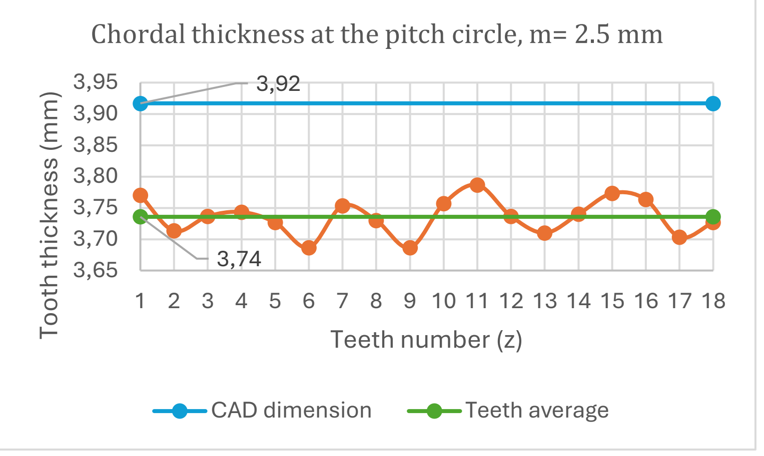


Figure 8. Chordal thickness at the pitch circle, m= 2.5 mm (-0.18 mm between blue & green lines).

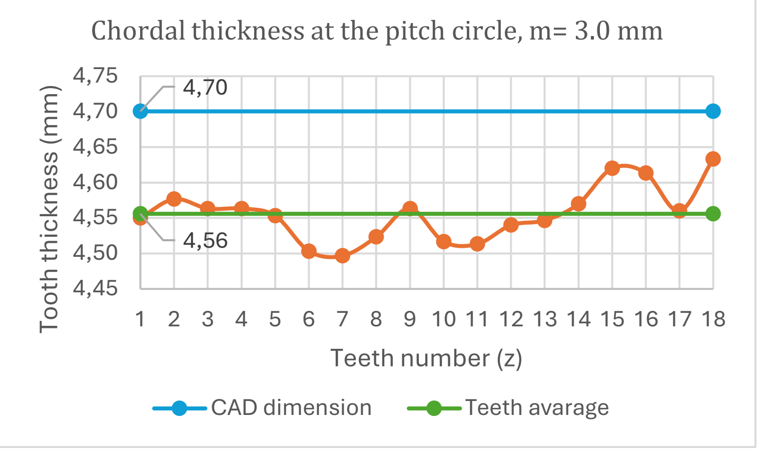


Figure 9. Chordal thickness at the pitch circle, m= 3.0 mm (-0.14 mm between blue & green lines).

b) Gear span

As shown in Figure 10, span measurement (W) is a method to measure the tooth thickness over a number of teeth (k) using a special tooth thickness micrometer. The value measured is the sum of normal tooth thickness on the base circle, and normal pitch [9].

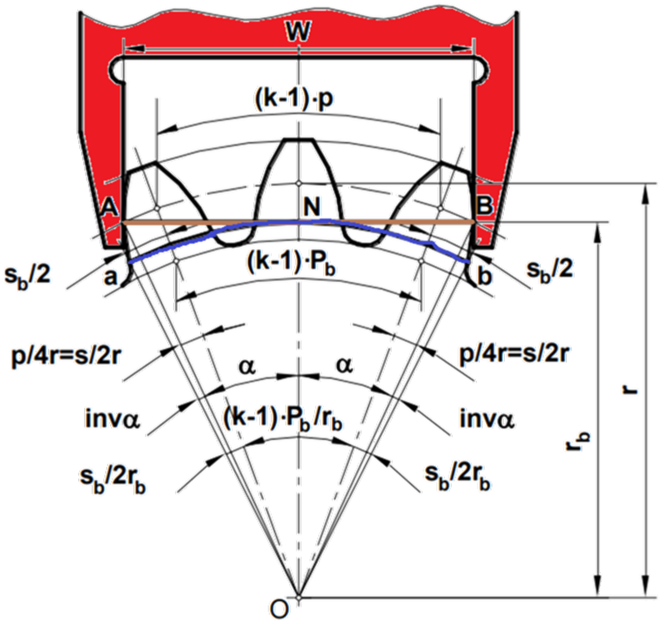


Figure 10. Gear span measurement.

Mathmatically, the gear span can be meaasured as shown below with the equations.

Teeth needed for measurement: $$k = z \, . \, \frac{\alpha}{180} + 0.5 \quad (3.1)$$

The value of the gear span

$$W = (k\text{-}1) \, . \, p_b + s_b \quad (3.2)$$

The base pitch

$$p_b = m \, . \, \pi \, . \cos(\alpha) \quad (3.3)$$

The tooth thickness (arc)

$$s_b = 2 \, . \, r_b \, . \, (\frac{s}{2r}) + inv(\alpha) \quad (3.4)$$

The calculation of inv(α)

$$inv(\alpha) = \tan(\alpha) - \alpha \, . \, \frac{\pi}{180} \quad (3.5)$$

So, the gear span:

$$W = [(k\text{-}0.5) \, . \, \pi + z . \, inv(\alpha)] \, . \, m \, . \cos(\alpha) + 2 \, . \, x . \, m . \sin(\alpha) \quad (3.6)$$

x = profile shift coefficient

Practically, the gear span can be measured by the micrometer as presented in Figure 11.

Figure 11. gear span measuring methodology.

The mathematically initial results come from Table 2, and from Table 3 are the measured results that come from the use of the micrometer. It is obvious that difference between the two results is so small, subsequently, the FDM technique can be considered accurate and reliable in the gear manufacturing industry.

Table 2. Gear span (calculated)

Module (mm)	Gear Span (mm)
1.5	11.44864
2	15.26486
2.5	19.08107
3	22.89728

Table 3. Gear span (measured)

Module (mm)	Gear Span (mm)
1.5	11.42466667
2	15.23083333
2.5	19.01583333
3	22.8505

c) Runout

Runout is mainly affected by roundness errors and, to a lesser extent, by concentricity errors. Figure 12 illustrates that runout is determined in relation to the central hole of the gear. The position of the central hole is determined, and its geometrical center point has been defined as the datum center point (DCP), as seen in Figure 12a. The concentricity characterizes the deviation between the datum center point DCP, denoted by "O" and the center point of gear teeth, denoted by "X". The property of being concentric, it can be regarded as almost twice the eccentricity error (f_e), representing the distance between "X" and "O" points in Figure 12b. The roundness error is defined as the radial difference between the largest circumscribed circle and the smallest circumscribed circle, both sharing the same center point, that encloses all tooth positions, as illustrated in Figure 12c. The radial runout includes both concentricity error and roundness error, as seen in Figure 12d [10].

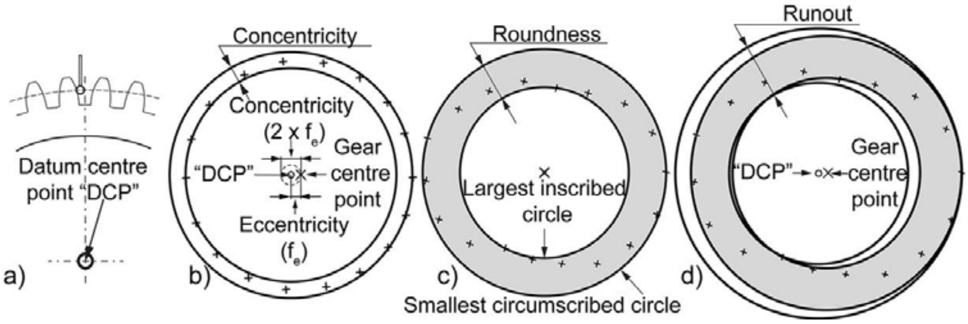


Figure 12. runout measurement, a) tooth position probed relative DCP, b) concentricity error, c) roundness error and d) runout[10].

Figure 13 shows the runout device, the yellow platform (base) has been designed and 3D printed so the gear can fit properly. The dimensions of the prism pair V-block were designed to fit the shaft diameter. The dial indicator of the measuring device consists of 2 measuring dials, the bigger dial gives the runout measurement with hundreds of millimeters for 100 steps by 0.01 mm for each step, and the smaller dial indicates millimeters and how many times does the runout move with a range of 10.0 mm. Later the gear will be mounted to the shaft by a Trantorque Mini while taking into consideration the concentricity. Then, the contact prob will touch the top land of the tooth (in 3D printing technology when printing a gear, the top land and the flank will be manufactured at the same time and what results we get from the first it will give an information about the other, so measuring at the top land or at the flank will give same results while using 3D printing) and the radial runout is measured by giving the readings for the 18 teeth.

Figure 13. Gear runout device.

The results as shown in Table 4 revealed that dimensional accuracy in 3D printed gears highly depends on the gear module. The results varied across the modules, with the lowest runout at 2.5 mm (0.0051 mm). These findings indicate that shrinkage effects play a substantial role in determining accuracy.

Table 4. Runout measurements results.

Module (mm)	Runout (mm)
2.0	0.0990
2.5	0.0051
3.0	0.0624
3.5	0.0131

4. Conclusion:

The research investigated both dimensional precision and shrinkage responses of spur gears produced through Fused Deposition Modelling (FDM) techniques. The printed gears showed consistent deviations from their CAD nominal dimensions, primarily material shrinkage. Chordal thickness measurements resulted in a gear dimension that was smaller than the nominal CAD dimensions, while gear span results showed almost identical between the theoretical and measured values. Runout analysis indicated an acceptable levels of concentricity and roundness errors. In summary, the results confirm the reliability of the FDM printing process under controlled conditions while shrinkage and dimensional deviations are inherent to the FDM technology, 3D printed gears can achieve sufficient geometric accuracy for practical applications when carefully designed and manufactured.

5. Future work:

For future work, several 3D prints will be conducted in order to get more closer to the nominal CAD dimension. An average error is going to be added to the original dimension for the purpose of compensating the shrinkage happened to the printed gear, while the material remains same (tough PLA). The average error is the error between the printed gear and the nominal CAD dimensions that occurred for the 18 teeth and was calculated from the first print by subtracting the printed chordal thickness from nominal CAD chordal thickness for the different modules at the pitch circle. As a second print, half of the average error will be added, regarding the third print, whole average error will be used to create a new involute curve for the spur gear design. As a result of the error compensation, one print will be chosen to create a spur gear design able to handle the shrinkage and get proper results more precise to the nominal dimensions.

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