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THE INVESTIGATION OF DIMENSIONAL, FORM AND ORIENTATION ACCURACY OF POLYMER GEARS PREPARED BY ADDITIVE MANUFACTURING

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Abstract

Among the additive manufacturing techniques Fused Deposition Modeling (FDM) is a widely used process, due to its rapid development in the recent years, and its consequent drop in price. 3D printing has multiple process parameters, which affect the dimensional, form, and orientation accuracy, and thus the usability of the final product. In this work the effects of layer thickness, printing speed, and infill on the dimensional and geometric deviations were studied with a 3 factor Box-Behnken experimental design. The measured deviations were within the tolerance range specified by the standards. Based on this, it can be stated that 3D printing is a promising gear manufacturing technology for light and medium load applications.

Keywords*: spur gear, 3D printing, additive manufacturing, accuracy, Box-Behnken.*

1. Introduction

Gear drives are among the most important mechanisms in power-transmission applications. The market share of gears is increasing each year, and according to projections will reach USD 218.7 billion by 2030 **[1]**. The demand for gears used in light and medium load applications is especially high, and in these cases plastic gears are a potential replacement for metal ones. They have several advantages, including low weight, increased vibration dampening, smooth operation, easier and cheaper production, and operation without a lubricant **[2]**.

Additive manufacturing provides a promising alternative for the production of plastic gears on a small scale **[3]**. Fused Deposition Modeling (FDM), due to its widespread availability, makes it possible for the average user to produce completely unique parts at home. The process consists of a plastic filament being fed into a heated chamber called an extruder, during which the plastic becomes semi-molten. The plastic melt exits the chamber through a nozzle and, using a CNC machine, is deposited on a flat surface layer-by-layer, until the part is fully built. FDM has various production parameters, some of which influence the surface roughness and geometrical accuracy of the product.

The aim of this work is to study the effect of three printing parameters, namely layer thickness, printing speed, and infill density on the dimensional, form, and orientation accuracy of printed spur gears.

2. Experimental

2.1. Materials

The gears were printed from a poly(lactic acid) (PLA) filament (Sunlu PLA Black 1510101A) with a 1.75 mm thickness.

2.2. 3D model generation

The 3D model of the gear was created in CATIA V5R17 in the Generative Shape Design module. The gear had 21 teeth, a module of 3 mm, and base radius $r_a = 29.6$ mm. The involute tooth profile was generated with the following parametric equations:

$$\begin{cases} x = r_a \sin\theta - r_a\theta\cos\theta \\ y = r_a \cos\theta + r_a\theta\sin\theta \\ z = 0 \end{cases} \quad (1)$$

The involute was generated once, and then multiplied with mirror and pattern functions.

2.3. Experimental design

The 3-factor Box-Behnken design was generated in MiniTab 16. The selected parameters were the layer thickness, printing speed, and infill density. Scouting experiments were performed in order to determine the limiting values for each parameter. **Table 1** shows the values for the three levels in each case. The design was created with 3 center points.

Table 1. *Box-Behnken experimental design parameters and levels.*

Printing parameter	Low (-1)	Middle (0)	High (+1)
Layer thickness [mm]	0.1	0.15	0.2
Printing speed [mm/min]	40	80	120
Infill [%]	10	30	50

The studied response variables were the dimensions of the addendum circle (LOC1), the dedendum circle (LOC2), and the bore (LOC3), the flatness of the frontal surface (FLAT1), the cylindricity of the bore (CYLY1), the circularity of the addendum (CIRC1) and dedendum circles (CIRC2), the perpendicularity of the bore to the frontal surface (PERP1), and the concentricity of the addendum and dedendum circles with the bore (CONCEN1, CONCEN2).

2.4. 3D printing

The printing was performed with an Artillery Sidewinder X2 3D printer. The G-code used by the printer was generated in the Prusa slicer software based on its 0.2 mm SPEED Prusa preset, and only the parameters listed in **Table 1** were adjusted. The operating temperatures of the nozzle and the table were set at 210°C and 60°C respectively. The gears were printed with a honeycomb (hexagonal) infill pattern.

2.5. Coordinate metrology

Coordinate measurement was carried out on a Hexagon Tigo SF coordinate measuring machine (CMM). The setup involved a medium force (MF) touch trigger probe equipped with 40 mm long steel stylus and a spherical ruby tip of 2 mm diameter. The measurements were carried out at 18±0.5 °C.

Planes were measured with 12 points (frontal surface), circles with 7 points (addendum and dedendum circles), and cylinders with 25 points (bore), as seen in **Fig. 1**. In every case the least squares method was used for fitting the respective geometric objects on the point sets. The raw data processing was carried out in Hexagon PC-DMIS 2019 software.

The gears were positioned using the fixture shown in **Fig. 1**. Three pins were lodged between the teeth, and these came in contact with the jaws of the vice, ensuring a consistent rotation. A vice stop and a gauge block serving as a spacer were used to determine the linear position parallel to the vice jaws

Fig. 1. *The gear held by the fixture.*

3. Results and Discussion

Fig. 2 shows the frontal view of the gear and the involute tooth profile. The circles marked in the drawing belong to the addendum (D_a, 69 mm), dedendum (D_d, 56 mm), and bore (D_b, 15 mm).

The studied geometric tolerances can be seen in Fig. 3.

The printing conditions, as given by the Box-Behnken design, and the measurement results for each gear are presented in Table 2. Gears produced with 0.15 mm layer thickness, 80 mm/min printing speed, and 30% infill density appear 3 times in the table, hence the three center points.

As a basis of comparison, tolerances from the ISO 2768-cL standard were taken according to the c (dimensions) and L (form and orientation) tolerance classes. Table 3 contains the intervals of the measured values and the associated dimensional, form, and orientation tolerances.

All three measured dimensions (D_a, D_d and D_b) were smaller than their nominal value on the 3D model. This can be attributed to the shrinkage during printing, and it can be compensated for by making the 3D model 1-2% larger. As for the form and orientation tolerances, the largest deviations reached the 0.3-0.45 mm range, flatness being the only exception, where the values were one order of magnitude lower. However, all values were within their specified tolerance.

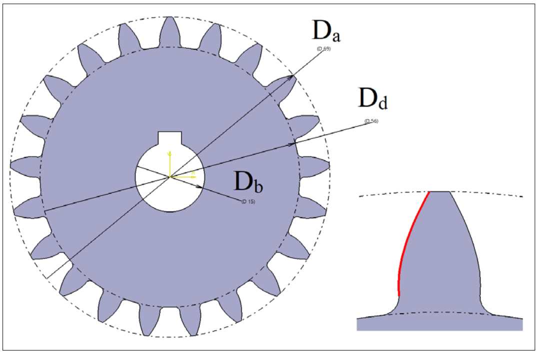

Fig. 2. *Frontal view of the 3D model of the gear in CATIA V5. The involute generated from the equations is drawn in red.*

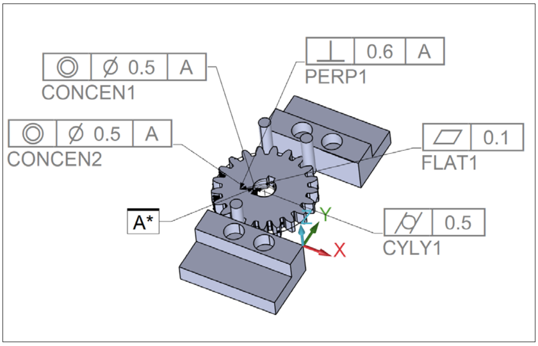

Fig. 3. *Definition of the form and orientation tolerances featured in the study. The axis of the central bore was chosen as datum A.*

Table 2. *Printing conditions of the 15 produced gears.*

No.	Layer thickness [mm]	Printing speed [mm/min]	Infill [%]
1	0.15	120	50
2	0.1	120	30
3	0.15	80	30
4	0.2	80	10
5	0.1	80	10
6	0.2	80	50
7	0.15	40	50
8	0.1	80	50
9	0.15	80	30
10	0.2	120	30
11	0.15	120	10
12	0.15	80	30
13	0.15	40	10
14	0.2	40	30
15	0.1	40	30

Table 3. *Measured values for the studied features.*

Feature	Measured value [mm]	Tolerance* [mm]
Addendum circle diameter deviation (ΔD_a)	−0.449 - −0.072	±0.8
Dedendum circle diameter deviation (ΔD_d)	−0.392 - −0.083	±0.8
Bore diameter deviation (ΔD_b)	−0.126 - −0.01	±0.5
Flatness (FLAT1)	0.013 - 0.06	0.1
Cylindricity (CYLY1)	0.064 - 0.149	0.5
Perpendicularity (PERP1)	0.132 - 0.44	0.6
Concentricity (bore-addendum) (CONCEN1)	0.009 - 0.315	0.5
Concentricity (bore-dedendum) (CONCEN2)	0.045 - 0.354	0.5

*according to ISO 2768-cL.

The response surface regression analysis based on the Box-Behnken experimental design was used to determine which printing parameters affected the dimensional/geometric deviations. The ANOVA of each response variable did not indicate any statistical significance for the effect of the printing parameters on the various geometric features. Out of the linear, squared, and interaction terms of all the studied features only in case of the PERP1 were the linear and squared terms of the infill significant in the 95% confidence interval, as indicated by p-values of 0.048 (infill) and 0.03 (infill*infill) respectively. The regression model had an adjusted R-squared of 51.04% (R-sq. = 82.51%), showing a relatively good fit and indicating that the created regression model can somewhat explain the variability of the data. This was the highest of all the adjusted R-sq. values, which otherwise ended up being 0-30%. The results showed that the deviations were lowest at 30% infill, and higher on the two extremes, as shown by the main effects plot (**Fig. 4**). As for the absolute value of the main effect, it can be seen that the average perpendicularity error decreased from 0.35 mm to 0.21 mm when the infill was increased from 10% to 30%, and increased to 0.32 when at 50% infill. The probable explanation for why, at an infill density of 30, the perpendicularity error was lowest is that at high infill densities, due to the larger amount of bulk material, the higher shrinkage-induced stress causes the part to deform. At low infill the part consists mostly of a shell, in which case the thermal stresses throughout the shell overwhelm the significantly reduced inner structural support, also resulting in deformation

While according to the regression model the effect of the infill was only significant on the PERP1 (**Fig. 4**), the majority of the main effects plots for the other features also showed the trend of the geometric deviation being lowest at 30% infill, but it may be due to random chance.

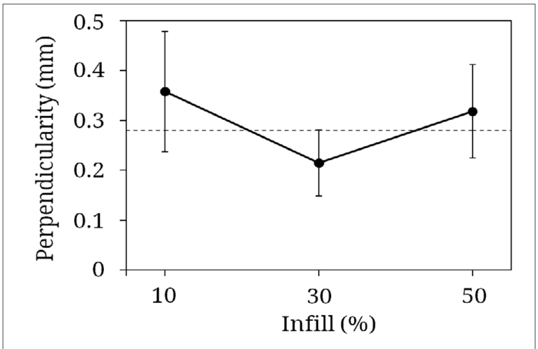

Fig. 4. *Main effects plot of PERP1.*

Others have found that in general increasing the layer thickness causes the form/orientation deviations to increase **[4]**. The explanation is that at a higher layer thickness shrinkage becomes more pronounced, especially in the stacking (usually vertical) direction **[5]**, and this in turn induces higher stresses. In our data set both increasing and decreasing trends can be observed, but since there is no indication for any correlation, it can only be attributed to randomness. Regarding the increasing printing speed, the published results are conflicting. Some reported decreased dimensional accuracy **[4]**, while others observed an overall improvement **[6]**.

Another contributing factor, not included in the study was the surface roughness of the parts. Besides the roughness caused by the layering, usually burrs are present on the vertical faces (such as the surface of the bore), which can interact with the measuring probe. The gears did not receive any surface treatment (aside of the removal of the larger burrs that would have prevented the measurement) in order to preserve the results created by the printer as faithfully as possible, so these surface deviations could have caused a lot of random noise in the data.

4. Conclusions

The dimensional, form, and orientation deviations of spur gears produced by FDM were within their respective tolerance ranges, as defined by the ISO 2768-cL standard. According to the statistical analysis only the infill density had a significant effect on the perpendicularity, while no other correlations were found, and this indicates that FDM is a robust manufacturing process.

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