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PRECISION ASSESSMENT IN ADDITIVE MANUFACTURING OF PLASTIC GEARS

Bloju A.V.[1], Korka Z.I. [*2], Bara A.[3], Traistaru D.E.[4], Sfetcu C.R.[5]

1. Department of Engineering Science, Babeş-Bolyai University, Cluj-Napoca, Romania, alin.bloju@ubbcluj.ro
2. Department of Engineering Science, Babeş-Bolyai University, Cluj-Napoca, Romania, zoltan.korka@ubbcluj.ro
3. Department of Engineering Science, Babeş-Bolyai University, Cluj-Napoca, Romania, aurel.bara@ubbcluj.ro
4. Department of Engineering Science, Babeş-Bolyai University, Cluj-Napoca, Romania, elena.traistaru@ubbcluj.ro
5. Department of Engineering Science, Babeş-Bolyai University, Cluj-Napoca, Romania, camelia.sfetcu@ubbcluj.ro

[*]Corresponding author: zoltan.korka@ubbcluj.ro

Abstract: *In recent decades, a significant increase in the use of plastic gears has been observed. Thus, in terms of quantity, their production exceeds that of ferrous material gears. The advantages of additive manufacturing, linked to the elimination of injection mould costs, has allowed an explosive development of this technology in the field of plastic gear. The present study aims to assess the precision of additive manufactured (AM) plastic gears. Therefore, in a first step, the optimal thickness of the deposited material layer was determined, which would ensure the required accuracy in the shortest manufacturing time. Further, using this technological parameter, gears with different widths (6, 7, 8 and 10 mm) were printed and the influence of the width on the main indicators, which define the manufacturing accuracy of the gears, was evaluated. The results obtained are likely to complete the knowledge on additive manufacturing of plastic gears.*

Keywords: additive manufacturing, gears, *plastic material, precision*

INTRODUCTION

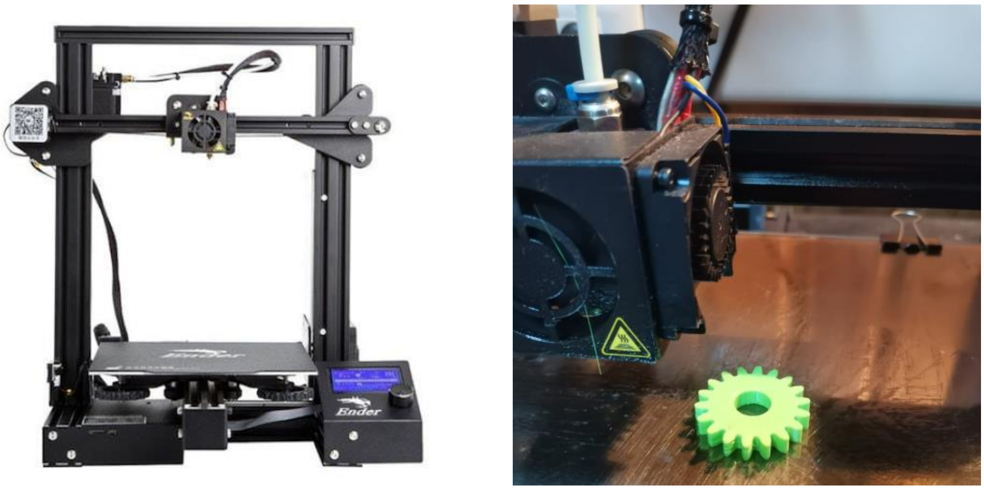
Using computer-aided design (CAD) or 3D object scanners, AM allows the creation of gears with precise geometric shapes and little waste [1]. These are built layer by layer, unlike traditional manufacturing, which often requires machining or other techniques to remove excess material. The lack of material waste ensures cost savings for high-value parts manufactured by AM technology [2].
Thus, producing high-quality gears at low cost is no longer a challenge after the development of this technology [3]. Scientific instruments, harmonic drives, printers, robotic drives, home appliances, office machines and electronic gadgets etc. are some typical application areas of gears created by AM.
The first additive manufacturing equipment was developed in 1980 by Hideo Kodama, when he invented two additive methods for manufacturing 3D parts [4]. From then untill now, the technology was developed and perfected for the manufacturing of complex engineering parts such as gears. This technology follows a bottom-up approach to manufacture complex gear shapes of all types starting from their CAD shapes by depositing material layer by layer [5]. Figure 1 depicts the steps followed by AM technology in order to manufacture gears.

Figure 1: Steps in AM of gears

Benefits of additive manufacturing of gears over conventional manufacturing are multiple, among which the following can be listed [6]: high quality with good surface integrity, capability to produce metallic or non-metallic gears, flexibility, less tooling costs, energy efficiency, less wastage, low environmental footprints due to low emissions and short process chain.
As the results obtained in this research are promising, the authors are encouraged to follow other investigations in the direction of AM of gears.

1. MATERIALS AND METHODS

The aim of this research was to evaluate the influence of two parameters, namely the layer thickness of the deposited material and the gear width, on the precision of plastic gears produced by AM technology.
Therefore, using a 3D printer Creality Ender 3 Pro were printed by Fused Deposition Modeling (FDM) technology four gears with different layer thicknesses of the deposited material: 0.12, 0.16, 0.20 and 0.28 mm respectively.
Figure 2 shows a general view of the printer and an image during the manufacturing process, while Table 1 presents the main geometric characteristics of the printed gears.



a. b.

Figure 2: 3D printer (a. general view; b. image during the manufacturing process)

The deposition of green PLA type filament, with a diameter of 1.78 mm, was done through a standard nozzle having an inner diameter of 0.4 mm, by using a printing temperature of 205°C and a build plate temperature of 65°C. The infill was done with a triangles type pattern having a 100% infill density.

Table1. Geometric characteristics of the printed gears

Geometric characteristic	Symbol [M.U.]	Value
Teeth number	z [-]	18
Normal module	m_n [mm]	1.5
Tooth width	b [mm]	5
Helix angle	β [°]	0
Normal pressure angle	α [°]	0
Addendum mod. coeff.	x	0
Tipp diameter	d_a [mm]	30
Reference diameter	d [mm]	27
Root diameter	d_f [mm]	23.25

Each obtained gear was measured on a Computer Numeric Control (CNC) gear tester of type PNC 150, manufactured by Klingelnberg, Germany. This gear tester was also involved in different previous researches [7, 8]. A general view of the tester and an image of the measurement process are shown in Figure 3.

a.

b.

Figure 3: PNC 150 gear tester (a. general view; b. image during the measurement process)

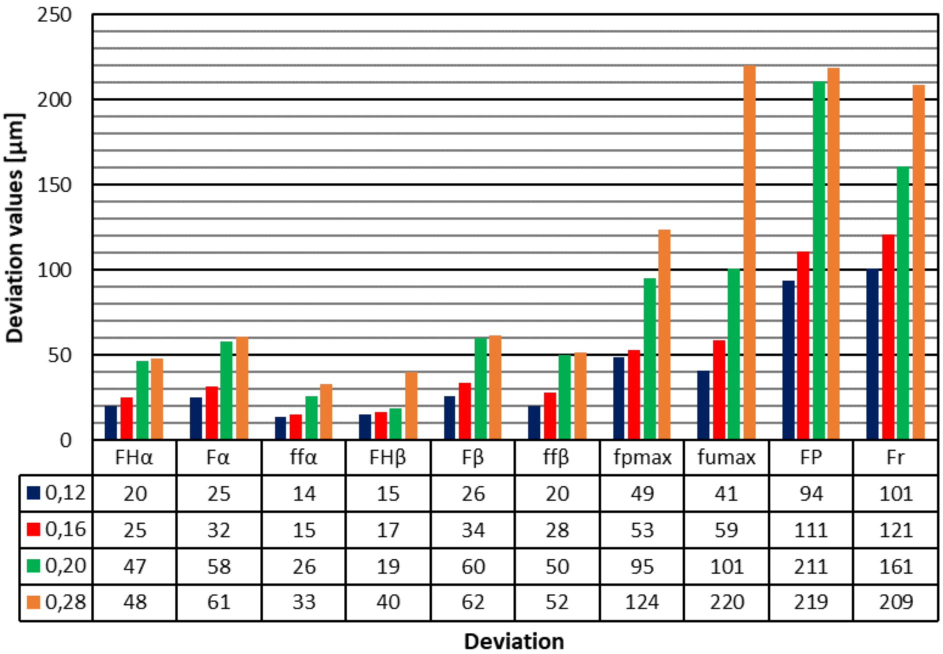
Based on the measurement results, the optimal thickness of the deposited material layer was determined. The optimization criteria was the shortest manufacturing time which ensures the required accuracy.

Further, another four gears with different widths (6, 7, 8 and 10 mm) were printed, by using this optimal layer thickness. The purpose of this approach was to evaluate the influence of the gear width on their manufacturing accuracy.

2. RESULTS AND DISCUSSION

The measurement results of the gears manufactured with the four different layer thicknesses (0.12, 0.16, 0.20 and 0.28 mm) of the deposited material are shown in Figure 4. Following deviations were evaluated according to ISO 1328-1:2013 [9]:

- Profile slope deviation ($F_{H\alpha}$);
- Total profile deviation (F_{α});
- Profile form deviation ($f_{f\alpha}$);
- Helix slope deviation ($F_{H\beta}$);
- Total helix deviation (F_{β});
- Helix form deviation ($f_{f\beta}$);
- Maximum single pitch deviation (f_{pmax});
- Maximum adjacent pitch difference (f_{umax});
- Cumulative pitch deviation (F_P);
- Radial runout (F_r);



	FHα	Fα	ffα	FHβ	Fβ	ffβ	fpmax	fumax	FP	Fr
0,12	20	25	14	15	26	20	49	41	94	101
0,16	25	32	15	17	34	28	53	59	111	121
0,20	47	58	26	19	60	50	95	101	211	161
0,28	48	61	33	40	62	52	124	220	219	209

Figure 4: Influence of layer thickness on the gear accuracy

The printing processes required the times shown in Table 2.

Table 2. Deposition time depending on layer thickness

Layer thickness [mm]	0,12	0,16	0,20	0,28
Deposition time [min]	57	37	30	24

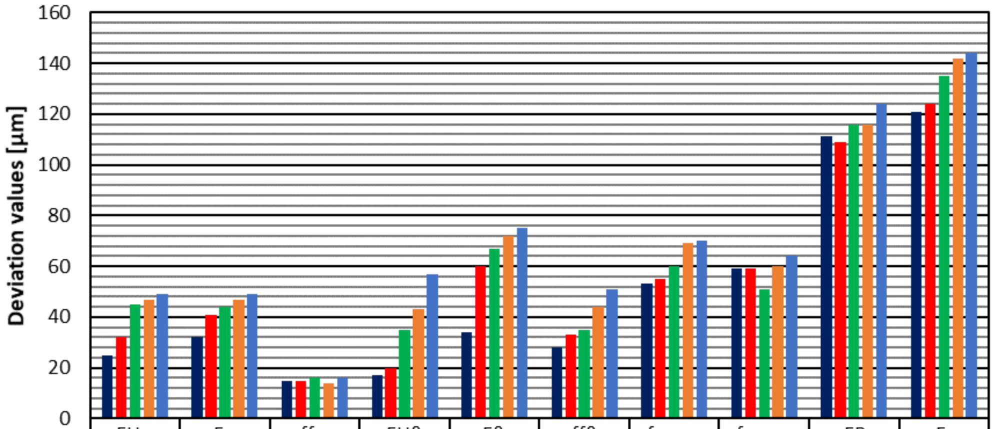
As one can observe, with the decrease of the deposited material layer thickness, the deviations from the ideal shape of the gears decrease. This leads to an increase of their precision. The deviations measured on the gears obtained with higher deposition thicknesses (0.28 and 0.20 mm), makes these gears to be classified in quality class Q12, according to ISO 1328, while the deviations measured on the gears printed with a lower deposition thickness (0,16 and 0,12 mm) corresponds to quality class Q11.
A lower layer thickness determines a longer duration of the printing process and an increase of the deposition layers. According to Cojocaru et. al. [10], increasing the layer numbers leads to a re-heat effect of the deposited layers, which improves their diffusion and adhesion, affecting positively the manufacturing accuracy.
Furthermore, a decrease of the layer thickness from 0.28 to 0.12 mm leads to a more than double increase of the deposition time (from 24 to 57 min), while the gear related deviations decrease between 57.6% ($f_{f\alpha}$) and 81.4% (f_{umax}).

Considering the fact that the printed gears with a layer thickness of 0.16 mm have a Q11 precision class, just like those made with layers of 0.12 mm, but the manufacturing time is 35% shorter (37 min, compared to 57 min), it was considered that the optimization criterion is satisfied by printing with deposition thicknesses of 0.16 mm. Thus, the following four wheels (with widths of 6, 7, 8 and 10 mm) were printed with this layer thickness. The printing processes required the times shown in Table 3.

Table3. Deposition time depending on layer thickness

Gear width [mm]	5	6	7	8	10
Deposition time [min]	37	40	47	54	67

Figure 5 presents the measurement results of the gears having different widths, which were obtained with a layer deposition thickness of 0.16 mm.



	FHα	Fα	ffα	FHβ	Fβ	ffβ	fpmax	fumax	FP	Fr
5	25	32	15	17	34	28	53	59	111	121
6	32	41	15	20	60	33	55	59	109	124
7	45	44	16	35	67	35	60	51	116	135
8	47	47	14	43	72	44	69	60	116	142
10	49	49	16	57	75	51	70	64	124	144

Deviation

Figure 5: Influence of gear width on the accuracy

As it may be observed, with the increase of the width, the deviations of the gear profile also increase. Thus, by raising the width from 5 to 7 mm, the deviations are growing in average with 36.8%, while by doubling the width, the deviations are increasing in average with 66.5%. The most sensitive parameters to the gear width variation are those related to the gear helix ($F_{H\beta}$, F_β and $f_{f\beta}$), while the the pitch associated deviations are not significantly influenced by the gear width.

3. CONCLUSIONS

The present research assesses the precision of plastic gears manufactured by 3D printing. From the results presented in this study, it can be concluded that both, the thickness of the deposited material layer and the gear width, are influencing essentially the manufacturing precision. Thus, the decrease of the layer thickness from 0.28 to 0.12 mm, even if it more than doubles the deposition time (from 24 to 57 min), it leads to an decrease of the gear related deviations in average with 60.8%. In addition, by growing the gear

width from 5 to 10 mm, increases the gear related deviations with an average value of 66.5%.
As the obtained results may contribute to the completion of knowledge in the field of plastic gears manufacturing, the authors are encouraged to extend their research in the field of failure analysis of gears obtained by additive manufacturing (AM).

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