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RESEARCH ARTICLE

FDM 3D PRINTING PROCESS PARAMETERS OPTIMIZATION USING TAGUCHI METHOD FOR IMPROVING THE GEAR STRENGTH

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Abstract

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In the recent years, 3D printing has become a topic of great interest from both academic and the industrial sector through the increasing importance of Industry 4.0. This technology is based on layer-by-layer melting of materials to create a three-dimensional object. It is also known as additive production, and it is feasible through several different methods such as stereolithography, selective laser melting and sintering (SLM, SLS), these are just some of the examples, but fused decomposition modeling (FDM) has become the most interesting technique.This paper seeks to analyze the fracture strength (torque) of coupled gears made out of PLA plastic produced by the 3D printing process. To reduce the number of experimental measurements, the Taguchi $L_8(2^7)$ orthogonal array was used to analyze the influence of factors on two level. Investigated factors were: wall thickness, infill and number of infill lines, layer height, temperature, cooling and speed. Finally, optimization of most influential factors according to maximum torque was preformed, using Taguchi method too.

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Introduction:-

The technology so called 3D printing has become a topic of great interest from both academic and the industrial sector through the increasing importance of Industry 4.0. This technology is based on layer-by-layer melting of materials to create a three-dimensional object [1]. In 2020, the 3D printing industry was worth 12.6 billion, with growth of 17% expected between 2020 and 2023 [2]. Fused decomposition modelling (FDM) is most versatile additive manufacturing process that provides functional parts and prototypes in many thermoplastic polymer due to its capability to produce complicated geometrical parts neatly and safely with eco-friendly environment [3].

The mechanical properties of 3D printed parts depend on a large number of parameters, which must be optimally adjusted and controlled in order to enable optimal characteristics in the final elements. Methods are required to support the generation of a technological knowledge base and identify the cause–effect relationships of the 3D machines process parameters with the outputs obtained to establish the minimum standards required to produce high-quality parts [4]. These parameters also affect other aspects of 3D printed elements such as dimensional precision, finishing, or cost. To produce good functional parts and increase the market share of FDM parts, it is necessary to produce parts with stable qualities to meet specific requirements [5].

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Numerous studies have been conducted in the form of manuals or websites on the effects of some of the parameters. The diagram in Figure 1 shows the parameters that affect the mechanical properties and production time of the printed element based on research. As shown in Figure 1, the most influential parameters are: infill orientation, model orientation, layer height, infill, wall thickness. However, some of the process parameters are less analyzed such as temperature, print speed and cooling. Even if these parameters are efficiently analyzed, interactions between some of the parameters not only make it difficult to predict the mechanical response of the material, but are also crucial for the development of robust process relationships and design-facilitating properties. However, not all parameters have the same effect on mechanical properties. In this context, experimental design procedure with appropriate data analysis are used to find the best combination of parameters that improves mechanical properties of printed products. In these studies, different processing parameters and their effects of interactions were investigated simultaneously.

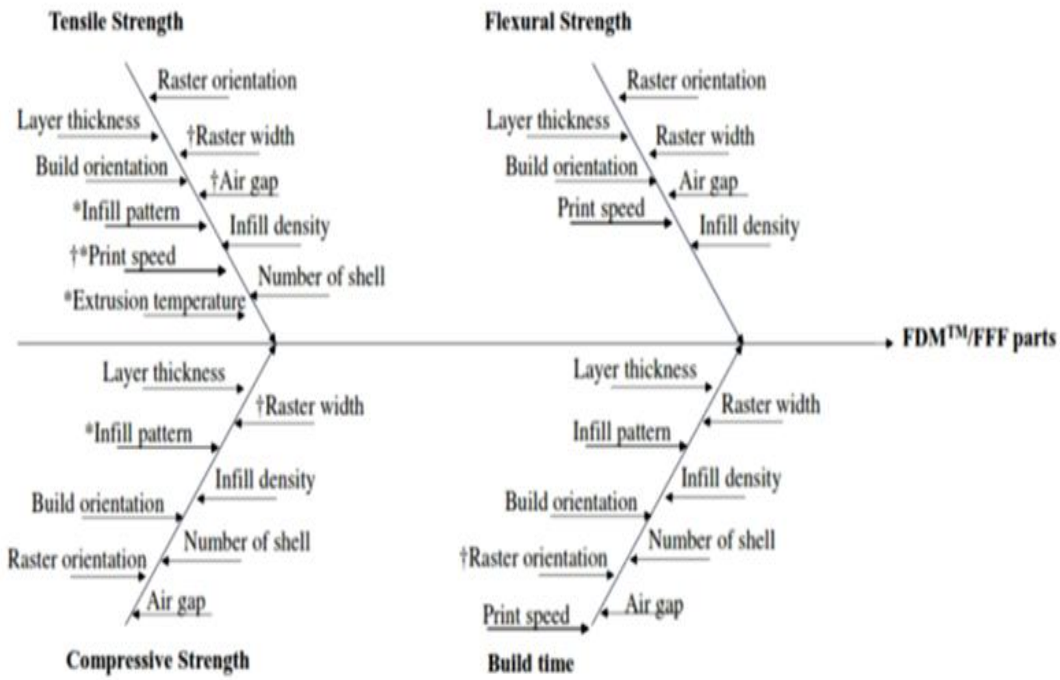

Figure 1:- Diagram of influencing parameters (factors) on the 3D printing process [1].

After researching the literature, it was concluded that the most influential factors on the quasi-static mechanical response of 3D printed parts are: a) infill, b) number of infill lines, c) wall thickness, d) temperature, e) layer height, f) cooling, and g) speed. These seven parameters were selected as factors for the experiment, and serve as parameters for the establishing (calculation) of orthogonal arrays.

a) Infill. This parameter regulates the infill percentage of the test gear interior. A maximum fill of 100 % results in a fully filled model. Increasing the infill has a positive effect on breaking resistance.

b) Infill line multiplier. Infill line multiplier, i.e. the number of lines that make up the infill structure. Increasing the value has a positive effect on the strength, but increases the time of the printing process. The aim of testing this parameter is the ratio of the number of lines and density to the strength of the printed model.

c) Wall thickness. The wall thickness is actually the width of the outer layer of the model. Increasing the value has a positive effect on the strength of the piece. In this experiment, the upper and lower values were varied from 0.1 to 0.8, which is the largest range of all parameters.

d)Nozzle temperature. Defines the nozzle temperature. Good practice for PLA filament is 180 ° C to 215 ° C. Increasing the temperature theoretically increases the strength since the plastic thread bonds better at higher temperatures. However, higher temperature means longer cooling, and increased possibility of deformation of the model.

e)Layer height. It defines the height of each individual layer, and therefore the number of layers that the model will have. It is the most influential factor on production time. Choosing a thinner layer means it will be necessary to print more layers, increasing the production time. Ranges of 0.1 to 0.3 mm layer height are taken into account, which are certainly the minimum and maximum printing limits for a nozzle of 0.4 mm in diameter.

f)Part fan cooling. Regulates the power of the nozzle cooler. Cooling can change the mechanical properties of the model by increasing the curing time of the dissolved layer with increasing the power of the cooler. However, sometimes the layer can be cooled before the next dissolved layer comes on it, which leads to a decrease in strength between the layers. The parameters were tested from 10 % to 90 % of the fan power. With 90 %, the fan was gradually increased by 10 % with each layer to ensure optimal monitoring of the melting temperature. Otherwise, if the jump from 10 % to 90 % were established directly, the nozzle would clog.
g)Printing speed. It means the speed of printing, i.e. the speed of the tool head in relation to the model. This parameter, although it has a greater impact on the quality and strength of the print, was in minimal upper and lower variations, given the sensitivity of the device. Increasing the speed above 45 mm / min often meant clogging or cessation of flow.

Materials and methods:-

The material used to make the test gears is thermoplastic wire PLA Polylactic Acid (Ender series 3D printing filament) manufactured by Creality from China. All samples were modelled in the CAD software package Fusion 360, with a script for automatic gear modelling by entering parameters such as modulus, number of teeth, thickness, etc. CAM was performed in the UltimakerCura software package, which also varied the parameters of this experiment. The FDM printer used to make the test samples is home-made, upgraded and calibrated for many years, with the build volume 200x200x200mm, 0.4mm nozzle diameter, PID controllers on heaters and ARM Cortex M3 32bit processor. For testing, a test bracket with the maximum infill density was made, screwed to the base. The tests were performed using aIngco CDLI1211 cordless screwdriver with an adjustable torque of 5 to 20 Nm. The gears were tested in conjunction with a test fixed gear and a metal gear connected to a screwdriver. Test specimens were made with a minimum gap between the carrier and the specimen to reduce the possibility of slippage. The samples were tested by gradually increasing the torque from 5 Nm upwards to the breaking point. The metal gear is made of C40 UNI 7845 steel according to DIN 3962, DIN 3964 and DIN 3967. Figure 2 shows 3D printer, test gears and testing rig. Characteristics of the gear are given on the Figure 3.

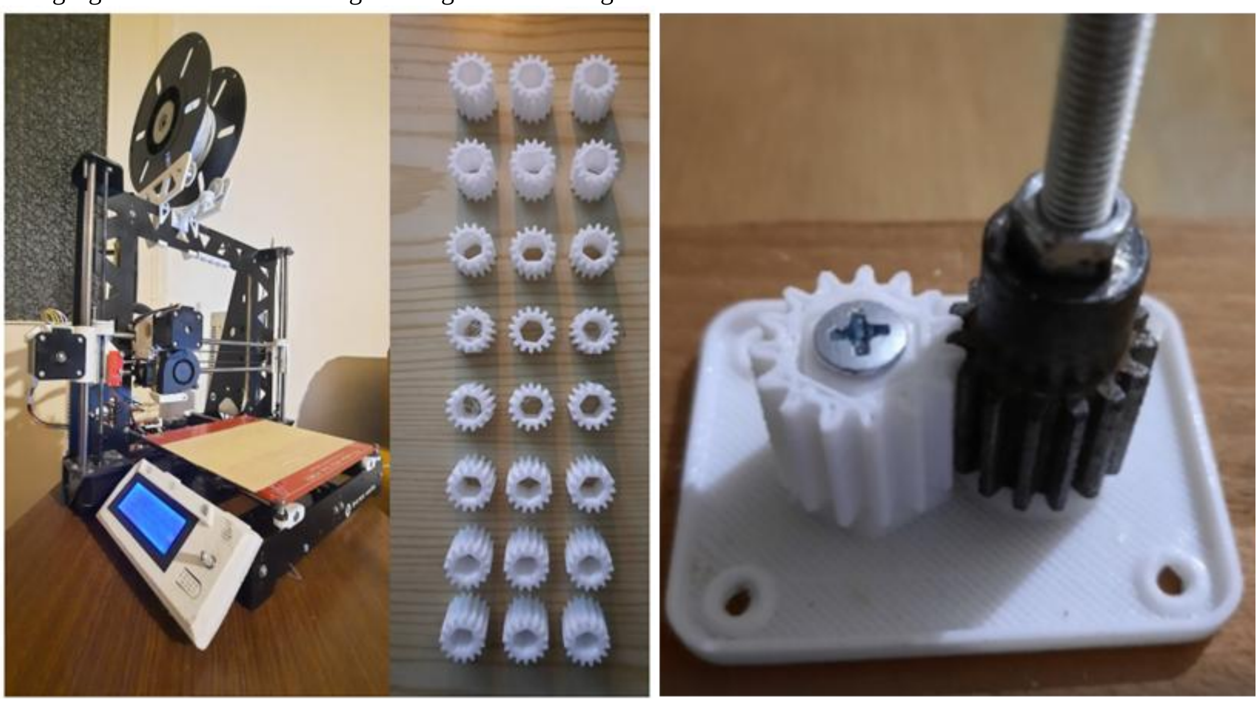

Figure 2:- 3D printer, test gears and testing rig

Figure 3:-Gear specifications.
Modulus m=1 mm, Z=15, h=15 mm, H=25 mm, De=17 mm, Dp=15 mm, d=12 mm, D=6 mm

Experimental setup – Factor's influence:-

As mentioned before, the most influential factors on the quasi-static mechanical response of 3D printed parts are: i) infill, ii) number of infill lines, iii) wall thickness, iv) temperature, v) layer height, vi) cooling, vii) speed. These seven parameters were selected as factors for the experiment, and serve as parameters for the calculation of orthogonal arrays.

Taguchi experimental plan was used in the form of orthogonal arrays and linear graphs that give different combinations of parameters and their levels for each experiment. Based on this technique, the entire parameter space with the minimum number of experiments was used. This is a very powerful tool when the process is influenced by a large number of parameters. In Taguchi design, the choice of orthogonal arrays and appropriate linear graph are very important in order to draw valid conclusions after conduction of experimental runs. Table 1 shows Taguchi orthogonal arrays $L_8(2^7)$; eight experimental runs with two level of the each seven factors. Also, the experimental results are shown in the same table. Corresponding natural values of factors levels are shown in the Table 2

Table 1:-Taguchi orthogonal arrays $L_8(2^7)$ and experimental results.

Exp. runs	Infill	Infill multiplier	Wall thickness	Temp.	Layer height	Cooling	Speed	Experimental results, Torque, Nm		
	1	2	3	4	5	6	7	I	II	III
1	1	1	1	1	1	1	1	5	8	8
2	1	1	1	2	2	2	2	6	5	8
3	1	2	2	1	1	2	2	19	20	20
4	1	2	2	2	2	1	1	20	20	20
5	2	1	2	1	2	1	2	20	18	20
6	2	1	2	2	1	2	1	17	19	20
7	2	2	1	1	2	2	1	10	11	11
8	2	2	1	2	1	1	2	12	8	10

Table 2:-Factors levels and natural and coded values.

Level	Infill, %	Infill multiplier, No.	Wall thickness, mm	Temperature, ^{o}C	Layer height, mm	Cooling, %	Speed, mmpmin
1	10	1	0.1	195	0.1	10	30
2	40	2	0.8	215	0.3	90	40

In order to find the influential factors of the gear fracture torque, the influences of the factors on the mean values as well as the signal-to-noise (S/N) ratio were analyzed for each factor individually. Table 3, and Table 4 are representing response tables for means and S/N ratio. The main effects of gear strength on the breaking point were calculated by Taguchi analysis with the result that wall thickness (Column 3, Table 1), number of infill lines (Column 2, Table 1) and infill (Column 1, Table 1) are the most influential factors. Using the delta value (i.e. effect) of each factor as a relative measure, it is clear that the most influential factor is wall thickness, Table 3, and Table 4. It is clear from the same tables that the factors temperature, layer height, cooling and printing speed have no significant effects on gear fracture resistance. It is also important to emphasize that some parameters are selected with a larger interval than others, which also affects the intensity of the influence of certain factors. The reason for this choice is the limit values of the printing process parameters, otherwise a successful process is questionable. "Larger is better" was taken as an approach in the Taguchi method for the analysis of experimental results. Signal-to-Noise ratios for each combination of factors and interactions were calculated using the following equation:

$$\frac{S}{N} = -10log\left(\frac{1}{N}\sum\frac{1}{Y^2}\right), \text{dB} \qquad (1)$$

Finally, Figure 4 represents main effect plot for means according to results in the Table 3.

Table 3:-Response table for means.

Level	Infill	Infill multiplier	Wall thickness	Temperature	Layer height	Cooling	Speed
1	13.2	12.8	8.5	14.2	13.8	14.1	14.1
2	14.7	15.1	19.4	13.8	14.1	13.8	13.8
Delta	1.5	2.3	10.9	0.4	0.3	0.3	0.3
Rank	**3**	**2**	**1**	**4**	**6(7)**	**6(7)**	**5**

Table 4:-Response table for S/N ratio.

Level	Infill	Infill multiplier	Wall thickness	Temperature	Layer height	Cooling	Speed
1	20.92	20.71	17.99	22.08	21.78	21.90	22.04
2	22.81	23.02	25.74	21.65	21.95	21.83	21.69
Delta	1.89	2.3	7.74	0.44	0.17	0.07	0.35
Rank	**3**	**2**	**1**	**4**	**6**	**7**	**5**

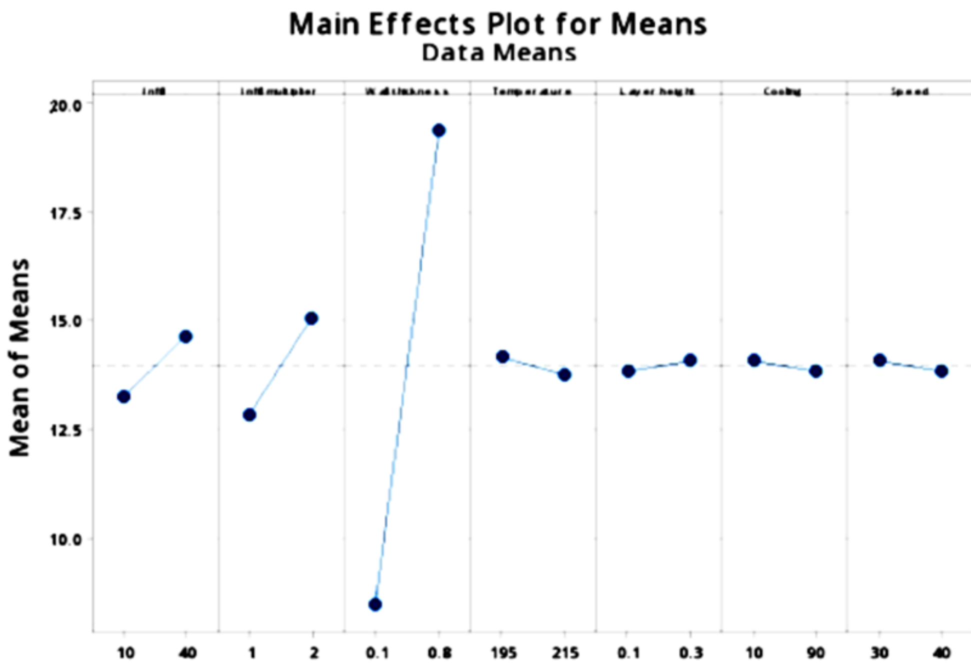

Figure 4:- Main effects plot for means.

Experimental setup – Optimization:-

In order to optimize 3D printing process, a new Taguchi orthogonal arrays $L_8(2^7)$ is designed. The experiment was repeated with the first four most influential factors, according to the rank given from the table of mean values (Table 3); wall thickness (Factor A), infill multiplier (Factor B), infill (Factor C) and temperature (Factor D). Table 5 shows Taguchi orthogonal arrays $L_8(2^7)$; eight experimental runs with two level of the four factors and three interactions (A*B, A*C, and A*D), according to standard linear graph shown on Figure 5. Also, the experimental results are shown in the same table.

Table 5:-Taguchi orthogonal arrays $L_8(2^7)$, and experimental results.

Exp. runs	Wall thickness	Infill multiplier		Infill			Temp.	Experimental results, moment, Nm		
	A	B	A*B	C	A*C	A*D	D			
	1	2	3	4	5	6	7	I	II	III
1	1	1	1	1	1	1	1	5	5	6
2	1	1	1	2	2	2	2	6	8	6
3	1	2	2	1	1	2	2	20	19	20
4	1	2	2	2	2	1	1	20	20	20
5	2	1	2	1	2	1	2	8	7	7
6	2	1	2	2	1	2	1	8	9	9
7	2	2	1	1	2	2	1	15	15	18
8	2	2	1	2	1	1	2	18	18	19

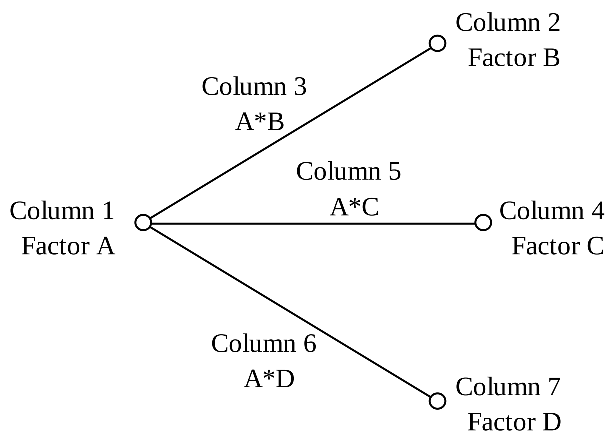

Figure 5:- Standard linear graph for $L_8(2^7)$

The influences of the factors on the mean values (Taguchi approach "Larger is better") were analyzed for each factor individually. Table 6 is representing response tables for means. The main effects of gear strength on the breaking point were calculated by Taguchi analysis with the following results. According to level of the influence, ranking of the factors is:

1. Wall thickness (Column 1, factor A, Table 5), delta value is 11.75 (Table 6)
2. Interaction A*B: wall thickness – infill multiplier (Column 3, Table 5), delta value is 2.34 (Table 6)
3. Number of infill lines (Column 2, factor B, Table 5), delta value is 2.09 (Table 6)
4. Infill (Column 4, Table 5), delta value is 1.09 (Table 6)
5. Temperature (Column 7, Table 5), delta value is 0.25 (Table 6)
6. Interaction A*C: wall thickness – infill (Column 5, Table 5), delta value is 0.5 (Table 6), and
7. Interaction A*D: wall thickness – temperature (Column 6, Table 5), delta value is 0.05 (Table 6).

Table 6:-Response table for means.

Level	Wall thickness	Infill multiplier		Infill			Temperature
	A	B	A*B	C	A*C	A*D	D
	1	2	3	4	5	6	7
1	7.00	11.83	11.58	12.33	13.00	12.73	13.00
2	18.75	13.92	13.92	13.42	12.50	12.78	12.75
Delta	11.75	2.09	2.34	1.09	0.5	0.05	0.25
Rank	**1**	**3**	**2**	**4**	**6**	**7**	**5**

Table 6 implies that factor A – wall thickness is a factor with strongest influence on the quasi-static mechanical response (torque moment, Nm) of 3D printed parts because the difference of 11.75 Nm between mean values on the level 1 and level 2, for this factor, is the highest. Second order strongest factor is interaction A*B (wall thickness – infill multiplier) with delta = 2.34, then, factor B – infill multiplier with delta = 2.09, and finally, factor C – infill with delta = 1.09.

According above mentioned, optimal levels of the most influent factors are given in the Table 7. Predicted value of torque moment (21 Nm) and S/N ratio (26.9528 dB) are given in the same table.

The verification tests has been performed according to the levels of factors given in the Table 7. The results for all three repeated tests were minimum 20 Nm. This value is very close to predicted value (21 Nm), Table 7.

Table 7:- Optimal levels of the factors and prediction for S/N ratio and means (torque moment).

FACTOR	Designation	Value	S/N Ration, dB	Means, Torque, Nm
Wall thickness	A_2	0.8 mm	26.9528	21
Infill multiplier	B_2	2		
Infill	C_2	40%		
Temperature	D_1	195 ^{O}C		

Conclusions:-

This paper presents a method for optimizing the influencing factors on the fracture strength (torque) of gears made by FDM 3D printing technology using the Taguchi method. The material used for printing is Polylactic PLA thermoplastics. The experimental research is divided into two parts. In the first part, the degree of influence of the seven selected influencing factors is analyzed. These factors are infill, infill line multiplier, wall thickness, nozzle temperature, layer height, part fan cooling and printing speed. The second part presents the process of optimizing the most influential factors. Optimization was performed using the “Larger is better” Taguchi method approach according to $L_8(2^7)$ orthogonal arrays.

The results showed that the highest torque is obtained with the optimal values of the factors as follows: wall thickness, 0.8 mm, infill multiplier, 2, infill, 40%, and temperature, 195 ^{O}C. The predicted maximum value of torque is 21 Nm.

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