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Optimizing Fused Deposition Modelling Process Parameters for Medical Grade Polymethylmethacrylate Flexural Strength

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ABSTRACT

The production of functional parts, including those employed by the biomedical industry has been achieved a promising candidate in fused deposition modelling (FDM). The essential properties of these biomedical parts which manufactured by additive manufacturing as compared to some other conventional manufacturing processes depend on structural and process parameters rather than material properties alone. Regarding to the evaluation the flexural strength of medical-grade, polymethylmethacrylate (PMMA) has been received relatively very little investigation to date. PMMA is a biocompatible filament that be used in manufacturing of patient-specific implants such as dental prosthesis and orthopaedic implants. The proposed work explores the effect of three process parameters that vary with respect of three levels on the flexural strength. These levels can be specified by layer height (120, 200, 280 μm), infill density (40, 65, 90%) and skewing angle (0º, 45º, 90º) on the flexural strength of medical-grade PMMA. Maximum and minimum flexural strength that be obtained in this work about 93 and 57 MPa respectively. The analysis of variance (ANOVA) results shows that the most effective factor is the layer height followed by infill density. The flexural strength rises significantly with decreases layer height and the skewing angle is in zero direction. The process parameters have been optimized through utilizing of genetic algorithms. The optimal results that emerged based on genetic algorithm technique are approximately 276 μm as layer height, 46% infill density, and skewing angle 89º, which maximize the flexural strength to 97 MPa at crossover for ten generation.

Keywords: PMMA, flexural strength, fused filament fabrication, three-point bending, genetic algorithm.

INTRODUCTION

During the last decade, additive manufacturing (AM), also known as three-dimensional (3D) printing has been acquired a great progress. The precision, repeatability and dependability of AM-based manufacturing techniques have been improved with the aid of materials variety [1]. In several industries, 3D printing technology has been customized crucially in producing goods quickly and at a reasonable cost [2]. As a result, additive manufacturing has been emerged a feasible option for the manufacture of functional parts, particularly in high-value industries such as healthcare and aerospace. AM is exactly described as a fabrication procedure used to create 3D complex component models by integrating the material layer by layer derived from the data created by the 3D model software according to (ISO/ASTM 52900:2015) [1, 3].

One technology that falls under the heading of additive manufacturing is fused deposition modeling also known Fused filament fabrication (FFF). In FDM, the material is melted by feeding a thermoplastic filament through a heated nozzle. In order to produce a three-dimensional sculpture, the melted substance is subsequently extruded layer by layer [4], where every printing layer is deposited in a semi-molten condition. The hot building platform or the nozzle's motion pushes it slightly into the prior layer which is then heated once more. This process looks like plastic welding when pressure and heat are combined. The macromolecular chain structures can penetrates or inter diffuses on either side of the interface formed when the two layers come into contact [5, 6]. The major steps in FDM part fabrication are illustrated in the Figure 1.

Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are the most often employed materials in FDM technique. Polymethylmethacrylate PMMA and polyetheretherketone (PEEK), have been explored as a potential substitute for fused deposition modeling (FDM) in biomedical applications. Particularly, tissues engineering, denture and 3D printed implant models especially for cranial implants that be used in cranioplasty [7]. PMMA medical grade is a thermoplastic that is usually referred to as "organic glass". PMMA has several exceptional qualities such as high transparency, biocompatibility, light weight, high hardness, strong weather resistance, high elastic modulus, minimal shrinkage, and others [8].

One important mechanical characteristic that indicates a material's capacity to tolerate bending or deformation under applied load is a flexural strength [9]. Flexural strength testing is frequently carried out in the context of 3D printing utilizing FDM to assess the mechanical performance of produced specimens. Bending strength is the most important mechanical property, that offering a clear understanding for the entire spectrum of mechanical characteristics, which includes tensile, compressive, and shear properties. These potential properties make it essential for an accurate assessment of the performance of a material in various applications, particularly when the material is a biocompatible and used for manufacturing implants.

The effects of many parameters on the qualities of FDM components printed have been documented by numerous researchers [10, 11]. The component strength to weight ratio has a major role in infill pattern selection; lighter components print more quickly and with less material consumption. Compared to material costs, print expenses have a greater influence on production costs [12]. The results indicated by optimizing process variables such as: layer thickness, infill density, infill patterning, raster direction and component build orientation, etc. While the quality of printed parts manufactured by the FFF method may be improved. Abdullah et al. [13] has been examined the impact of raster angle and layer thickness on the tensile and flexural strengths of FDM items made of two different materials specified by polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Results indicate that the angle of the raster and layer thickness have a greater impact on the testing specimen's flexural strength as compared with the results achieve on the material's tensile strength. The effect of differed layer thicknesses of 3D printing PLA on flexural properties has been discussed in [14]. In this work, the results revealed that layer thickness influenced the flexural strengths of PLA samples. Furthermore, the ductility reduced as the layer thickness grew. According to these results, the highest achievable flexural strength reached 59.6 MPa at 0.5 mm layer thickness, and the lowest flexural strength was 43.6 MPa at 0.1 mm layer thickness. Saty Dev and Rajeev Srivastava [15] uses a hybrid statistical technique based on response surface methodology (RSM) and genetic algorithms (GA). The FDM process factors of ABS have been investigated and optimized. Print head speed, nozzle temperature, and layer thickness are three process parameters that varied at

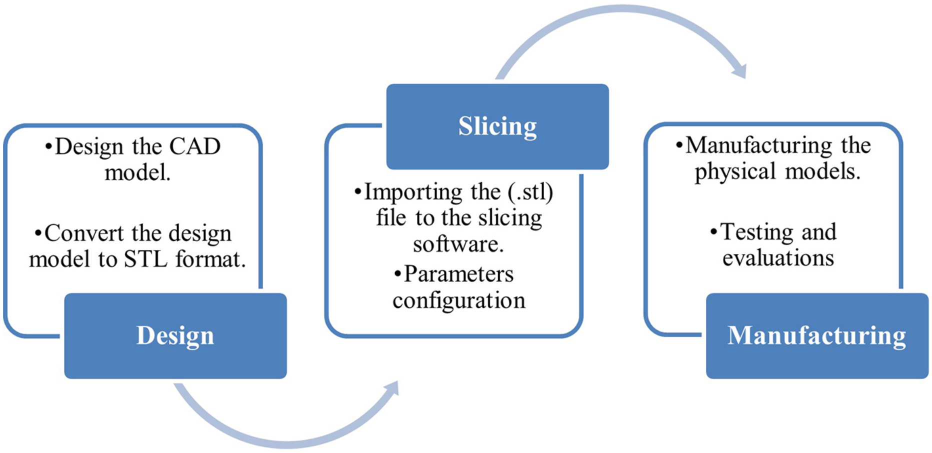

Fig. 1. The major steps in the FDM process

three different levels. The flexural strength of 58.34 MPa, as predicted by RSM-GA, is confirmed through experimentation. Mohankumar et al. [16], explores the effects and flexural strength of short glass fiber (SGF) in the ABS matrix as a reinforcement. Composites are made of SGF-ABS polymers by mixing 15% and 30% SGF with ABS. By adding SGF, the flexural and impact strength characteristics were significantly improved, and it cleared the way to investigate other reinforcement levels inside the matrix. Sofia et al. [17], create a bi-material lamination employing FDM, and study how the accuracy and roughness of the surfaces of a PLA-PMMA laminate effect its tensile strength. Three processing parameters (layer height, infill density, and raster width) were considered for investigating their effect on tensile properties and quality attributes. The layer height of the specimen is greatly affected by thickness. Surface roughness seems to be highly impacted by layer height, but tensile strength is affected exponentially by raster width.

Along these lines, there is no relevant research investigating the mechanical properties of medical-grade PMMA. So, the novelty of this work is utilizing the newest PMMA material as the filamentous solid state. The mechanical properties of the printed part change depending on changes in the FDM process parameters. Accordingly, the objective of this work is based on investigating and optimizing the process parameters by utilizing the genetic algorithm GA approach to medical-grade PMMA as a solid state. Flexural strength is crucial mechanical property of the orthopedic and the implants, as the PMMA applies, due to the ability of material for bending as well as deformation under all mechanical loads of tensile, compression and shear. Therefore, the parameters that have been examined for flexural strength in this work are as follows: layer height, infill density, and skewing angle, with three levels for each parameter.

MATERIALS AND EXPERIMENTAL WORK

Raw material

Polymethyl methacrylate PMMA is acrylic or plexiglass of diameter 1.75 mm three-dimensional printing transparent filament of medical grade from Ossfila Medical follow up the ISO 13485 has been used in this work as depicted in Figure 2.

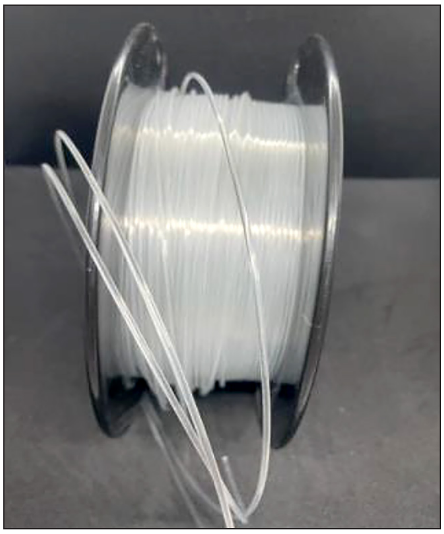

Fig. 2. Medical grade PMMA filament that was used in this study

Regarding it's steady to gamma radiation, the mass density of 1.19 g/cm^3 at ambient temperature with excellent strength, non-toxic adequate for sterilization. The most widely non-metallic implant material in orthopedics is (PMMA) which is considered to be lightweight, synthetic polymer, an affordable, and undegradable polyacrylate. PMMA is advised for printing surgical models or orthopedic implants made specifically for individual patients.

3D printer characterization

The three-dimensional printer used in this work based on fused fabrication filament is an extrusion procedure where the product is constructed by layering molten material. A print head moves over the printing surface, depositing the material and creating the part. Large fully enclosed premium 3D printer Qidi Tech X-Max has been utilized in this investigation as depicted in Figure 3. Tables 1 provide information on the features and technical characteristics of the FFF 3D printer.

FDM 3D printing process

A 3D computer-aided design (CAD) model of the specimen is the first step in the FDM process. The specimens utilized in this investigation have been manufactured in accordance with the American Society for Testing and Materials (ASTM) D790 standard which can be considered as the same as ISO 178 for testing the material's flexural properties for the three-point bending method. The specimens' geometry is designed by using

Fig. 3. X-MAX QIDI 3D printer

Table 1. The technical characteristics of the FFF 3D printer

Parameters	Technical characteristic
Nozzle diameter	0.4 mm
Filament diameter	1.75 mm
Building size	300×250×300 mm
Extruder quantity	Single
Max nozzle temperature	300 °C
Max bed temperature	120 °C
Compatible software	QIDI print, Simplify 3D

SOLIDWORK software with the three-point bending test for flexural properties as shown in Figure 4. This model will be saved as an standard tessellation language (STL) file which is expoerted from a CAD modeling tool and then imported into the 3D printer sliced software QIDISlicer in order to create a G-code file for the purpose of printing test specimens on the 3D printer. The computer slicing program divides the STL file into horizontal slices that are identical in height to the layers in a 3D printer. Through a feeding tube, a rod-shaped filament is delivered to the machine. A single computer-controlled 0.4 mm-diameter nozzle is used to extrude the liquid thermoplastic material which is then laid down layer by layer according to a predetermined laydown pattern. The nozzle creates a layer in the X, Y plane by moving in a raster pattern. After layer deposition is completed, the working bed is lowered in the Z direction and the subsequent layer is extruded. The chamber has been enclosed and the printing temperature is set at 250 °C while the bed temperature has been set at 120 °C. Structural supports must be inserted into complex anatomical geometries such as cranial implants and the 3D component with support structures is printed layer by layer as well as joining the layers to one another.

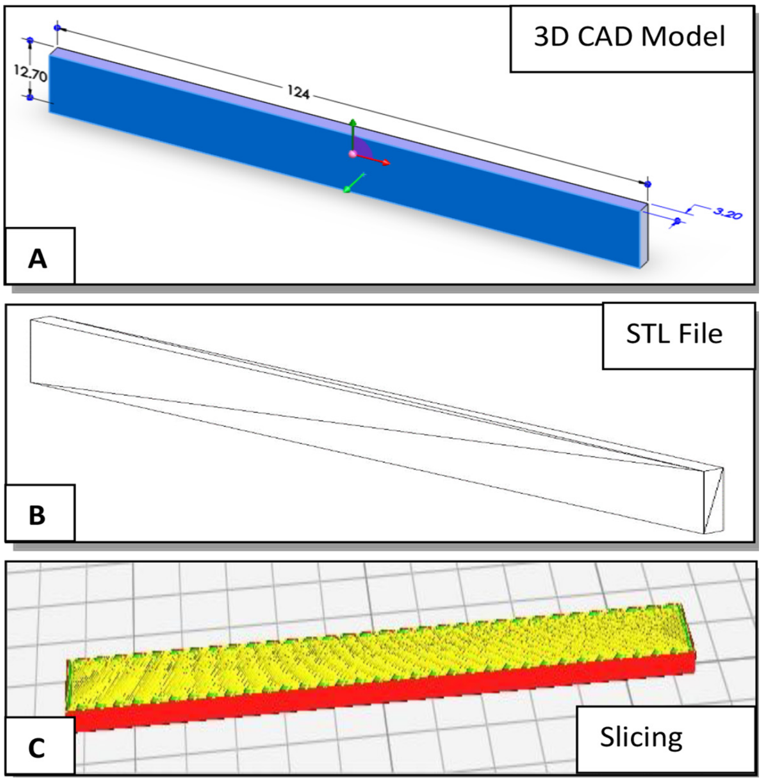

Fig. 4. (A) 3D CAD model of 3-point bending specimen (all dimensions in mm), (B) STL file SolidWorks specimen, (C) slicing the specimen by using QIDISlicer software

Selection of design-based parameters

The Taguchi analysis method is a statistical measurement of the rendering that is employed in the present work in order to estimate the signal-to-noise and orthogonal array analysis [18, 19]. Three main parameters of the 3D printing process (layer height, infill density and skewing angle) with three levels have been selected as a main parameters. The specified levels and factors have been used to create a mathematical orthogonal array L9 (3^3) for the experimentation. Three samples have been manufactured and tested for each set parameter, and the average of the flexural strength was taken to obtain the accuracy of the results. Table 2 summarized the main parameters and their levels.

Table 2. The main FDM parameters and their levels that were utilized in this study

No.	FDM parameters	Level 1	Level 2	Level 3	Units
1	Layer height	120	200	280	µm
2	Infill density	40	65	90	%
3	Skewing angle	0	45	90	°

Three-point bending test

The computerized universal testing machines system model (WDW-200E) has been utilized in order to carry out the three-point bending test as depicted in Figure 5. It has a load cell with a 200 kN capacity. At the University of Technology's Production Engineering and Metallurgy Department, the three-point bending test examines have been carried out in the Strength of Materials Laboratory. The speed of loading is 3 mm/min [16]. The three-point bending specimens test of medical-grade PMMA are shown in Figure 6.

Genetic algorithm

GA is considered to be an unconventional technique for multi-parameter optimization [20].

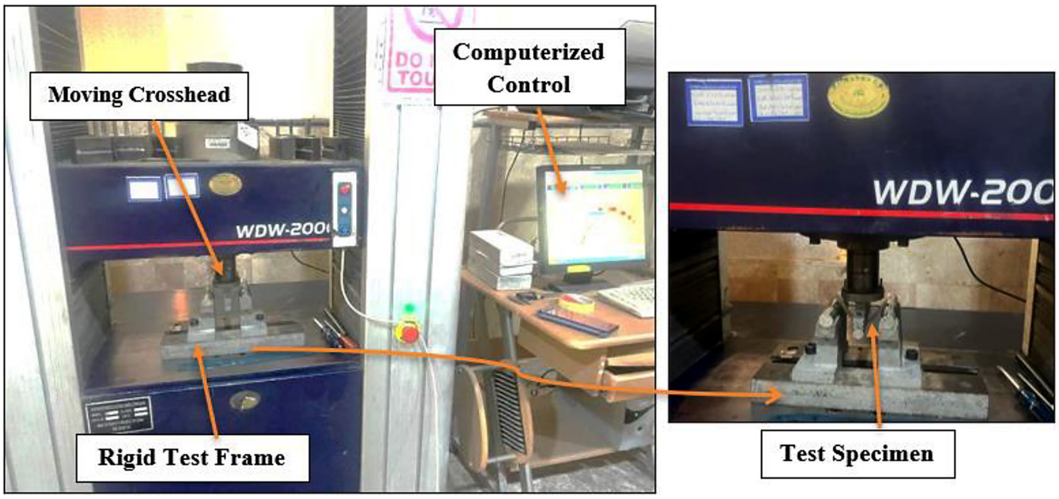

Fig. 5. Three point bending testing setup that was used in this study

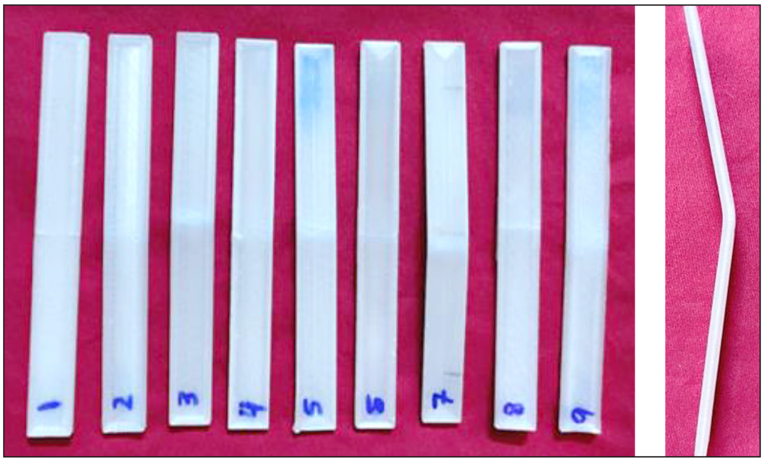

Fig. 6. Testing specimens of medical grade PMMA

Genetic algorithms create generations iteratively as well as abstracting the issue from area to be an estimated population of individuals and attempting to discover the most suitable individual [21]. As illustrated in Figure 7, the suggested strategy has been taken into account in order to optimize the FDM process parameters regarding to the following actions: (i) set the population's initial values, (ii) parameter value creation, (iii) invoking the response surface methodology-created fitness function, (iv) a population exhibiting crossover and mutation and evaluating the fitness function in order to determine the optimal level of flexural strength.

RESULTS AND DISCUSSION

During a three-point bending test which involves supporting a beam at two points and loading it at the third, the test specimen's outside surface experiences its highest level of stress. The following equations for flexural stress and flexural strain have been used to transform the load-deflection curves acquired in bending into stress-strain curves:

$$\sigma_f = \frac{3\mathrm{PL}}{2bd^2} \tag{1}$$

$$\varepsilon_f = \frac{6\mathrm{Dd}}{L^2} \tag{2}$$

where: σ_f and ε_f – a midpoint stress and strain in the outermost fibers,
F – the force,
L – the support span,
b – the width of the specimen,
d – the beam thickness and maximum center-of-beam deflection.

Table 3 shows the flexural strength of the medical grade PMMA tested manufactured samples. As illustrated in Figure 8, the flexural strength can be viewed as a bar chart. The Main impact plot and signal-to-noise ratio of flexural strength are shown in Figures 9 and 10 respectively. It is very evident that the flexural strength rises significantly with decreases layer height as the skewing angle is in zero direction. Meanwhile, it may not be realistic to say with certainty that reducing layer thickness consistently will increases flexural strength in fused deposition modeling of medical grade PMMA. In fact, the connection across layer thickness and flexural strength might vary based on various parameters. Moreover, other parameters is affected on the layer thickness of the flexural strength. Therefore, reducing the thickness of the layers will increases the adhesion between them which could contribute to improve the flexural strength. As a result of improved fusion between neighboring layers, thinner layers enable more accurate material deposition. Hence, better mechanical properties can be carried out from a more homogeneous organization due to the enhanced interlayer bonding. While layers have been deposited towards zero degree, the prior layer's surface area is larger for the newly added layer to be attached which is possibly resulting a stronger layer bonding than 45 or 90° orientations.

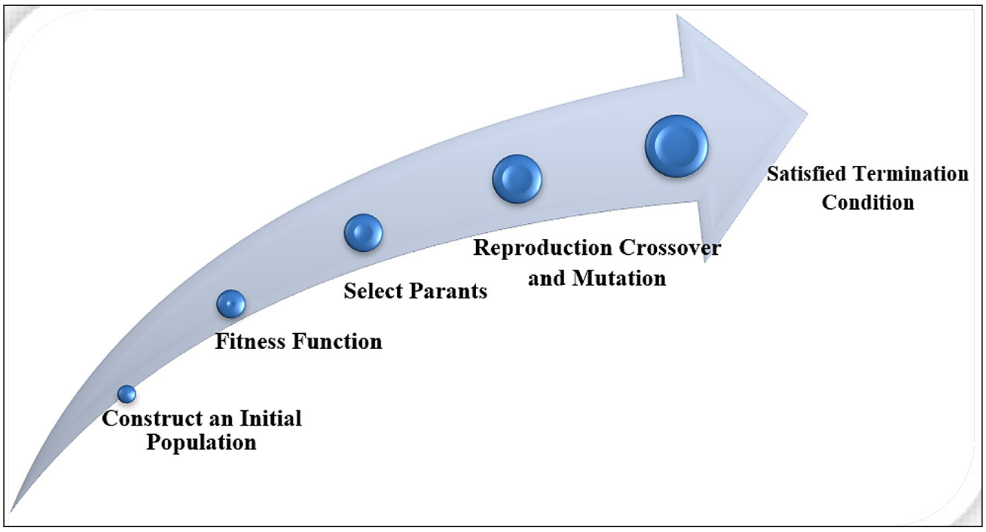

Fig. 7. Genetic algorithm general framework

Table 3. Experimental results of flexural strength

No. of runs	Layer height (µm)	Infill density (%)	Skewing angle (°)	Flexural strength (MPa)
1	120	40	0	92.607
2	120	65	45	73.119
3	120	90	90	75.567
4	200	40	45	78.351
5	200	65	90	66.067
6	200	90	0	80.588
7	280	40	90	63.871
8	280	65	0	57.169
9	280	90	45	61.936

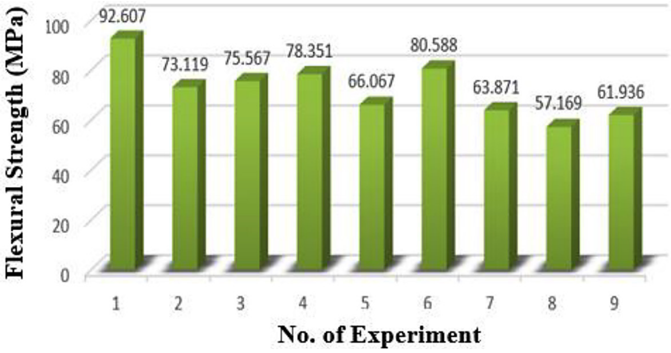

Fig. 8. Flexural strength of medical grade PMMA of manufactured samples

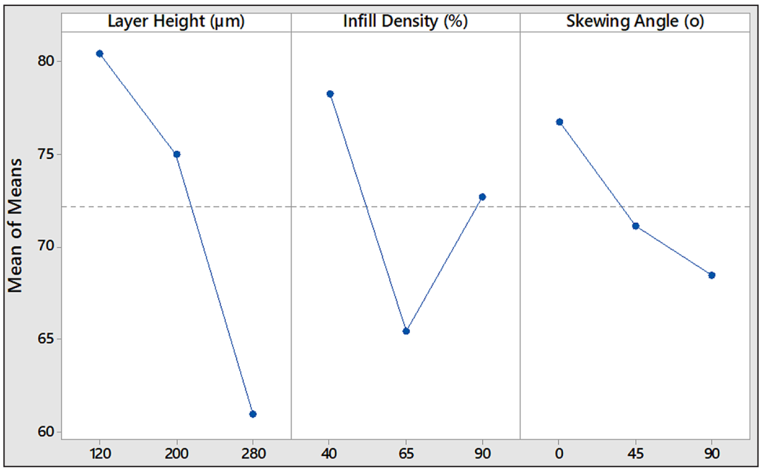

Fig. 9. Flexural strength main effect plots

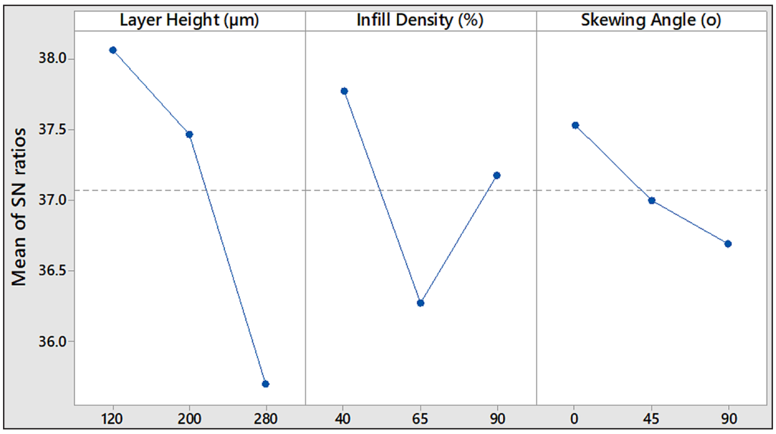

Fig. 10. Flexural strength signal to noise ratio plots (signal to noise – largen is better)

Analysis of variance results

Analysis of variance (ANOVA) is utilized to explain the impact of FDM process parameters which significantly affecting on the flexural strength. Table 4 illustrates the ANOVA results on the response, in addition to determine the significance of the model summery. The greatest outcome of the F-value among the other parameters has been achieved for layer height 38.25. So that, this parameter represents the most effected variable on the flexural strength and is about two and a half times the infill density that has been accomplished at 15.72. The less important factor is skewing angle which has the F-value about 6.82. ANOVA provides a clear standard for choosing the important variables. The ANOVA results which have been presented confirm the previous results of the flexural strength main impact plot and signal-to-noise ratio.

Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.80885	98.38%	93.53%	67.23%

Table 4. ANOVA results of flexural strength

Source	DF	Adj SS	Adj MS	F-value
Layer height (μm)	2	603.63	301.814	38.25
Infill density (%)	2	248.10	124.048	15.72
Skewing angle (°)	2	107.55	53.776	6.82
Error	2	15.78	7.890	
Total	8	975.06		

Note: DF – stands for degree of freedom, SS – for the sum of squares, and MS – for the mean square.

Genetic algorithm results

To get started, this stage needs the selected transactions in the program GA which specified by the population size 10, the total length of the bit strings 15, the chromosomes duration is 6, the possibility for crossover is 0.85, single point operator the probability for mutation is 0.03, and fitness parameter (layer height, infill density, skewing angle). It regards the FDM process parameters as binary characteristics for these parameters. The bit strings are fifteen bits long in total, with the first five bits representing the layer height parameter, the following five bits representing infill density, and the last five bits representing the skewing angle. These three parameters represent the chromosomal substrings. The lower and upper bounds of process parameters are represented by the strings in this formula (00000 00000 00000), (11111, 11111, 11111), where it is possible to choose the lower and upper bounds for the process parameters between the first and third levels of each parameter.

Figures 11, show the program that has been implemented after finding fitness function and inserting all information in GA. Whereas, number of generations is 10, crossover fraction is 0.85 with 9472.9 best value and 9474.35 mean value.

Then generated the FDM process parameters for ten generation and add another five generation to get fifteen in order to obtain best results as showed in Table 5. Regarding the promising results of Table 5, the optimal value for flexural strength is 84.66 MPa at the variables: layer height 225.40 μm, infill density 82.63% and the skewing angle 79.8°.

In view of improving the precision of the results, the crossover as well as mutation processes produced an optimal solutions at several parameters, which are shown in Tables (6, 7

Table 5. FDM process parameters for fifteen best generation

No. of runs	Layer height (μm)	Infill density (%)	Skewing angle (°)	Flexural strength (MPa)
1	125.60	44.1	0	83.2222
2	135.32	46.8	44.5	80.31242
3	143.16	49.2	85.3	77.775
4	160.34	63.4	75.6	75.858
5	176.14	82.3	79.40	73.529
6	211.56	43.60	41.66	71.204
7	232.14	62.40	43.20	69.44
8	218.76	73.75	76.40	72.584
9	225.40	82.63	79.8	84.66
10	243.60	88.60	83.77	73.895
11	262.17	43.16	86.4	65.358
12	274.60	47.5	83.2	63.919
13	256.70	66.44	0	67.98
14	247.32	74.16	42.3	66.40
15	279.40	89.63	44.6	62.894

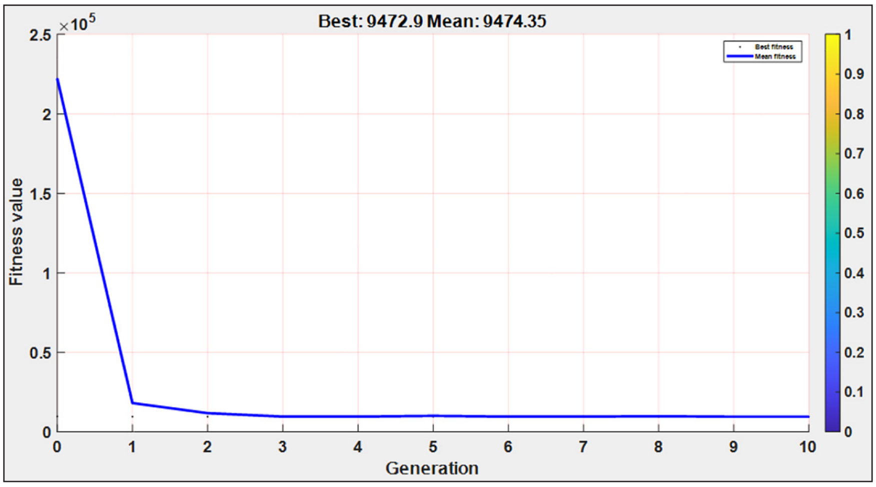

Fig. 11. The implemented data on GA

and 8). Table 7 shows that the optimal result is about 96.72 MPa of flexural strength at 276.46 µm of layer height, 45.82% of infill density, and 89.4° of skewing angle in crossover operator. While Table 8 gives an optimal value for flexural strength about 86.73 MPa at 236.33 µm of layer height, 63.8% of infill density, and 72.1° of skewing angle in mutation operator.

CONCLUSIONS

There is an essential connection between the process variables and the mechanical characteristics of fused deposition modelling parts. An effective technique for enhancing fused deposition modelling process parameters using GA is presented in this work. The conclusions that have been carried out from these investigations could be summarized as follows:

1. Flexural strength is a mechanical property that increases dramatically when layer height decreases, and the skewing angle is zero.

Table 6. The optimum results for several solutions for various genetic algorithm parameter values

No.	Crossover	Mutation	Optimal solution	
			Beat	Mean
1	0.65	0.01	9321.9	9322.9
2	0.65	0.02	9431.6	9432.5
3	0.65	0.03	9432.7	9434.2
4	0.65	0.04	9411.3	9412.2
5	0.6	0.05	9461.2	9462.3
6	0.7	0.01	9321.2	9331.4
7	0.7	0.02	9472.9	9473.2
8	0.7	0.03	9472.9	9474.35
9	0.7	0.04	9464.3	9465.3
10	0.7	0.05	9455.1	9456.3
11	0.75	0.01	9323.4	9343.3
12	0.75	0.02	9365.2	9366.4
13	0.75	0.03	9462.7	9467.8
14	0.75	0.04	9466.9	9467.1
15	0.75	0.05	9456.3	9468.1
16	0.8	0.01	9361.2	9364.1
17	0.8	0.02	9465.4	9467.7
18	0.8	0.03	9487.7	9489.1
19	0.8	0.04	9476.3	9478.5
20	0.8	0.05	9469.5	9478.9

Table 7. Operating parameters for ten generation in crossover operator

No. of runs	Layer height (µm)	Infill density (%)	Skewing angle (°)	Flexural strength (MPa)
1	123.66	41.6	0	83.49
2	225.43	46.33	47.6	69.252
3	276.46	45.82	89.4	96.72
4	129.34	67.42	43.1	80.82
5	273.48	63.4	0	64.98
6	229.2	66.1	75.4	67.46
7	127.88	85.6	79.4	79.346
8	227.83	75.1	0	70.36
9	263.81	89.2	44.7	64.1
10	213.63	59.8	47.9	70.48

Table 8. Operating parameters for ten generation in mutation operator

No. of runs	Layer height (µm)	Infill density (%)	Skewing angle (°)	Flexural strength (MPa)
1	124.63	41.5	0	83.37
2	236.33	63.8	72.1	86.73
3	276.89	43.2	89.4	61.455
4	126.81	66.7	44.6	81.06
5	231.2	43.6	42.3	68.79
6	277.8	89.2	41.4	62.53
7	141.36	89.4	0	80.63
8	237.21	81.77	47.8	67.96
9	269.61	63.2	67.1	64.96
10	277.61	73.11	43.21	62.71

2. Layer thickness is an important factor in fused deposition modelling printing since it directly impacts interlayer bonding, anisotropy actions and overall mechanical characteristics. To manufacture 3D-printed products with excellent flexural strength and mechanical performance, the proper balance of layer thickness, infill density and skewing angle parameters must be achieved.
3. Based on the analysis of variance, the most significant parameter for flexural strength, is the layer height followed by infill density.
4. Genetic algorithm technique has been managed in order to ascertain the ideal conditions between experimental data levels.
5. The genetic algorithm technique explored that optimal flexural strength value is 96.72 MPa for the following variables: skewing angle 79.8°, infill density 82.63%, and layer height 225.40 µm at crossover for ten generation.

REFERENCES

1. Zadpoor AA. Design for additive bio-manufacturing: from patient-specific medical devices to rationally designed meta-biomaterials. International Journal of Molecular Sciences. 2017 Jul 25;18(8):1607. https://doi: 10.3390/ijms18081607.
2. Rajan K, Samykano M, Kadirgama K, Harun WS, Rahman MM. Fused deposition modeling: process, materials, parameters, properties, and applications. The International Journal of Advanced Manufacturing Technology. 2022 May;120(3-4):1531-70. https//doi: 10.1007/s00170-022-08860-7.
3. Uthayakumar M, Raj SA, Ko TJ, Kumaran ST, Davim JP. Handbook of research on green engineering techniques for modern manufacturing. 2019. https//10.4018/978-1-5225-5445-5.
4. Karupaiah V, Narayanan V. Quasi-static and dynamic mechanical analysis of 3D printed ABS and carbon fiber reinforced ABS composites. Materiale Plastice. 2022 Sep 1;59(3):152-79. https//doi: 10.37358/MP.22.3.5613.
5. Lu B, Lamnawar K, Maazouz A, Zhang H. Revealing the dynamic heterogeneity of PMMA/PVDF blends: from microscopic dynamics to macroscopic properties. Soft Matter. 2016;12(13):3252-64. https//doi: 10.1039/C5SM02659H.
6. Yousfi M, Belhadj A, Lamnawar K, Maazouz A. 3D printing of PLA and PMMA multilayered model polymers: An innovative approach for a better-controlled pellet multi-extrusion process. 2021. https// doi: 10.25518/esaform21.1024.
7. Sukindar NA, Samsudin NM, Shaharuddin SI, Kamaruddin S. The effects of FDM printing parameters on the compression properties of polymethylmethacrylate (PMMA) using finite element analysis. International Journal of Integrated Engineering. 2022 Jun 12;14(2):86-92. https// doi: 10.30880/ijie.2022.14.02.013.
8. Linh NT, Huy KD, Dung NT, Luong NX, Hoang T, Tham DQ. Fabrication and characterization of PMMA/ZrO2 nanocomposite 3D printing filaments. Vietnam Journal of Chemistry. 2023 Aug;61(4):461-9. https// doi: 10.1002/vjch.202200185.
9. Archana R, Baldia M, Jeeva JB, Joseph M. Strength analysis of cranioplasty PMMA flap material. Materials Today: Proceedings. 2019 Jan 1;15:167-72. https// doi: 10.1016/j.matpr.2019.04.188.
10. Deshwal S, Kumar A, Chhabra D. Exercising hybrid statistical tools GA-RSM, GA-ANN and GA-ANFIS to optimize FDM process parameters for tensile strength improvement. CIRP Journal of Manufacturing Science and Technology. 2020 Nov 1;31:189-99. https// doi: 10.1016/j.cirpj.2020.05.009.
11. Kumar V, Kumar A, Chhabra D, Shukla P. Improved biobleaching of mixed hardwood pulp and process optimization using novel GA-ANN and GA-ANFIS hybrid statistical tools. Bioresource technology. 2019 Jan 1;271:274-82. https// doi: 10.1016/j.

biortech.2018.09.115.

12. Hamed MA, Abbas TF. The impact of FDM process parameters on the compression strength of 3D printed PLA filaments for dental applications. Advances in Science and Technology. Research Journal. 2023;17(4). https// doi: 10.12913/22998624/169468.
13. Abdullah Z, Ting HY, Ali MA, Fauadi MH, Kasim MS, Hambali A, Ghazaly MM, Handoko F. The effect of layer thickness and raster angles on tensile strength and flexural strength for fused deposition modeling (FDM) parts. Journal of Advanced Manufacturing Technology (JAMT). 2018;12(1 (4)):147-58.
14. Nugroho A, Ardiansyah R, Rusita LA, Larasati IL. Effect of layer thickness on flexural properties of PLA (PolyLactid Acid) by 3D printing. InJournal of Physics: Conference Series 2018 Nov 1 (Vol. 1130, p. 012017). IOP Publishing. https// doi: 10.1088/1742-6596/1130/1/012017.
15. Dev S, Srivastava R. Optimization of fused deposition modeling (FDM) process parameters for flexural strength. Materials Today: Proceedings. 2021 Jan 1;44:3012-6. https// doi: 10.1016/j.matpr.2021.02.436.
16. Mohankumar HR, Benal MGM, Pradeepkumar GS, Tambrallimath V, Ramaiah K, Yunus Khan TM, Bhutto JK, Ali MA. Effect of short glass fiber addition on flexural and impact behavior of 3D printed polymer composites. ACS omega. 2023 Mar 1;8(10):9212-20. https//doi: 10.1021/acsomega.2c07227.
17. Sofia J, Kumar KK, Ethiraj N, Nikolova MP. Characterisation of PLA-PMMA laminate without resin fabricated by FDM. Academic Journal of Manufacturing Engineering. 2023;21(3).
18. Abbas AS, Mahdi BS, Abbas HH, Sayyid FF, Mustafa AM, Annon IA, Abdulsahib YM, Resen AM, Hanoon MM, Obaeed NH. Corrosion behavior optimization by nanocoating layer for low carbon steel in acid and salt media. Corrosion Science and Technology. 2023; 22(1): 1-9. https://doi.org/10.14773/cst.2023.22.1.1.
19. Obaeed NH, Abdullah MA, Muath M, Adnan M, Amir H. Study The effect of process parameters of CNC milling surface generation using Al-alloy 7024. Diyala Journal of Engineering Sciences. 2019 Sep 1:103-12. https// doi: 10.24237/djes.2019.12312.
20. Alduroobi AA, Ibraheem MQ, Obaeed NH. Predict the best variants of cutting in turning process using genetic algorithm technique. In: 2nd International Conference for Engineering, Technology and Sciences of Al-Kitab (ICETS), 2018, Dec 4, pp. 33-38. IEEE. https// doi: 10.1109/ICETS.2018.8724617.
21. Haldurai L, Madhubala T, Rajalakshmi R. A study on genetic algorithm and its applications. Int. J. Comput. Sci. Eng. 2016 Oct;4(10):139-43. https// doi: 10.56726/irjmets32980.