IOP Conference Series: Materials Science and Engineering

Parametric multi-objective optimization of fused deposition modelling (FDM) with biopolymer using Grey-Taguchi method

Parametric multi-objective optimization of fused deposition modelling (FDM) with biopolymer using Grey-Taguchi method

Kuldeep Sharma[1,2], Kapil Kumar[1,3]

[1] Department of Mechanical Engineering, Greater Noida Institute of Technology, Greater Noida, Gautam Buddha Nagar- 201310, UP, India

[2] E-mail: kldpsh7@gmail.com

[3] E-mail: kapil.me@gniot.net.in, er.kapil.kr@gmail.com

Abstract. For ecological sustainability, the synthetic polymers are being continuously replaced by biopolymers due to their unique properties of biocompatibility and biodegradability. Ploy-lactic acid (PLA) is a well-known engineering biopolymer because of its versatile use in bioengineering, textile and packing industries. For the customized engineering applications, the mechanical properties, namely tensile strength and shore hardness of PLA specimens printed by FDM which is an economical 3D printed technique has been investigated in this article. Taguchi's L9 orthogonal array (OA) is used as a design of experiment. The influence of process parameters namely layer height, nozzle temperature, raster angle and surrounding pressure on mechanical properties of 3D printed specimens has been analysed by using Analysis of variance (ANOVA). ANOVA is employed to identify the significance and percent contribution of a particular process parameter on each mechanical property separately. In the end, grey relational analysis (GRA) is used as a multi-objective optimization tool to fabricate a better specimen with comprehensive mechanical properties.

Keywords: 3-D printing, Fused deposition modelling, Mechanical properties, Taguchi method, Grey relational analysis

1. Introduction.

Over the past few years, Additive Manufacturing or 3D printing has gained great popularity by virtue of its ability to fabricate complex shapes with ease, size availability, easy handling, wide range of functional materials and its applications in engineering industry especially in aeronautics, construction, automotive industry, textile industry, food industry and medical sciences Espalin et al. [1]. Additive manufacturing has a number of methods which are being used as per their properties, some of these methods are stereolithography, selective layer sintering, syringe extrusion, Fused Deposition Modelling (also known as Fused Filament Fabrication) etc. But FDM has become extensively implemented technique of 3D printing among other methods Prashantha and Roger [2]. In FDM method, a heated printing head unit extrudes semi-liquid thermoplastic through a fixed orifice nozzle on a build area (printer bed) one layer upon other in order to form a 3-dimensional shape Alafaghani et al [3].

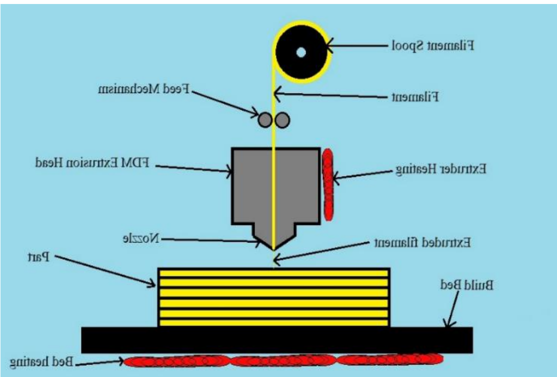

Figure 1 Diagrammatic representation of FDM Process

The relative motion between printing head and print bed in all three dimensions is governed by a software of computer aided manufacturing (Zein et al., 2002). Basics of a FDM 3D printer are shown in Figure 1(Sharma et al., 2021).

Optimization of FDM process parameters has been a field of interest for researchers over the last few years and studies have been performed to understand effects of different process parameters on different characteristics of 3D printed parts. Through optimization of process parameters, a range of settings can be defined for a FDM 3D printer where upon the strength, printing time, material used, dimensional accuracy or any other aspect of fabricated part can be optimized. Raster angle, layer height, line width, bed temperature and nozzle temperature are some of the most commonly optimized process parameters [4–7]. Conventionally, researchers vary one process parameter while keeping others constant to study its effects and then next parameter. While this technique is proven to work but it is very time and resource consuming as number of experiments grow exponentially when more than one parameter is optimized and intersection terms of different parameters are not taken into consideration. To overcome this, Taguchi method is used in this experimental study which is an efficient design of experiment method to screen a number of control parameters while keeping the number of experiments significantly low [8]. L_9 orthogonal array of Taguchi's method is used to study the effects of different process parameters on tensile strength and shore hardness of specimens. Subsequently, ANOVA is used to determine optimum process parameters with their effective contribution.

2. Literature Review

(Srivastava et al. [4] Conducted a Response surface methodology (RSM) on FDM Maxum, 3D printer using ABS thermoplastic polymer. Here, a hybrid approach was proposed to optimize the material volume of model along with built time through FDM by establishing optimal conditions as per grey analysis method with 0.654 mm contour width and 0.0254 mm air gap, orientated at 0.0° with 0º raster angle. Prashantha and Roger [2] printed specimens for the fabrication of conductive polymer Nano composites using FDM based 3D printer. Parameters set as nozzle temperature 210° C and its diameter, 0.4 mm. During printing, bed temperature was set at 60º C, while distance between the nozzle and bed was set at 0.2 mm. Printed specimens were of two surface layer shells stacked in between 45° and -45º at 0.2 mm layer height. The infill density was chosen 100 percent along with linear infill pattern. Panda et al.[5] adopted a recently developed Bacterial foraging optimization algorithm due to its ease of implementation. By using surface method for prediction process, a functional relationship was developed between strength and process parameters like thickness, raster width, raster angle, build orientation and air gap. Hmeidat et al. [6] printed Nano composites using EPON 826 resin and DGEBPA resin having 178-186 weight per epoxide with density of 1.162 g/cc. The designed thermoset composite products found to have significant higher strength range of 80 to 143 MPa because of cross-linked process, resulted in excellent layer to layer bonding. Papon and Haque [7] used a laboratory mixing extruder to develop small batches of polymers of Poly lactic acid biopolymers (PLA) and Cellulose Nano fibril (CNF) filaments. PLA granulates of 3 mm were selected as matrix material that was melted at 175° C while, CNF with 400 nm length & average diameter of 50 nm used as reinforcement material. In their study, it was concluded that CNF/PLA Nano composites with 0.5 percent CNF results in improved strength and modulus elasticity set against neat PLA. Extruder orifice and printer nozzle also affects the geometry of bed spreading and orientation of CNF. Cataldi et al. [9] produced Nano composites of polyvinyl alcohol and cellulose Nano crystals using a single screw extruder. In the produced specimens PVOH was used as matrix material. It was found that, by introducing CNC into the composited stiffness of filament increased which resulted in tougher and less dense products. Alafaghani et al. [3] studied the effect of different control parameters on dimensional accuracy along with their mechanical properties. In the study, it was concluded that the dimensional accuracy along with their mechanical properties of the 3D printed material were affected more by extrusion temperature, building direction and height of layer than the printing speed, infill pattern and percentage. B. Coppola et al. [10] did the comparative study of specimens of PLA and PLA/CLAY Nano composites at varying temperatures using FDM technique. In the study, semi-crystalline PLA was used as matrix and dog bone specimens were printed to mechanically test the samples at different temperatures: 185º C, 200º C and 215º C. It was concluded that Nano composite samples exhibit higher modulus of elasticity than the PLA specimens which increases with increasing printing temperature. Ceretti et al.

[11] studied the effect of extrusion technology and process parameters on the deposited material by producing multi-layered Poly-caprolactone (PCL) scaffolds varying configurations and adding human foreskin fibroblast cells at cellular density of 4000 cells/cm. Though, any significant effect of extrusion head on the geometry of samples was not found but grain extrusion head suggest to be preferred. Bartolomeo Coppola et al. [12] studied the relation between printing temperature and the thermoplastic polymer architecture used in additive manufacturing technology. They produced the specimens of PLA reinforced layer-wise with silicate using single screw extruder at 10rpm with operating temperature varied in the range of 160º C - 180° C. They fixed the nozzle diameter 0.35 mm, bed temperature at 50º C along with layer height 0.2 mm and raster angle at +/-45° C. From the study it was concluded that, transparency of a specimen is directly affected by printing temperature, as it increases with increases in temperature. (Balchan and Drickamer [13] studied the effects of pressure on the resistance of selenium and iodine in the specimens. They experimented in the pressure range of 60 to over 400 kbar and found a sharp drop in the resistance between 60 to 128 kbar for selenium and 60 to 255 kbar for Iodine. Sobczak et al. [14] observed the influence of pressure in metal castings. Parameters such as nucleation growth, interfacial energy, phase diagrams and diffusion coefficient were considered. It was concluded that reduced critical radius, decreased interfacial free energy and reduced rate of new phase nucleation resulted in refinement structure formation. Dean and Unal [8] notified the benefits of using Taguchi technique in the specimen's production and stated that Taguchi method is a powerful tool to produce products with robust quality and improved cost efficiency, simultaneously. Mohan Pandey et al. [15] explained layered manufacturing into two categories. The slicing algorithms employed in the process have been classified into rectangular build edge and slope. Ahn et al. [16] presented formulation of surface roughness in the specimens produced by FDM technique. They concluded that cross-section of filament, surface angle, thickness of layer influences the surface roughness of fabricated FDM parts. Boschetto and Bottini [17] performed a case study with 60 different deposition angles taken in the range 0° to180° using a thermoplastic polymer, ABS and prepared a method to predict surface roughness and dimensional accuracy. After investigation, they concluded that the process parameters like layer thickness and deposition angle greatly influence the dimensional deviations. Bellini et al. [18] evolved a new extrusion method by using granules rather than filament in the field of fused deposition modelling of ceramics to overcome the limitations of filaments being used. Pandey et al. [19] evaluated surface roughness of FDM part which majorly caused due to staircase effect. They presented a semi empirical model and used HCM (Hot cutter machine). ANOVA was used to evaluate the significant index of process and concluded that, by using HCM method, 0.3 µm level of surface finish has been achieved with 87% confidence level.

The intensive literature review indicates that in order to optimize mechanical properties of 3D printed parts through FDM process, usually the process parameters which are controlled through FDM machine itself are optimized and external conditions such as surrounding temperature, surrounding pressure, humidity etc. are not taken into account. The quality characteristics of 3D printed parts is affected by the external factors, physicist P.W. Bridgman [20] conducted a thorough study on properties and characteristics of materials under high pressure. J.D. Bernal [21] stated that under sufficiently high pressure, all matter should behave like metals. In this study one of these factors, surrounding pressure is taken under consideration for optimization and treated as a process parameter. Taguchi technique and GRA together are proven as a great tool for the purpose of multi-objective optimization as so that is why these analysis methods are employed as well.

3. Experimentation

3.1 Process parameters and their range

After intensive literature review, the process parameters like layer height, raster angle and nozzle temperature have been greatly influenced the mechanical properties of 3D printed specimens. In this research study, a new process parameter, i.e., surrounding pressure is taken under consideration in order to understand its influence on the mechanical properties such as tensile strength and shore hardness of FDM 3D printed specimens. To perform experimentation, L_9 orthogonal array of Taguchi's design of experiment have employed in which each process parameter considered at three levels. These three levels are selected based on 3D printer manual and pilot test performed on a 3D printer. The ranges and subsequent levels of variable process parameters taken for this study are as shown in Table 1. In 3D printing of specimens, some process parameters of FDM 3D printer have taken fixed during each experiment, which are as follows: bed temperature at 60° C, 0.4 mm nozzle diameter, relative density at 100%, printing speed at 3600 mm/min, three number of solid layers and 0.4 mm extrusion width.

Table 1: Levels and range of process parameters

Control Factors	Symbols	Units	Levels		
			I	II	III
Layer Height	A	mm	0.1	0.15	0.2
Raster Angle	B	Degree	0	45	90
Nozzle Temperature	C	º C	200	210	220
Surrounding Pressure	D	psi	0	50	100

3.2 Materials

The polylactic acid (PLA) filament, white colour, of diameter 1.75 ± 0.03 mm was selected to print the test specimens for analysing the mechanical properties. PLA, a thermoplastic polyester, is one of the most commonly used 3D printing filaments and its chemical formula is $(C_3H_4O_2)_n$.

3.3 Experimental Setup

FDM machine used for sample preparation is Inferno i3 3D printer. Maximum print volume for this particular model is 220*220*250 mm. ABS (Acrylonitrile butadiene styrene), PVA (Polyvinyl Alcohol), PLA (Polylactic Acid), high density polyethylene and similar materials can be used to print by this 3D printer. A print bed that can be heated is installed in this printer which is very helpful to adhere the bottom layer of the specimen. Firmware used in this machine is Marlin. To print on this machine G-code of the part is send to the printer with a SD card or over USB. The FDM printer is kept inside the air-tight pressure chamber and the lid of the chamber is shut closed with the help of fasteners, the air compressor is turned on to increase the air pressure around FDM printer, the compressed air is first filled in the cylinder of compressor and then transferred to the pressure chamber containing FDM machine with the help of a high-pressure pipe.

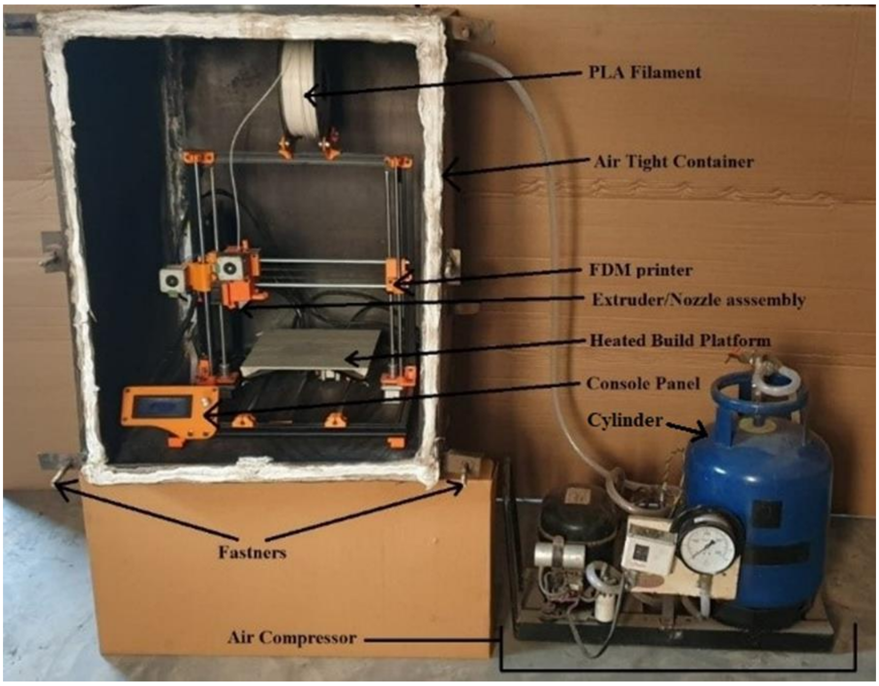

Figure 2: Experimental Setup

Desired pressure is set in the pressure switch which automatically turns the compressor off once that pressure is achieved. After maintaining required surrounding pressure, FDM process starts, the test specimen is printed and pressure is released, then specimen is taken out and whole process is repeated to print next specimen. Thus, a pressure chamber along with an air compressor is used to control and change surrounding pressure as per the requirement, the printer is kept inside pressure chamber. All other process parameters are set while creating the G-code file and sent to the printer along with the G-code. The experimental setup used in this study is displayed in Figure 2 [22].

3.4 Sample Preparation

In this study, ISO 527-2 (Model 5A) standard is used for testing of tensile properties of PLA [23]. Figure 3 [22] shows shape and dimensions in mm used to prepare CAD 3D model for samples. Samples are 3D printed using PLA on Inferno i3 FDM 3D printer.

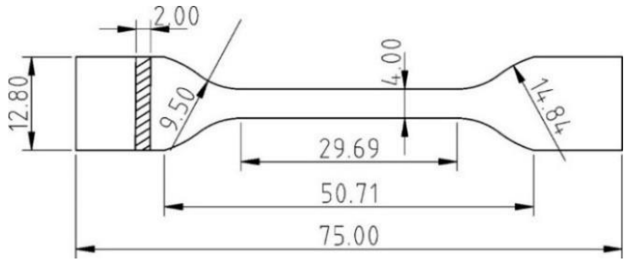

Figure 3: CAD model of tensile specimen

To understand the effects of process parameter variation on tensile strength of FDM produced specimens, the specimens were fabricated as per ISO 527-2 standard and tested on Tax-care digital tensile testing machine. Shore hardness of specimens was also measured using a shore durometer. Figure 4 shows fractured specimen after tensile testing.

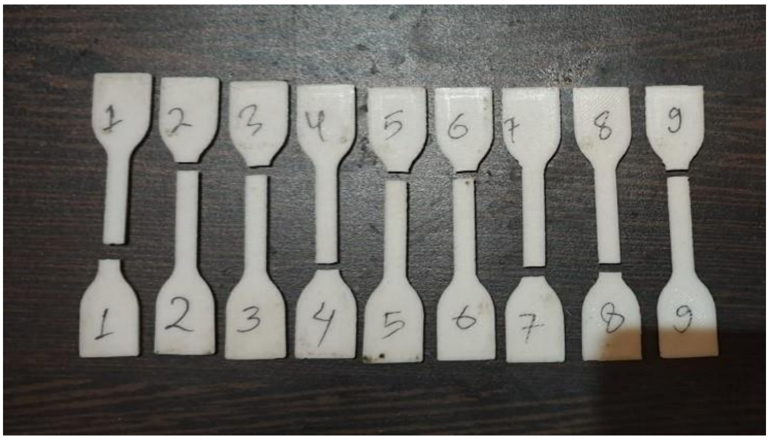

Figure 4: Fractured samples after tensile test

3.5 Experimental design using Taguchi technique

Taguchi method is an efficient technique to design experiments for a process with multiple variables in order to upgrade the product quality when experimenter ought to keep number of experiments significantly low[24]. Taguchi method is used in this study to evaluate the effects of control factors of FDM process on the mechanical properties of FDM printed specimens.

In Taguchi methodology, quality of a product is realized as an estimation of loss to the society interconnected with that product. Here, loss can be defined as deviations and variations found in function of the product. A comparison of how much each unit differs from other in the way it operates shows loss from variation in function, greater variance means more significant loss. This study focuses on strength of specimens which is desired as high as possible, so "higher the better" method of quality characteristics is preferred for the responses. Equation (1) shows the formula used to calculate S/N ratio. Table 2 shows response values for shore hardness and tensile strength by using Taguchi's L9 orthogonal array.

$$^{S}/_{N}\ ratio = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_j^2}\right) \quad (1)$$

Where, y_j = response for performance characteristics

n = Number of repetitions

Table 2: Response values for tensile strength and shore hardness using L9 orthogonal array

					Tensile Strength (MPa)				Shore Hardness (BHN)			
S. No.	A	B	C	D	Trial 1	Trial 2	Trial 3	S/N ratio (dB)	Trial 1	Trial 2	Trial 3	S/N ratio (dB)
1	1	1	1	1	59.32	63.3	68.28	36.03	91	93	96	39.39
2	1	2	2	2	72.96	76.94	81.92	37.73	92	94	97	39.49
3	1	3	3	3	62.85	66.83	71.81	36.50	91	92	95	39.33
4	2	1	2	3	58.79	62.77	67.75	35.96	93	94	97	39.52
5	2	2	3	1	54.38	58.36	63.34	35.32	93	95	98	39.58
6	2	3	1	2	60.2	64.18	69.16	36.15	93	95	98	39.58
7	3	1	3	2	47.98	51.96	56.94	34.31	92	94	97	39.49
8	3	2	1	3	55.67	59.65	64.63	35.51	94	96	99	39.67
9	3	3	2	1	67.05	71.03	76.01	37.04	93	95	98	39.58

4. Results and Discussion

Figure 5 shows the effects of control factors on desired mechanical properties namely, tensile strength and shore hardness of FDM produced specimens, a graph is plotted between mean of S/N ratios of each parameter at different levels and as our approach here is "higher the better", parameters at level A_1, B_3, C_2 and D_1 are best suitable in order to achieve maximum tensile strength. In a similar fashion, parameter A_3, B_2, C_1 and D_2 forms best setting which ensures maximum shore hardness.

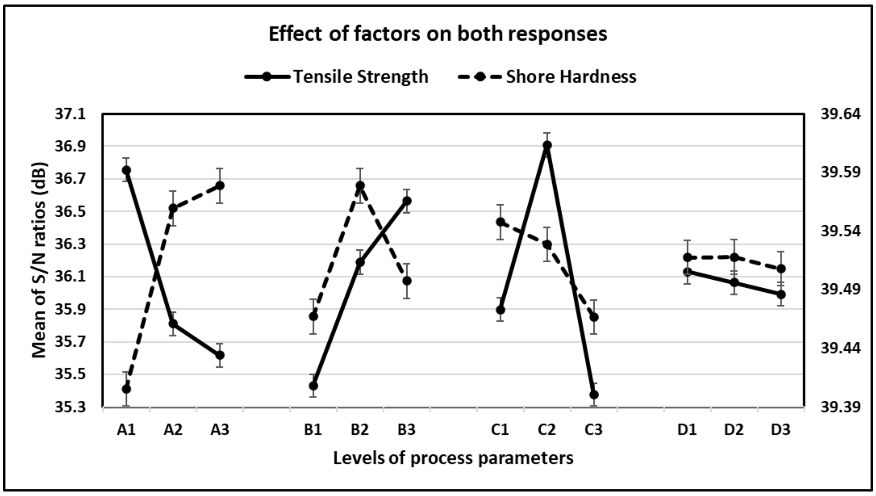

Figure 5: Influence of control factors on tensile strength and shore hardness

Analysis of variance (ANOVA) is performed in order to understand significance of each process parameter on tensile strength and shore hardness of final part respectively. Table 3 reveals that nozzle temperature (Factor C) is the highest significant control factor which affects tensile strength of FDM produced part with 45.74% contribution followed by layer height (Factor A) which contributes 27.86%, raster angle (Factor B) has 24.95% contribution while surrounding pressure (Factor D) turns out to be an insignificant factor for tensile strength within the range considered in this study.

Table 3: Pooled ANOVA for Tensile Strength

Factors	DOF	Sum of Square	Variance	F-ratio	P (%)
A	2	2.2253	1.1127	78.00	27.86
B	2	1.9964	0.9982	69.98	24.95
C	2	3.6360	1.8180	127.45	45.74
Error	2	0.0285	0.0143		1.45
Total	8	7.8862			100

$F_{0.05}(2,2) = 19\ (Tabulated)$, DOF-Degree of Freedom, P (%)- percentage contribution

Table 4: Pooled ANOVA for Shore Hardness

Factors	DOF	Sum of Square	Variance	F-ratio	P (%)
A	2	0.05410	0.02705	286.54	63.51
B	2	0.01993	0.00996	105.54	23.25
C	2	0.01074	0.00537	56.89	12.43
Error	2	0.00019	0.00009		0.81
Total	8	0.08490			100

$F_{0.05}(2,2) = 19\ (Tabulated)$, DOF-Degree of Freedom, P (%)- percentage contribution

Table 4 indicates percentage contribution of factors A, B and C in affecting the shore hardness of final part. Layer height (Factor A) proved to be the highest significant parameter having a contribution share of 63.51% followed by raster angle (Factor B) and nozzle temperature (Factor C) with a contribution of 23.25% and 12.43% respectively while surrounding pressure (Factor D) is an insignificant factor here as well.

4.1 Grey Relational Analysis

Grey relational analysis (GRA) is used in this study as a method of multi-objective optimization. Multiple attributes of a decision making problem are consolidated into a single value in this method [25]. The data obtained from Taguchi's method is processed into grey relational coefficient and then subsequently processed into grey relational grade (GRG), GRG is an index which deals with multiple performance characteristics. The data received from S/N ratio of tensile strength and shore hardness is processed into linear normalization, original sequence is converted between 0.00 and 1.00 for the purpose of comparison, it is known as grey relational generating. Equation (2) is used for normalization of original data. For a multi-objective optimization, it is observed that highest performance is indicated by highest GRG [26].

$$x_i^*(t) = \frac{x_i^o(t) - min\, x_i^o(t)}{max\, x_i^o(t) - min\, x_i^o(t)} \qquad (2)$$

Where, $x_i^*(t)$ represents normalized value of t^{th} response within i^{th} experiment, $x_i^o(t)$ represents original sequence value of t^{th} response within i^{th} experiment, $\min x_i^o\,(t)$ and $\max x_i^o(t)$ represents lowest and highest values of $x_i^o(t)$ respectively. Equation (3) is used to calculate grey relational coefficient which is then used to establish a correlation between best value and experimental value.

$$\gamma_i(t) = \frac{\Delta\, min + \partial \Delta max}{\Delta_{oi}(t) + \partial \Delta max} \qquad (3)$$

$0 < \gamma_i(t) \leq 1$

Where, ∂=0.5

Equation (4) is used to calculate grey relational grade, $G(y_o, y_i)$

$$G(y_o, y_i) = \frac{1}{k}\sum_{t=1}^{k} \gamma_i\,(t) \qquad (4)$$

Computational values of grey relational analysis are indicated in table 5. Highest value of GRG corresponds to experiment no 2, which indicates that highest value of tensile strength and shore hardness can be achieved through parameters used in experiment 2.

Table 5: Grey relational analysis

	Normalization		Deviation sequence		Grey Relational Coefficient (GRC)			
Exp. No.	UTS	Hardness	UTS	Hardness	UTS	Hardness	Grade	Rank
1	0.5036	0.1798	0.4964	0.8202	0.5018	0.3787	0.4403	8
2	1.0000	0.4561	0.0000	0.5439	1.0000	0.4790	0.7395	1
3	0.6418	0.0000	0.3582	1.0000	0.5826	0.3333	0.4580	7
4	0.4822	0.5534	0.5178	0.4466	0.4912	0.5282	0.5097	6
5	0.2965	0.7295	0.7035	0.2705	0.4155	0.6489	0.5322	5
6	0.5388	0.7295	0.4612	0.2705	0.5202	0.6489	0.5845	4
7	0.0000	0.4561	1.0000	0.5439	0.3333	0.4790	0.4062	9
8	0.3523	1.0000	0.6477	0.0000	0.4356	1.0000	0.7178	2
9	0.7968	0.7295	0.2032	0.2705	0.7111	0.6489	0.6800	3

4.2 Confirmation Experiment

A confirmation experiment is preformed to validate the results obtained through analysis. Process parameters for confirmation experiment are considered as per experiment 2 which should give optimum values of tensile strength and shore hardness. Satisfactory results are obtained after confirmation experiment which are shown in Table 6.

Table 6 Results of confirmation experiments

	Tensile Strength	Shore hardness	Grey relational grade
Trial 1	74.97	92	
Trail 2	77.89	94	
Trail 3	79.92	97	
S/N ratio	37.79	39.49	
Initial Process Parameters	A1B2C2D2		0.7395
Confirmation test	A1B2C2D2		0.7414

4.3 Surface Morphology

In order to analyse and study micro-structure of FDM produced parts, microscopic evaluation was done using an optical microscope. It is observed that by increasing the layer height, the irregularities between two layers are to be increased that can be perceived in Fig. 6, 7 and 8.

Figure 6: Optical micrograph of specimen printed at 0.1mm layer height

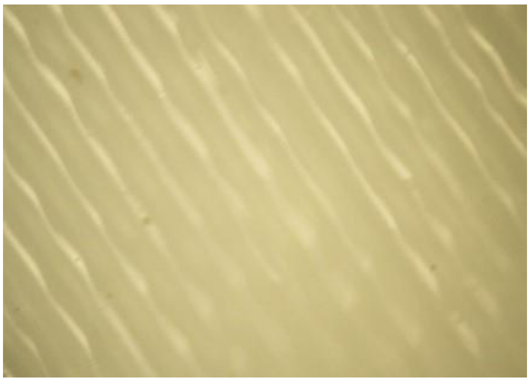

Figure 7: Optical micrograph of specimen printed at 0.15 mm layer height

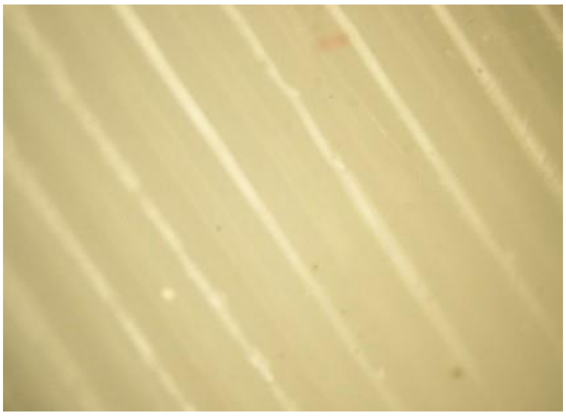

Figure 8: Optical micrograph of specimen printed at 0.2 mm layer height

5. Conclusions.

To fabricate a specimen of PLA which has comprehensive mechanical properties namely tensile strength and shore hardness was the primary objective of this study, the major outcomes of this experimental study are as follows:

1. The tensile strength of FDM produced specimen is affected the most by nozzle temperature with the contribution of 45.74% and secondly affected by the layer height with the contribution 27.86% and the lastly affected by the raster angle with the contributes of 24.95%.

2. The shore hardness of FDM produced specimen is affected the most by layer height with the contribution of 63.51% and secondly affected by the raster angle with the contribution 23.25 % and the lastly affected by the nozzle temperature with the contributes of 12.43%.

3. It is observed that surrounding pressure does not have any significant effect on tensile strength and shore hardness of FDM produced specimens within the range considered under this study. However, the effect of surrounding pressure might be possible by increasing the range of surrounding pressure that would be future research scope.

4. The comprehensive mechanical properties in the printed specimen has been successfully fabricated by printing the specimens at level of optimum process parameters obtained through Grey Relational

Analysis, which are surrounding pressure(D_2), nozzle temperature(C_2), raster angle(B_2) and layer height(A_1).

5. Thus, grey relational analysis has been observed an effective technique to perform multi-response optimization.

References.

[1]. Espalin D, Muse DW, MacDonald E, Wicker RB. 3D Printing multifunctionality: Structures with electronics. Int J Adv Manuf Technol. 2014;72(5–8):963–78.

[2]. Prashantha K, Roger F. Multifunctional properties of 3D printed poly(lactic acid)/graphene nanocomposites by fused deposition modeling. J Macromol Sci Part A Pure Appl Chem. 2017 Jan 2;54(1):24–9.

[3]. Alafaghani A, Qattawi A, Alrawi B, Guzman A. Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-Manufacturing Approach. Procedia Manuf. 2017;10:791–803.

[4]. Srivastava M, Maheshwari S, Kundra TK, Rathee S. Estimation of the effect of process parameters on build time and model material volume for fdm process optimization by response surface methodology and grey relational analysis. In: Advances in 3D Printing and Additive Manufacturing Technologies. Springer Singapore; 2016. p. 29–38.

[5]. PANDA SK, PADHEE S, SOOD AK, MAHAPATRA SS. Optimization of Fused Deposition Modelling (FDM) Process Parameters Using Bacterial Foraging Technique. Intell Inf Manag. 2009;01(02):89–97.

[6]. Hmeidat NS, Kemp JW, Compton BG. High-strength epoxy nanocomposites for 3D printing. Compos Sci Technol. 2018 May 26;160:9–20.

[7]. Papon EA, Haque A. Tensile properties, void contents, dispersion and fracture behaviour of 3D printed carbon nanofiber reinforced composites. J Reinf Plast Compos. 2018 Mar 1;37(6):381–95.

[8]. Dean EB, Unal R. Taguchi Approach to Design Optimization for Quality and Cost: An Overview. Annu Conf Int Soc Parametr Anal. 1991;1–10.

[9]. Cataldi A, Rigotti D, Nguyen VDH, Pegoretti A. Polyvinyl alcohol reinforced with crystalline nanocellulose for 3D printing application. Mater Today Commun. 2018 Jun 1;15:236–44.

[10]. Coppola B, Cappetti N, Di Maio L, Scarfato P, Incarnato L. Influence of 3D printing parameters on the properties of PLA/clay nanocomposites. In: AIP Conference Proceedings. American Institute of Physics Inc.; 2018.

[11]. Ceretti E, Ginestra P, Neto PI, Fiorentino A, Da Silva JVL. Multi-layered Scaffolds Production via Fused Deposition Modeling (FDM) Using an Open Source 3D Printer: Process Parameters Optimization for Dimensional Accuracy and Design Reproducibility. In: Procedia CIRP. Elsevier B.V.; 2017. p. 13–8.

[12]. Coppola B, Cappetti N, Maio L Di, Scarfato P, Incarnato L. 3D printing of PLA/clay nanocomposites: Influence of printing temperature on printed samples properties. Materials (Basel). 2018 Oct 11;11(10).

[13]. Balchan AS, Drickamer HG. Effect of pressure on the resistance of iodine and selenium. J Chem Phys. 1961;34(6):1948–9.

[14]. Sobczak JJ, Drenchev L, Asthana R. Effect of pressure on solidification of metallic materials. Int J Cast Met Res. 2012;25(1):1–14.

[15]. Mohan Pandey P, Venkata Reddy N, Dhande SG. Slicing procedures in layered manufacturing: A review. Rapid Prototyp J. 2003;9(5):274–88.

[16]. Ahn D, Kweon JH, Kwon S, Song J, Lee S. Representation of surface roughness in fused deposition modeling. J Mater Process Technol. 2009;209(15–16):5593–600.

[17]. Boschetto A, Bottini L. Accuracy prediction in fused deposition modeling. Int J Adv Manuf Technol. 2014;73(5–8):913–28.

[18]. Bellini A, Shor L, Guceri SI. New developments in fused deposition modeling of ceramics. Rapid Prototyp J. 2005;11(4):214–20.

[19]. Pandey PM, Reddy NV, Dhande SG. Improvement of surface finish by staircase machining in fused deposition modeling. J Mater Process Technol. 2003;132(1–3):323–31.

[20]. Bridgman PW. The physics of high pressures. London: G. Bell & Sons, Ltd.; 1931.

[21]. Bernal JD. The problem of metallic state. 1929;

[22]. Sharma K, Kumar K, Singh KR, Rawat MS. Optimization of FDM 3D printing process parameters using Taguchi technique. IOP Conf Ser Mater Sci Eng. 2021;1168(1):012022.

[23]. ISO 527-2. International Standard. 2019.

[24]. Kumar K, Agarwal S. Multi-objective parametric optimization on machining with wire electric discharge machining. Int J Adv Manuf Technol. 2012;62(5–8):617–33.

[25]. Kuo Y, Yang T, Huang GW. The use of grey relational analysis in solving multiple attribute decision-making problems. Comput Ind Eng. 2008;55(1):80–93.

[26]. Tsao CC. Grey-Taguchi method to optimize the milling parameters of aluminum alloy. Int J Adv Manuf Technol. 2009;40(1–2):41–8.