Jurnal Kejuruteraan 36(1) 2024: 113-122
https://doi.org/10.17576/jkukm-2024-36(1)-11

Multi Objective Optimization of FDM Parameters Using Taguchi Grey Relation Analysis for PLA Specimen

Khushbu Patel [a*], Shailee Acharya [b] & G. D. Acharya [c]

[a]*Gujarat Technological University, Ahmedabad, Gujarat, India*

[b]*SVIT, Gujarat, India*

[c]*Aatmiy University, Rajkot, Gujarat, India*

**Corresponding author: khushbutpatel@gmail.com*

Received 11 March 2023, Received in revised form 22 May 2023
Accepted 22 June 2023, Available online 30 January 2024

ABSTRACT

Polylactic acid (PLA), is a thermoplastic polyester that has many uses in both consumer goods and industrial settings. The mechanical characteristics of PLA specimens created using Fused deposition modeling (FDM), a cost-effective 3D printing process, including tensile strength, shore hardness, and dimensional precision, have been studied for use in specialised engineering applications. Layer height, infill density, and printing speed are the choices made for the specimen's 3D printing. Design of experiments use Taguchi's L9 orthogonal array. Using analysis of variance (ANOVA), designers can determine the relative importance and percentage contribution of each process parameter to each answer. Using Taguchi method while conducting test for individual responses result shows that for tensile strength printing speed is 70 mm/s, layer height 0.2mm and 40% infill density as optimum parameters while for the hardness it is 60 mm/s,0.3mm and 40%, and for the dimensional deviation found 60 mm,0.2 mm, 40% respectively. Proposed TGRA method found optimum parameter for all the responses in single test as printing speed is 70 mm/s, layer height 0.3 mm and 40% infill density also validated by conducting confirmation test. Finally, a superior specimen with all-around mechanical characteristics is fabricated using Taguchi based grey relational analysis (TGRA) as a multi-objective optimization technique.

Keywords: FDM; PLA; TGRA; ANOVA

INTRODUCTION

Additive Manufacturing (AM), often known as 3D printing, has been more popular in recent years due to its versatility and broad variety of potential applications in the engineering sector, particularly in the fields of aeronautics, construction, automotive, textile, culinary, and medical sciences (J. Singh, Singh, and Singh 2017) , (Cern and Ze 2023).

FDM is a new kind that is gaining popularity in many different industries since it can make very accurate, fast prototypes for aerospace applications and tools without the need for a laser (Jain and Kuthe 2013). The FDM method builds 3D things straight from 3D CAD files. To begin the FDM procedure, a .STL file of a model is imported into pre-processing software. The tool paths are reviewed and transferred to a FDM machine (S. Singh and Singh 2016) once the path data has been generated. Thermoplastic material is extruded layer by layer via a temperature-controlled nozzle (Dakshinamurthy and Gupta 2018). A metal or plastic filament is unwound from a coil and fed into an extrusion nozzle, which controls the rate of flow. In order to melt the material, a numerically controlled mechanism controlled entirely by computer-assisted manufacturing (CAM) software system heats the nozzle and allows it to spin in both the vertical and horizontal directions (Ukey, Hiremath, and Majumder 2021).

Research into the impact of varying FDM process settings on final 3D printed item attributes has been a hot topic in the past several years. The strength, printing duration, material utilised, dimensional accuracy, hardness, or any other element of the manufactured component may be tuned by the definition of a range of settings for an FDM 3D printer (Sharma and Kumar 2022).

The study by Patil et al. 2021 presents a multi-objective optimization methodology to fine-tune FDM printing settings for PLA parts. Research variables include infill patterns, infill%, printing speed, and layer thickness. The primary emphasis of this study is on the infill pattern as a process parameter. Feedback is used to evaluate surface roughness, printing time, and filament length utilised. The L27 (3^13) Taguchi array is employed for the study. When optimising FDM process settings, we use Grey Relational Analysis (GRA), which is well-suited for situations with various replies. In another piece of work, the infill density of 3D-printed thermoplastics is adjusted from 15% to 30% to 50% to 90% to 100%. Tensile testing is used to look at how infill density affects the material. The maximum tensile strength of 69 Mpa was achieved in 3D printed Nylon samples with 15%, 30%, 50%, 90%, 100% infill density (Johnson and French 2018). Taguchi experimental design was utilised to plan many 3D printed PETG and PLA material specimens for testing. Printed specimen characteristics are shown to be affected by process factors such material type, filament diameter, fluidity, and deposition rate (Santana, Lino Alves, and da Costa Sabino Netto 2019).

Minimizing wear requires a surface hardness that is just right. Orthopedic implant wear causes the release of hazardous particles. Better surface hardness of implant is necessary to reduce implant wear (P. Kumar, Ahuja, and Singh 2016).

Alafaghani et al. 2017 looked at how changing the values of certain control factors altered the precision with which measurements and mechanical characteristics were made. The research found that extrusion temperature, building orientation, and layer height had a greater impact on the dimensional accuracy and mechanical qualities of the 3D printed material than printing speed, infill pattern, or infill %.

FDM was used to compare PLA with PLA/CLAY Composite materials at different temperatures (Coppola et al. 2018). Dog bone samples were 3D printed using the semi-crystalline PLA matrix, and mechanical tests were conducted at 185°C, 200°C, and 215°C. In conclusion, when printing temperature is raised, the Nano composite samples show a greater elasticity modulus than just the PLA specimens. Balchan and Drickamer 1961, looked into how pressing on specimens affected the resistivity of selenium and iodine. By conducting experiments at pressures ranging from 60 to more than 400 kbar, they discovered that the resistance to current flow drops dramatically between 60 and 128 kbar for selenium with between 60 and 255 kbar for iodine.

The effects of pressure on metal castings were noted in (Sobczak, Drenchev, and Asthana 2012). In this analysis, authors took into account elements including nucleation growth, phase diagrams, interfacial energy, and the diffusion coefficient. It was determined that refinement structure creation occurred as a consequence of a lowered critical radius, interfacial free energy, and rate of innovation phase nucleation. It was noted in Dean and Unal 1991, that the Taguchi method is indeed a potent instrument for concurrently producing items with strong quality and increased cost efficiency.

Surface roughness in FDM-created specimens was formulated and described in Ahn et al. 2009. It was determined that now the surface roughness of FDM components is affected by the filament's cross section, surface angle, and layer thickness. When trying to solve problems with fused deposition modelling of ceramics, Bellini, Shor, and Guceri 2005 developed a novel extrusion process that employed granules instead of filament.

Using a staircase effect as a primary driver, Pandey, Reddy, and Dhande 2003 measured the surface roughness of an FDM component. They employed HCM in a somewhat empirical model presentation (Hot cutter machine). Through ANOVA, authors were able to determine that the HCM approach produced a surface polish of 0.3 m with a confidence level of 87%.

According to the reviewed literature, when trying to improve the mechanical properties of a 3D printed part using the FDM process, it is common practise to focus on optimising the parameters within the FDM machine itself rather than considering external conditions like temperature, pressure, humidity, etc.

Due of the influence of environmental conditions on 3D printed objects, physicists Silveira, Camargo, and Caldas 2021 investigated the properties and features of materials when subjected to extreme pressure. In (Bernal JD 1929), it was said that all matter should act like metals at extreme conditions. As such, this research treats ambient pressure as a process variable to be optimised together with other similar parameters.

From the in-depth literature review, summarized that majority researchers used TM for the optimization of FDM process parameters. Few tries TGRA but in limited domain. Nobody used proposed combinations of input with responses.

Detailed review of literature and discussion with senior personals of foundry guided towards the selection of input parameters with their ranges, responses and TGRA methodology which yet to be implemented particularly for the multi-objective optimization as per authors knowledge.

EXPERIMENTATION

PROCESS PARAMETERS AND THEIR RANGES

It has been determined via extensive research and consultation with industry leaders that the mechanical characteristics of 3D printed specimens are strongly impacted by process factors such as printing speed, layer height, & infill density. The L9 orthogonal array of Taguchi's design of experiment has been used to conduct the experiments, with three degrees of consideration given to each process parameter. These three settings were determined by consulting a user handbook and doing a trial run on even a 3D printer.

Table 1 displays the studied ranges and resulting levels of the variable process parameters.

MATERIAL

White filament made of PLA, which was chosen to be used in the printing of test specimens for the purpose of analysing the material's mechanical qualities. PLA, which is a thermoplastic polyester, is among the 3D printing filaments that is used the most often. Properties of PLA material is shown in the Table 2.

TABLE 1. Process parameters and their Levels

Factors	Units	Level 1	Level 2	Level 3
Print speed (PS)	(mm/s)	60	65	70
Layer height (LH)	(mm)	0.2	0.25	0.3
Infill density (ID)	(%)	20	30	40

TABLE 2. Properties of PLA material

Property	Range
Extrude temperature	180-220
Bed temperature	20-55
CTE	85
Tg	60-65

SPECIMEN PREPARATION

In this research, the tensile characteristics of PLA are examined using ASTM D638. Figure 1 depicts the sample's form and measurements in millimeters for use in creating the CAD 3D model (Arifin et al. 2021). Initially cad model is imported to CURA software in. STL format. DAMBoy ET-200 FDM 3D Printer is used to produce PLA samples (Figure 2). Each individual component printed with the same specifications, including a filament diameter of 1.75 mm, a printing speed of 50 mm/s, and a heating bed temperature of 110 ^{0}C. All the test parts were printed in the exact equal advert in the central of the printing bed.

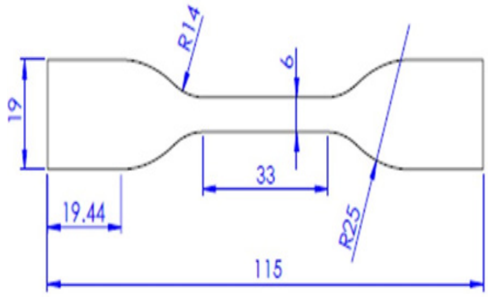

FIGURE 1. CAD model of Tensile Specimen

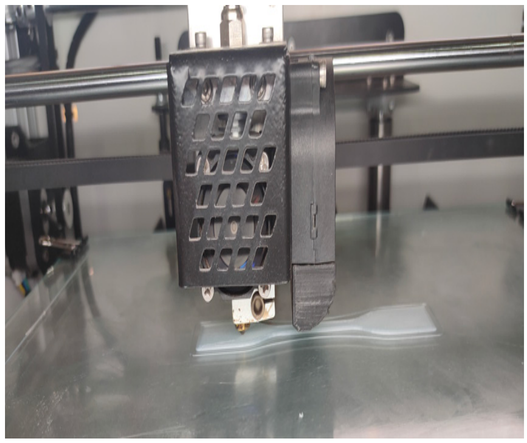

FIGURE 2. 3D printing of Specimen

MEASURED RESPONSES

The experiment was carried out at Engineering Technique Vadodara. ASTM D638 specimens were created and evaluated using Autograph Shimadzu Universal Testing Machine (Figure 3) (Source: CIPET, Ahmedabad) to determine the impact of process parameter change on the tensile strength of FDM-produced specimens. Shore hardness of samples was also tested using shore hardness tester.

FIGURE 3. Autograph Shimadzu Universal Testing Machines

By measuring the specimen's length (L), width (W), and thickness (T) with a digital venire caliper (WORK ZONE 0-150mm) with a least count of 0.01 mm, the dimensional accuracy of FDM was assessed. Each sample is subjected to three parameters along each of the three dimensions (L, W, and T), with the average serving as the possible result (figure 4).

Responses that fixed by using Taguchi's L9 Orthogonal Array for tensile strength (TS), shore hardness (SH), and dimensional deviation (DD) are shown in Table 3.

TABLE 3. Measured Response values

Exp. No.	Print Speed	Layer Height	Infill density	Dim. deviation (mm) (DD)	Shore Hardness (BHN) (SH)	Tensile Strength (N/mm^2) (TS)
1	60	0.2	20	0.01	92	36.01
2	60	0.25	30	0.08	94	37.15
3	60	0.3	40	0.17	96	40.12
4	65	0.2	30	0.06	92	38.26
5	65	0.25	40	0.15	94	42
6	65	0.3	20	0.04	95	34
7	70	0.2	40	0.14	93	43.87
8	70	0.25	20	0.02	93	36
9	70	0.3	30	0.11	95	36.21

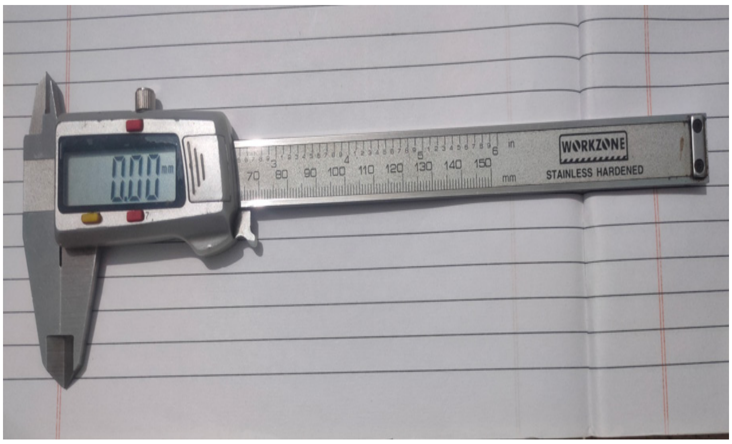

FIGURE 4. Digital Vernier caliper

RESULT AND DISCUSSION

THE TAGUCHI METHOD OF EXPERIMENTAL DESIGN

The Taguchi method is an effective strategy for designing trials for a process with various variables to improve product quality when the number of tests should be kept relatively small (K. Kumar and Agarwal 2012). In this investigation, the mechanical characteristics of FDM printed samples are analyzed in relation to the FDM process's control parameters using the Taguchi technique.

A product's quality is quantified in terms of the societal damage it may do, according to the Taguchi approach to risk analysis. Here, losses are thought of as irregularities in the product's usefulness. Loss due to variation in function may be seen by comparing how differently one-unit functions from the others; a larger difference indicates a larger loss. Because the specimens' strength is the primary focus of this research, and because it is optimal if it is as high as feasible, the "greater is better" approach to quality criteria is selected for the replies. The formula for S/N ratio calculation is shown in Equation 1.

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

Dimensional deviation values closer to zero are preferred, and the "lower is better" principle is favored when evaluating quality attributes of replies. The formula for determining the S/N ratio is given in Equation 2.

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

ANOVA is a common method of statistical analysis that has been used to determine the significance of the components at the 95% confidence level & their percentage contributions in influencing the answers. The significance of the variables has been tested by comparing the estimated F-ratio to the tabulated F-ratio at a predetermined significance threshold. When the estimated F-ratio of a factor is larger than the tabulated F-ratio, we say that the factor is significant.

ANOVA conducted for the individual responses. From the ANOVA for Tensile Strength (Table 4) Infill density is having highest impact on tensile strength followed by layer height and printing speed. From the ANOVA for Shore Hardness (Table 5) Layer height is having highest impact on Shore Hardness followed by infill density and printing speed. From the ANOVA for dimensional deviation (Table 6) Infill density is having highest impact on dimensional deviation followed by layer height and printing speed

TABLE 4. ANOVA for TS

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Print Speed	2	0.05387	0.02694	28.35	0.034	1.30662
Layer Height	2	0.52519	0.26259	276.38	0.004	12.73855
Infill density	2	3.54188	1.77094	1863.88	0.001	85.90874
Error	2	0.0019	0.00095			
Total	8	4.12284				

TABLE 5. ANOVA for SH

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Print Speed	2	0.001818	0.000909	0.91	0.524	1.364250
Layer Height	2	0.116114	0.058057	58.03	0.017	87.133423
Infill density	2	0.013328	0.006664	6.66	0.131	10.001501
Error	2	0.002001	0.001			
Total	8	0.13326				

TABLE 6. ANOVA for DD

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Print Speed	2	13.75	6.875	0.99	0.503	2.381
Layer Height	2	60.15	30.075	4.32	0.188	10.414
Infill density	2	489.78	244.888	35.16	0.028	84.796
Error	2	13.93	6.964			
Total	8	577.6				

GREY RELATIONAL ANALYSES

In this study, we provide a Taguchi approach to optimization for manufacturing issues with multiple responses, where the responses are represented graphically in greyscale. Optimization is performed using the Taguchi approach for each answer independently before GRA is applied to multi-response values.

Grey relational generation, grey relational conceits, and grey relational grade are all necessary quantitative indices that must be pre-processed before data can be utilised in GRA. The grey relational generating (Tsao 2009), (Liu and Lin 2010), (Pan et al. 2007) is used to conduct linear normalizing on the S/N ratio by turning the original features of S/N ratio into the decimal sequence within 0.00 and 1.00 for comparison. When "higher is better" values were desired, the S/N ratios were normalised using Equation 3. When the original sequence has a "lower is better" quality, it should be normalised using Equation 4.

$$y(t) = \frac{y_i^o(t) - \min y_i^o(t)}{\max y_i^o(t) - \min y_i^o(t)} \quad (3)$$

$$y(t) = \frac{\max y_i^o(t) - y_i^o(t)}{\max y_i^o(t) - \min y_i^o(t)} \quad (4)$$

The estimated grades are between 0.00 and 1.00, with 1.00 representing perfect congruence between the two sequences.

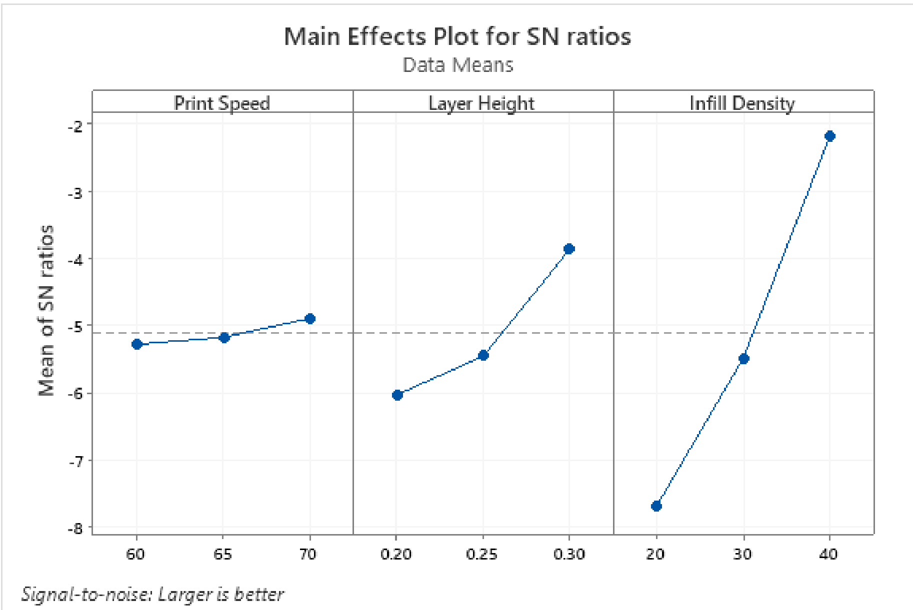

FIGURE 5. Graphical representation of effects of parameters responses and GRG

Grey relationship grade with the highest value among 9 experiments, i.e., experiment 3, perfectly stands for the best combination of factorial designs for FDM process in this study since grades are created by accumulating both performance qualities (Table-7).

From the Response Table of GRG (Table 8) concluded that, Infill density is having highest impact on tensile strength followed by layer height and printing speed.

TABLE 7. Result of GRA

EXP. No.	Normalised Values			Deviation Sequences			GRC			GRG
	DD	SH	TS	DD	SH	TS	DD	SH	TS	
1	0.0000	0.0000	0.2254	1.0000	1.0000	0.7746	0.3333	0.3333	0.3923	0.3530
2	0.7340	0.5053	0.3476	0.2660	0.4947	0.6524	0.6527	0.5027	0.4339	0.5298
3	1.0000	1.0000	0.6494	0.0000	0.0000	0.3506	1.0000	1.0000	0.5878	0.8626
4	0.6324	0.0000	0.4632	0.3676	1.0000	0.5368	0.5763	0.3333	0.4822	0.4640
5	0.9558	0.5053	0.8291	0.0442	0.4947	0.1709	0.9188	0.5027	0.7453	0.7222
6	0.4893	0.7540	0.0000	0.5107	0.2460	1.0000	0.4947	0.6702	0.3333	0.4994
7	0.9315	0.2540	1.0000	0.0685	0.7460	0.0000	0.8795	0.4013	1.0000	0.7603
8	0.2447	0.2540	0.2243	0.7553	0.7460	0.7757	0.3983	0.4013	0.3919	0.3972
9	0.8464	0.7540	0.2471	0.1536	0.2460	0.7529	0.7649	0.6702	0.3991	0.6114

TABLE 8. Response Table for GRG

Level	Print Speed	Layer Height	Infill Density
1	-5.282	-6.032	-7.699
2	-5.176	-5.455	-5.487
3	-4.892	-3.863	-2.164
Delta	0.391	2.169	5.535
Rank	3	2	1

To identify influential elements, an ANOVA is performed on the grey relationship grades shown in Table 8 and the accompanying Figure 6 show the critical parameters and their ideal values, such as A3 (Printing Speed 70), B3 (Layer Height (0.3 mm), and C3 (Infill Density 20), for incorporating the required qualities in the printed components. Table 9 shows that the infill density having highest contribution as 86.42% of the total variance, which is in-line with results of response table outcomes.

As some responses like Shore Hardness & Tensile Strength, required to maximize the output while other such as Dimensional Deviation need to minimize. Taguchi Method can't be used for such cases. So, individual response optimizes by Taguchi Method. The results show that that for tensile strength printing speed is 70 mm/s, layer height 0.2mm and 40% infill density as optimum parameters while for the hardness it is 60 mm/s, 0.3mm and 40%, and for the dimensional deviation found 60 mm,0.2 mm, 40% respectively.

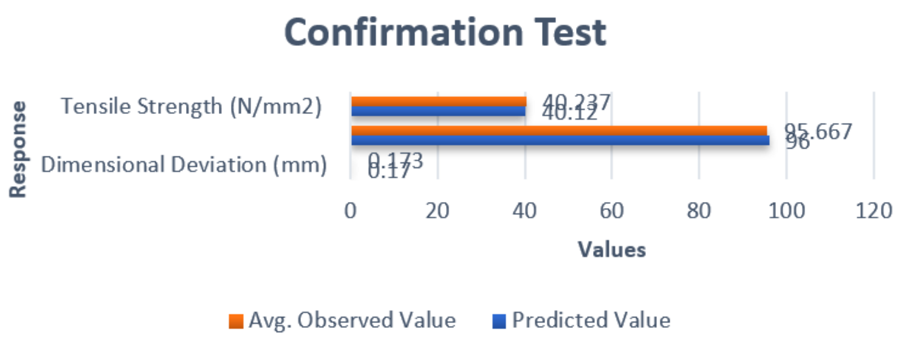

FIGURE. 6 Confirmation Test

TABLE 9. ANOVA for GRG

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Print Speed	2	0.001227	0.51%	0.001227	0.000613	0.68	0.596
Layer Height	2	0.029703	12.33%	0.029703	0.014852	16.44	0.057
Infill Density	2	0.208246	86.42%	0.208246	0.104123	115.28	0.009
Error	2	0.001806	0.75%	0.001806	0.000903		
Total	8	0.240982	100.00%				

To overcome the limitations of Taguchi Method TGRA method proposed that optimize the responses required to maximize and minimize simultaneously in single test. Proposed TGRA method found optimum parameter for all the responses in single test as printing speed is 70 mm/s, layer height 0.3 mm and 40% infill density. The result also validates by confirmation Test.

CONFIRMATION TEST

Confirmation tests are done to verify the results of the studies phase's findings. By performing the test with particular combination of variables and amounts previously assessed, the confirmation tests are carried out. Three confirmatory experiments were carried out in this research using the ideal values of the ideal process parameters. Using the gathered collection of optimal component values, confirmatory tests were run. The outcomes are displayed in Table-10 below. The findings are discovered to be fairly close to the values anticipated. (Figure-6)

TABLE 10. Result of Confirmation Test

Response	Predicted Value	Avg. Observed Value
Dimensional Deviation (mm)	0.17	0.173
Shore Hardness (BHN)	96	95.667
Tensile Strength (N/mm2)	40.12	40.237

CONCLUSION

The primary goal of this research was to determine the best set of process parameters for producing a component having good quality. Using Taguchi method-based grey relational analysis, optimized FDM process parameters that would result in a uniform set of PLAs adopted mechanical characteristics. The following are the major takeaways from the research based on the findings and discussions:

1. The following is a list, in decreasing order, of the most important elements, along with their relative amounts, that may be used to increase tensile strength: infill density, layer height and print speed having p value of 0.001, 0.004 and 0.034 respectively. infill density had the highest % Contribution of 85.90874%. There have been no observable inconsistencies.
2. With a p-value of 0.017 and a percentage contribution of 87.13342%, layer height ranks first among significant variables and their levels for improving Shore Hardness. Print speed as well as infill density have been identified negligible influences on Shore Hardness.
3. The infill density has a p value of 0.028 and % Contribution of 84.796%, making it the most important factor in reducing the Dimensional Deviation. It has been shown that print speed plus layer height have little effects on Dimensional Deviation.
4. Shortcomings of Taguchi Method are overcome by using Grey Relational Analysis (TGRG) as a multiple goal optimization, which yields optimal parameters for minimizing Dimensional Deviation while simultaneously optimizing for maximum Tensile strength with Shore Hardness.
5. In order to achieve a wide range of mechanical qualities in the finished product by TGRA, the following is a list of crucial ideal process parameters and the values at which they should be set. A3 (Printing Speed 70), B3 (Layer Height (0.3 mm), C3(Infill Density 40). Also, Infill Density having the highest impact with p value of 0.009, followed by Layer Height (0.057 as p value) and Print Speed with 0.596 as p value.

Summarized the above results, the proposed results claim same results with L9 OA, instead of L18 OA, that claimed by other researchers. Also, combinations for the optimization of proposed input parameters and responses with TGRA never used before. That shows the novelty in proposed research.

ACKNOWLEDGEMENT

Acknowledge the help from Engineering Technique, Baroda & CIPET IPT Ahmadabad for providing the data and Testing facilities for the Research.

DECLARATION OF COMPETING INTEREST

None

REFERENCES

Ahn, Daekeon et al. 2009. Representation of surface roughness in fused deposition modeling. *Journal of Materials Processing Technology* 209(15–16): 5593–5600.

Alafaghani, Ala'aldin, Ala Qattawi, Buraaq Alrawi, and Arturo Guzman. 2017. Experimental optimization of fused deposition modelling processing parameters: A design-for-manufacturing approach. *Procedia Manufacturing* 10: 791–803. http://dx.doi.org/10.1016/j.promfg.2017.07.079.

Arifin, Fatahul et al. 2021. Optimization of process parameters in 3D printing FDM by using the Taguchi and Grey Relational Analysis Methods. 15(1): 1–10. http://jurnal.umj.ac.id/index.php/sintek.

Balchan, A. S., and H. G. Drickamer. 1961. Effect of pressure on the resistance of iodine and selenium. *The Journal of Chemical Physics* 34(6): 1948–49.

Bellini, Anna, Lauren Shor, and Selcuk I. Guceri. 2005. New developments in fused deposition modeling of ceramics. *Rapid Prototyping Journal* 11(4): 214–20.

Cern, Yong Saan, and Yeoh Sheng Ze. 2023. The design of a new 3D print-in-place soft four-legged robots with artificial intelligence. 35(3): 717–33.

Coppola, B. et al. 2018. Influence of 3D printing parameters on the properties of PLA/Clay nanocomposites. *AIP Conference Proceedings* 1981.

Dakshinamurthy, Devika, and Srinivasa Gupta. 2018. A study on the influence of process parameters on the viscoelastic properties of ABS components manufactured by FDM process. *Journal of The Institution of Engineers (India): Series C* 99(2): 133–38.

Dean, Edwin B., and Resit Unal. 1991. Taguchi Approach to design optimization for quality and cost: An overview. *Annual Conference of the International Society of Parametric Analysts*: 1–10.

Jain, Pranjal, and A. M. Kuthe. 2013. Feasibility study of manufacturing using rapid prototyping: FDM Approach. *Procedia Engineering* 63: 4–11. http://dx.doi.org/10.1016/j.proeng.2013.08.275.

Johnson, Gabriel A, and Jesse J French. 2018. Evaluation of infill effect on mechanical properties of consumer 3D printing materials. *Advances in Technology Innovation* 3(4): 179–84.

Kumar, Kapil, and Sanjay Agarwal. 2012. Multi-objective parametric optimization on machining with wire electric discharge machining. *International Journal of Advanced Manufacturing Technology* 62(5–8): 617–33.

Kumar, Parlad, Inderpreet S Ahuja, and Rupinder Singh. 2016. Experimental investigations on hardness of the biomedical implants prepared by hybrid investment casting. *Journal of Manufacturing Processes* 21: 160–71. http://dx.doi.org/10.1016/j.jmapro.2016.01.001.

Liu, Sifeng, and Yi Lin. 2010. Introduction to Grey Systems Theory. *Understanding Complex Systems* 68: 1–399.

Pan, Lung Kwang, Che Chung Wang, Shien Long Wei, and Hai Feng Sher. 2007. Optimizing multiple quality characteristics via Taguchi Method-Based Grey Analysis. *Journal of Materials Processing Technology* 182(1–3): 107–16.

Pandey, Pulak M., N. Venkata Reddy, and Sanjay G. Dhande. 2003. Improvement of Surface finish by staircase machining in fused deposition modeling. *Journal of Materials Processing Technology* 132(1–3): 323–31.

Patil, Pooja, Dharmendra Singh, Sunil J. Raykar, and Jaiprakash Bhamu. 2021. Multi-objective optimization of process parameters of Fused Deposition Modeling (FDM) for Printing Polylactic Acid (PLA) polymer components. *Materials Today: Proceedings* 45: 4880–85. https://doi.org/10.1016/j.matpr.2021.01.353.

Problem, T H E, and Metallic State. 1929. P a r t 111.-Metals.

Santana, Leonardo, Jorge Lino Alves, and Aurélio da Costa Sabino Netto. 2019. Dimensional Analysis of PLA and PETG parts built by open source extrusion-based 3D printing. (August).

Sharma, Kuldeep, and Kapil Kumar. 2022. Parametric multi-objective optimization of Fused Deposition Modelling (FDM) with biopolymer using Grey-Taguchi Method. *IOP Conference Series: Materials Science and Engineering* 1248(1): 012107.

Silveira, F E M, R S Camargo, and I L Caldas. 2021. Concentration discontinuity of alkalies at high pressures. *Physics Letters A* 395: 127207. https://doi.org/10.1016/j.physleta.2021.127207.

Singh, Jaspreet, Rupinder Singh, and Harwinder Singh. 2017. Dimensional accuracy and surface finish of biomedical implant fabricated as rapid investment casting for small to medium quantity production. *Journal of Manufacturing Processes* 25: 201–11. http://dx.doi.org/10.1016/j.jmapro.2016.11.012.

Singh, S., and R. Singh. 2016. Development of functionally graded material by fused deposition modelling assisted investment casting. *Journal of Manufacturing Processes* 24: 38–45. http://dx.doi.org/10.1016/j.jmapro.2016.06.002.

Sobczak, J. J., L. Drenchev, and R. Asthana. 2012. Effect of pressure on solidification of metallic materials. *International Journal of Cast Metals Research* 25(1): 1–14.

Tsao, C. C. 2009. Grey-Taguchi Method to optimize the milling parameters of aluminum alloy. *International Journal of Advanced Manufacturing Technology* 40(1–2): 41–48.

Ukey, Kamal, Santosh Hiremath, and Himadri Majumder. 2021. Investigation of investment casting pattern using fused deposition modeling. *Engineering Science & Technology* 2(2): 201–7.