Journal of Information & Optimization Sciences
ISSN 0252-2667 (Print), ISSN 2169-0103 (Online)
Vol. 45 (2024), No. 1, pp. 25–46
DOI : 10.47974/JIOS-1137

Assessing quality in extrusion based additive manufacturing technologies

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Abstract

Quality is a magic word that has fascinated the people since the early days of civilization and today, quality is the only mantra to survive. Quality is the only relevant attribute associated with product and processes that makes any technology in-demand. The quality of the parts produced by Additive Manufacturing (AM) Technologies depends on many factors, like print speed, nozzle temperature etc. The aim of this work is the identification of influence factors that affect the performance measures of extrusion based Additive Manufacturing (AM) technologies, namely, Fused Deposition Modelling (FDM). These processes can be characterized by a set of influence factors, like print speed, infill density, temperature; layer thickness and build orientation are responsible for quality of the product. In this work, Grey relational Analysis (GRA) is employed. GRA is a method which enables determination of the relational degree of every factor in the system. The method can be used for systems that are not completely described and with relatively few available data. Reliable technique of optimization GRA is clubbed with another established technique; called Interrelation ship Diagram (ID), to identify and optimize the influence factors, that yields highest performance characteristics. Manufacturing Combinations are evaluated against performance measures. In the earlier research, the authors have applied same tool, GRA clubbed with 7QC tools, to evaluate extrinsic and intrinsic qualities of the parts produced by FDM, In this research, the entire focus is paid to the intrinsic properties of the parts produced by FDM. This research will have a greater impact on the quality of the parts produced by the FDM.

Subject Classification: *(2010) 65K10, Mechanics of deformable solids.*

Keywords: *Fused deposition modelling (FDM), Grey relational analysis (GRA), Interrelation diagram (ID).*

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I. Introduction

Quality is a magical word, everybody is obsessed with. In this competitive modern era, customer is striving for quality in all the areas and walk of life, be it product, processes, services or any other sector. Various definitions of quality are given by quality gurus; some definitions are given here; Quality is fitness for use, as described by Juran [1]. Cross by described quality, is conformance to requirements or specifications [2]. A V Feigenbaum discussed the aspects of quality as; Quality is the result of intelligent effort. Quality is a feature by which a product or service may be defined [3].International Organization of Standardization has defined the Quality as need for sustainability [4]. Taguchi defined "Quality is the loss that a product costs to the society after being shipped, other than losses, but its intrinsic function [5]. Quality is the defect free production, thereby prevention rather than detection is called "Zero defect" [6-7].Any process before being applied to mass production must, must be ascertained that it is capable of producing output that comprises to specifications or standard requirements [8]. A process is likely to inherent variables procedures, should be established to demonstrate the establish ability of specifications [9]. Quality is the totality of features and characteristics of a product in satisfying customers need and expectations on a continuous basis, in fact to delight the customer [10]. The implementation of quality systems has also been extended to additive manufacturing processes. Additive manufacturing processes are based on overlaying layers over each other [11]. AM is the advance manufacturing technology of new age with high volume of potential. The extrusion based additive manufacturing processes apply raw material in filament form, being extruded at slightly elevated at temperature from a nozzle jet injector that forms an entire layer. Extrusion based additive manufacturing technologies like Fused Deposition Modelling (FDM) are currently in high demand [12].These technologies are simple, energy efficient, easy to use, powerful and capable of manufacturing complicated and intricate shapes using almost all the materials including ceramics, glass and meta-materials[13-14].However, Quality and consistency of the parts produced by FDM is a major challenge. The high end application of this sophisticated technology also needs high end quality system implementation. Conformance to specifications is challenging task for a complicated process like additive manufacturing. To evaluate the trends and challenges posed in FDM process a systematic literature review was carried out, a summary has been presented in the section II.

II. Literature Review

Recent research related with optimization of process parameters of FDM has been summarized.

Durgun et. al. [15] in their investigation **Experimental investigation for improving mechanical properties and Production cost**' focussed properties like Tensile strength, flexural strength by taking the five different raster angles ,considering parameters like building orientations at five levels. Gorsky et. al.[16] in their research **Building orientation influence of impact strength – experimental investigation** targeted Impact strength by optimizing parameters raster angles at five levels, building orientation (three levels). Baich et. al. [17] in their study, **Infill parameter effect on mechanical properties and cost** focussed Tensile, compression, bending strength by considering Infill ratio at three levels. Ziemian et. al. [18] in their analysis, **Anisotropic mechanical properties**; considered mechanical properties; Tensile compressive, flexural impact and fatigue strength by considering four levels of raster angles ,defined machine default values for parameters. Onwubolu et. al. [19] in their study**, Mechanical properties characterization and optimization** focused Tensile strength by considering Layer thickness at two levels, orientation angles at two levels, raster angle at two levels, raster width at four levels, and air gap at two levels. Fernandez-Vincente et. al. [20] in their study **Infill effect on tensile strength for desktop3D printer** considered Tensile strength by optimizing parameters: Infill ratio at three levels , Infill pattern of three types. Torrado et. al. [21] in their investigative analysis **Failure analysis, anisotropy for tensile specimens with different geometries** focused property; tensile strength by considering three rastor patterns. Cantrel et. al. [22] in their investigation, **Mechanical properties of PC, ABS–experimental characterization ,** focused; Tensile strength, failure strength, Poisson ratio, Youngs modulus by optimizing Raster angles; building orientations (three levels) , considering process parameters constant on the same machine, but different printers. Tanikella et. al. [23] in their analysis **Mechanical properties of Rep Rap 3D printed objects** considered Tensile strength by taking process parameters; different co-materials and building orientations. Ransey et. al. [24] in their study **Experimental characterization of ABS parts tensile strength** by considering Tensile strength as output and Building orientations and infill ratio at three levels as input parameters.

The authors have earlier optimized the process parameters by combining GRA with 7QC [11] and also developed ANFIS model to portray the relationship between control factors and performance measures [51].

The conclusion from literature review indicates that major challenge in the FDM process is to ensure product quality. Many effective tools and technologies are applied to improve quality for sustainability. In this experimental investigation, an attempt has been made to improve quality of FDM process significantly. To improve the quality two most reliable techniques of quality assessment; i) Interrelationship Diagram & ii) GRA has been applied.

The objective of this research is:

i) To find the effect of influence factors on performance measures. This objective will be achieved by applying ANOVA, and interrelationship diagram will exhibit the relation between influence factor and performance measure.
ii) To find a suitable manufacturing process, that yields highest performance measures. To achieve this objective GRA will be deployed.
iii) To find the percentage contribution influence factors on performance measures. ANOVA will also work to determine percentage contribution of every influence factor on performance measures.

III. Interrelationship Diagrams

Affiliations or Interrelation ship diagrams are extensively used to relate the quality issues with the process parameters. These diagrams are based on input output modeling of causes. All the inputs and outputs are represented by boxes in a triangular manner. All the boxes are related to each other, depending upon the score of relativity. The boxes are connected with the arrows, originating from one box and terminating towards another box. Every tail of the arrow is considered as output and every head of the arrow is considered as input. Every box will have a score, ratio of input to output. Scores are depicted outside the box [25].

IV. Grey Relation Analysis

Grey Relation Analysis (GRA) is a systematic analytical method of comparing the effect of input parameters. GRA method is based on second degree of indices evaluation that measures the impact of process

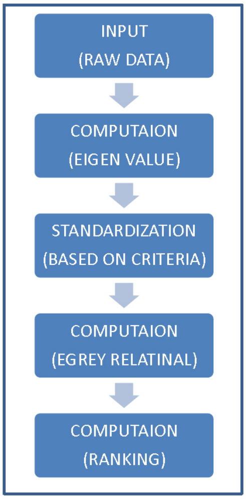

Figure 1

Flow diagram of Grey Relational Analysis

parameters on the selected output. Grey relational analysis is also used to determine the contribution of process parameters on the process output parameters [26].The degree of measure of correlations between two factors or systems is called grey correlation degree. The degree of correlation gauges the impact of relative change of the process parameters. The development process, when the relative changes of two factors or systems have basically the same trend of the changes, the factors will have a greater degree of grey correlation; otherwise, they will have a smaller degree of grey correlation [27]. Now, If the selection of reference sequence is the optimal value of each index, the sequence with large correlation degree is better than the sequence with small correlation [28-33].Grey relational analysis is being successfully applied to the optimization of process parameters in conventional machining processes, Fabrication, Friction Stir Welding,3D Printing. [34-44].GRA is already applied to the optimization of processes parameters in FDM [46-48].Flow diagram of Grey relation for FDM process is shown in Figure 1.

The equations applied and computations for this process is explained as under:

For the FDM processes, the manufacturing processes considered in this study are m, and the number of the influence factors are n.

The matrix [X] of order m x n is known as Eigen Value matrix and computed by the Equation 1[15] [38].

$$X = \begin{bmatrix} x_1(1), x_1(2), \ldots\ldots x_1(n) \\ x_2(1), x_2(2), \ldots. x_2(n) \\ \ldots. \\ \ldots. \\ x_m(1), x_m(2), \ldots. x_m(n) \end{bmatrix} \tag{1}$$

Where: $x_i(k)$ is the value of the number i listed manufacturing process and the number k influence factors. For optimization purposes: three types of influence factors are included:

1. Higher value is considered the better
2. Smaller value is considered better
3. Nominal value the considered better.

It is difficult to compare different kinds of factors because they exert different influences. Therefore, the standardized transformation of these factors must be performed. Three distinct equations are applied to achieve the purpose [3] [38].

$$x_i(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \tag{2}$$

$$x_i(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \tag{3}$$

$$x_i(k) = \frac{\left| x_i(k) - x_0(k) \right|}{\max x_i(k) - x_0(k)} \tag{4}$$

Grey Relational Degree can be computed by steps as follows:

a) The absolute difference of the compared series and the referential series should be obtained by using the following formula [15] [38]:

$$\Delta x_i(k) = \left| x_0(k) - x_i(k) \right| \tag{5}$$

ξ and the maximum and the minimum difference should be found.

b) The distinguishing coefficient p is between 0 and 1. Generally, the distinguishing coefficient p is set to 0.5.

c) Calculation of the relational coefficient and relational degree by (12) as follows.

In Grey relational analysis, Grey relational coefficient ξ can be expressed as follows [15][38]:

$$\xi_i(k) = \frac{\Delta \min + p\Delta \max}{\Delta x_i(k) + p\Delta \max} \tag{6}$$

Relational Degree is given by:

$$r_i = \sum \left[w(k)\xi(k) \right] \tag{7}$$

Where, ξ is the Grey relational coefficient, *w (k)* is the proportion of the number *k* influence factor to the total influence indicators. The sum of *w (k)* is 100%. The result obtained when using Equation 6 can be applied to measure the quality of the listed FDM processes [37-38].

V. Methodology and Experimental Details

This study is performed to find the effect of six influence factors (two levels of each factor) on four performance measures:

1) Hardness
2) Flexural Strength
3) Compressive Strength
4) Ultimate Tensile stress

The experimentation was designed and conducted as per the following outlines:

1) Experimental Design
2) **Specimen Design**
3) Machine
4) **Testing Machines**
5) Testing & Analysis
6) **Results**

Abovementioned components are discussed in details:

1) Experimental Design:

The whole experiment was designed using Minitab Software, to find the effect of six influence factors on performance measures. Influence factors considered in this study are:

1) Density Ratio
2) Layer height
3) Nozzle Speed
4) Fusion temperature
5) Print Temperature
6) Print Orientation

Performance measures are as follows:

1) Hardness
2) Flexural Strength
3) Compressive Strength
4) Ultimate Tensile stress

The experimentation design methodology is based on Taguchi's Method of experiment reduction. Software Minitab is applied to find the number of manufacturing combinations. The schematic of experimental design by software Minitab is given in the Table 3.

2) Specimen Design:

Specimens' design was selected as per American Standards of Testing Materials, ASTM D638-10, and standard test method for tensile properties of plastic material (PLA) and produced by the abovementioned machine. Specimens were tested on the testing machines, specified in next section for finding the hardness, flexural strength, compressive strength and UTS (Figure 2).

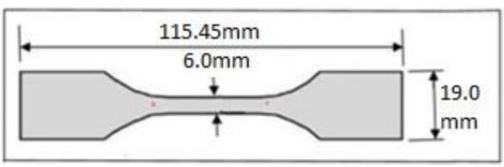

Figure 2

Test Specimen Design

3) **Machine**

Additive Manufacturing Machine Model, ARYA PRO, CADx Technologies Pvt. Ltd., India, is utilized produce specimens, having specifications:

Machine Volume : 490mm X 390mmX360mm Envelope Volume : 200 mm X 200mmX180mm Nozzle diameter : 0.35mm

Nozzle Speed : Upto 150mm/s Filament diameter : 1.50mm Filament Material : ABS, PLA etc

Print Temperature : Upto 260^0C

Layer thickness : 50-300µ additive : Open Source

Connectivity : USB

Software : CURA Version 15.04.6.

4) Testing Machines;

Hardness Testing Machine:

Model : TRSN-D

Make : FMI

Maximum Load : 150 (kgf)

Load Range : 60, 100 & 150 (kgf)

Initial Load Range : 10(kgf)

Maximum Test Height : 216(mm) Depth of throat : 133(mm)
Size of base : 171X445(mmXmm)
Machine Height : 635mm
Net Weight : 77(kg)
Test Performed : Rockwell & Brinell

Figure : 3

Universal testing machine:

The strength tests were performed on Universal Testing Machine of the following details:
Model : AMT,5A-5B
Make : HARRISS & TARRISS

Load Range : 20-1000 (kN) Maximum Load : 1000(kN) Initial Load Range : 20(kN) Accuracy : ±1% (0.01mm)

Clearance : 850mm

Power Supply 3 phase : 415 V, 50 Hz AC Size of base : 750mm x 750mm

Testing speed : 80 mm / min

Test Performed : Tensile, Compressive &

Bend/flex, and shear test ASTM Standards : E83, BS 3846, ISO 9513,

And EN 1002-4

Repeatability : 0.01mm

Figure : 4

5) **Testing & Analysis**

Hardness testing machine was used to test the specimens for hardness and Universal Testing machine was used to test the specimens for other performance measures. The observations thus collected in tabular form and presented in **TABLE 1**. The computations of GRA and ANOVA (For Interrelationship diagrams) were performed on the software MS Excel.

Computation of GRA Degree for Influence Factor

TABLE 2 shows six influence factors (A1-A6) of FDM (1–20) performed to produce test specimens, The influence factors are the positive type factors. Standardized transformation of this specimens can be performed by using equation 6, hence the results presented in **TABLE 3**. To compute next step, Absolute difference between the compared series and the referential series using (6) is found, Hence the maximum and the minimum values are found. The value of distinguishing coefficient p is set to 0.5. The Grey relational coefficient is computed using equation (8).

In the Equation (7), w (k) for every influence factor and for every factor report may be different. If we suppose: w (1) = 0.30, w(2) = 0.20, w(3) = 0.20, w(4) = 0.10, w(5) = 0.008, w(6) = 0.08, w(7) = 0.04, the relational degree can be obtained using (13). The results obtained are presented in **TABLE 4**, according to the relational degrees [38].

Table 1

Data set of the influence factors of FDM

Manufact-uring Combinat- ion Number (M.C.NO)	DR(%) A1	LH (mm) A2	NS (Mm/m) A3	FT(^{0}C) A4	PT(^{0}C) A5	PO(^{0}C) A6
1	40	0.1	100	200	60	45
2	40	0.1	100	200	50	60
3	40	0.1	100	210	60	60
4	40	0.1	100	210	80	45
5	40	0.1	120	200	60	60
6	40	0.2	120	200	80	45
7	40	0.1	120	210	60	60
8	40	0.1	120	210	80	60
9	40	0.2	100	200	60	60
10	40	0.2	100	200	80	45
11	40	0.2	100	210	60	45
12	40	0.2	100	210	80	60
13	40	0.2	120	200	60	45
14	40	0.2	120	200	80	60
15	40	0.2	120	210	60	60
16	40	0.2	120	210	80	45
17	60	0.1	100	200	60	60
18	60	0.1	100	200	80	45
19	60	0.1	100	210	60	45
20	60	0.1	100	210	80	60

Table 2

Original data of performance measures

M.C. NO.	HD (HRC) X1	CS (MPa) X2	FS (MPa) X3	UTS (MPa) X4
1	62	94.09091	31.70	19.37029
2	62	96.02716	32.84	19.39218
3	64	96.20184	33.16	19.38641
4	62	95.06032	32.00	19.38022
5	60	94.80881	31.90	19.38800

Contd...

6	65	96.88042	32.68	21.70388
7	64	96.38044	32.86	20.37029
8	66	98.72600	36.42	22.58986
9	64	96.32325	33.38	20.82066
10	62	96.00233	32.98	20.00842
11	61	95.20032	32.50	19.84662
12	61	95.82232	32.80	20.50102
13	62	94.59008	31.90	19.58480
14	62	95.0080	32.30	20.08040
15	64	95.50002	32.70	20.50822
16	62	95.00282	32.40	20.20183
17	62	94.45599	32.50	19.57884
18	64	94.55004	32.20	19.59227
19	65	94.5009	32.10	19.47029
20	62	94.40044	32.25	19.5585

Table 3

Neutralized values of performance measures

M.C. NO	X1	X2	X3	X4
1	1.00	1.00	1.00	1.00
2	0.30	0	0.09	098
3	0.10	0	0.55	0.80
4	0.40	0.42	0.55	0.98
5	0.90	0.83	0.36	1.00
6	0.30	0.67	0.73	0
7	0.00	0.43	0	0
8	1.00	0	0.18	0.53
9	0.40	0.67	0.55	0.53
10	0.10	0.50	1.00	0.66
11	0.10	1.00	0	0.80
12	1.00	1.00	1.00	1.00
13	0.30	0	0.09	1.00
14	0.10	0	0.55	0.80
15	0.40	0.42	0.55	0.97

Contd...

16	0.90	0.83	0.36	1.0
17	0.30	0.67	0.73	0
18	0.00	0.43	0	0
19	1.00	0	0.18	0.53
20	0.40	0.67	0.55	0.53

Table 4

Grey relational degrees

	X1	**X2**	**X3**	**X4**	**Relational degree**	**Rank**
ξ_1	0.63	1.00	1.00	0.85	1.00	1
ξ_2	0.83	1.00	1.00	0.48	0.96	2
ξ_3	0.56	1.00	0.54	0.48	0.739	5
ξ_4	0.36	1.00	0.38	0.58	0.534	10
ξ_5	0.63	1.00	0.43	0.41	0.733	6
ξ_6	0	0.50	0.54	1.00	0.420	12
ξ_7	0.33	0.50	1.00	0.74	0.659	7
ξ_8	0.56	0.50	0.43	0.48	0.495	11
ξ_9	0.83	0.33	0.50	0.33	0.568	9
ξ_{10}	0.83	0.33	0.33	1.00	0.572	8
ξ_{11}	0.63	1.0	1.00	0.85	0.88	4
ξ_{12}	0.83	1.0	1.00	0.48	0.94	3
ξ_{13}	0.56	1.00	0.54	0.48	0.739	5
ξ_{14}	0.36	1.00	0.38	0.58	0.534	10
ξ_{15}	0.63	1.00	0.43	0.41	0.733	6
ξ_{16}	0	0.50	0.54	1.00	0.420	12
ξ_{17}	0.33	0.50	1.00	0.74	0.659	7
ξ_{18}	0.56	0.50	0.43	0.48	0.495	11
ξ_{19}	0.83	0.33	0.50	0.33	0.568	9
ξ_{20}	0.83	0.33	0.33	1.00	0.572	8

GRA is performed on the data to find the rankings of the manufacturing combination of the influence factors.

VI. Results And Discussions

Interrelationship Diagram:

This diagram is made on the basis of ANOVA performed, to find the effect of influence factors. Table 4, depicts percentage contribution of these influence factors. Figure 7 Shows the relationships.

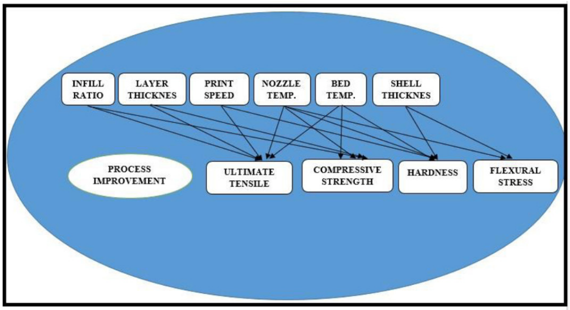

Figure 7

Interrelationship Diagram

The percent contribution of each influence factor is narrated in Table 5.

Table 5

Percentage contribution of influence factors

	Influence Factor	Contribution
A1)	Density Ratio	100%
A2)	Layer Height	85%
A3)	Nozzle Speed	85%
A4)	Fusion Temperature	54%
A5)	Print Temperature	54%
A6)	Print Orientation	52%

Grey Relational Analysis:

GRA ranks determine the best optimum solution of different set of influence factors. Higher the value of GRA Co-efficient will result in higher ranking. After normalization values, the GRA Co- efficient rank is estimated. The rank is presented in Table 4. This rank will depend upon the weighing value for each contributing factor. Hence, suitable factors are selected by increasing weights, based on the FDM process requirements.

The results are discussed in detail:

1) **Hardness:** The targeted value of hardness is 65 HRC, the combination that could achieve hardness is 63.15625 (Mean Value) with a deviation of 3.711%. This manufacturing combination is given in Table 6:

TABLE 6

Manufacturing combination for maximum hardness

	Influence	Factor Values
A1)	Density Ratio	40%
A2)	Layer Height	0.2
A3)	Nozzle Speed	120 mm/sec
A4)	Fusion Temperature	210^0C
A5)	Print Temperature	60^0C
A6)	Print Orientation	40^0

2) **Flexural Strength:** Targeted value of Flexural Strength is 35 MPa and the obtained mean value of F.S. is 33.42531. The mean square error is 6.2139, highest among all the errors. Manufacturing combination for this yield is presented in Table 7.

TABLE 7

Manufacturing combination for flexural strength

	Influence Factor	Values
A1)	Density Ratio	60%
A2)	Layer Height	0.2mm
A3)	Nozzle Speed	120 mm/sec
A4)	Fusion Temperature	210^0C
A5)	Print Temperature	60^0C
A6)	Print Orientation	40^0

3) **Compressive Strength:** The mean value of compressive strength is 36.06 MPa. Targeted Value of compressive strength is 36.00 that means the deviation is about 0.4301%.The target value of compressive

strength 36 MPa can be achieved by manufacturing combination , shown in Table 8:

Table 8

Manufacturing combination for maximum compressive strength

	Influence Factor	Values
A1)	Density Ratio	60%
A2)	Layer Height	0.2
A3)	Nozzle Speed	100 mm/sec
A4)	Fusion Temperature	200^0C
A5)	Print Temperature	80^0C
A6)	Print Orientation	60^0

4) **Ultimate Tensile Strength:** Targeted value of UTS is 20.64 MPa, and the mean value of UTS is 20.39002, hence error of 1.2747% is noted. This error is almost negligible. The UTS can be targeted 22.0 by the following optimal combination of input parameters, given in Table 9:

Table 9

Manufacturing combination for UTS

	Influence Factor	Values
A1)	Density Ratio	60%
A2)	Layer Height	0.2mm
A3)	Nozzle Speed	100 mm/sec
A4)	Fusion Temperature	210^0C
A5)	Print Temperature	80^0C
A6)	Print Orientation	60^0

Favorable conditions are hence found to achieve all the parameters.

VII. Conclusions

Objectives of this research are:

i) To find a manufacturing combination, that yields highest performance measures.

ii) To find the effect of influence factors on performance measures

iii) To find the percentage contribution influence factors on performance measures.

The first objective was achieved by deploying GRA.

The second objective was achieved by applying the ANOVA, there by achieving third objective.

Hence the study is performed successfully by mapping relationship between influence factor and performance measures; hardness, compressive strength, flexural strength and tensile strength (Figure 3, 4, 5, 6, 8).

Figure 3

Hardness Tester

Figure 4

UTM (Tensile Test)

Figure 5

Compression Test

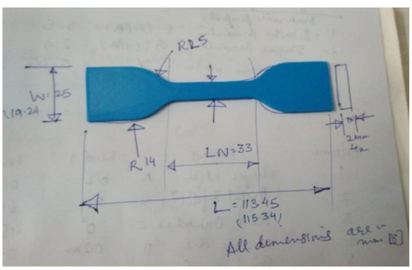

Figure 6

Printed Test Specimen

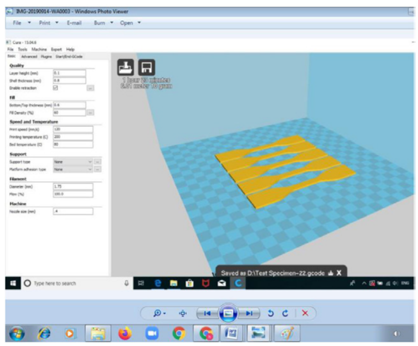

Figure 8

Software Cura 15.06.9

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Received June, 2021

Revised December, 2021