An Experimental Study of Effect of Printing Parameters on the Tensile Strength of PLA with Slate Powder Composite

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Abstract

3D polymer-based printers are widely available. These 3D printers use FDM technology. Most 3D printers use ABS and PLA. This study makes 3D things using polylactic acid (PLA) and slate powder (SP). Mechanical qualities of printed items must be known for specific applications. This study examines the tensile strength of poly lactic acid (PLA) printed materials based on raster angle, nozzle temperature, and printing speed. Results indicate that printing settings affect printed part mechanical characteristics. Response-process parameter empirical models are created. ANOVA tested response-printing parameter models. Printing settings are optimized for mechanical properties.

Keywords: 3D printing; Fused deposition modelling; Design of experiments; PLA; Tensile test.

1. Introduction.

Additive Manufacturing Technologies (AMTs) also called layered manufacturing technologies or, more recently, 3D printing, have been developed quickly. This has cut the time it takes to put a new product on the market by a large amount. With additive manufacturing, a digital model of an object (usually a CAD model) can be turned directly into a physical, three-dimensional shape of almost any complexity. No special tools are needed besides the ones that come with the machine that makes them. Rapid Prototyping, Rapid Manufacturing, and Rapid Tooling are all ways that additive manufacturing can be used. When a physical prototype of a designed part needs to be produced quickly, they are important [1,2]. The Fused Deposition Modelling technology, which can be used to create things out of thermoplastic materials, is one of the AMTs that is most widely employed for industrial reasons. Acrylonitrile butadiene styrene (ABS), the most used build material, guarantees moderately strong strength and tolerable thermal shrinkage. Additionally, it enables additional processing of the obtained pieces (using machining, coating, or glue). Compared to other additive manufacturing technologies, Fused Deposition Modelling machines are compact and simple to maintain. They can be used right in design studios because they are also quiet and clean. FDM models can be reprocessed and produce little trash, making the entire process environmentally friendly. A final object made with Fused Deposition Modelling technology can be identified by a set of coefficients that are impacted by a variety of parameters [4]. Unlike most manufacturing technologies, the values of additive manufacturing process parameters can be more important than the properties of the part material - two different sets of process parameters applied to the same geometry can result in two products with completely different properties, such as strength [4, 5] or accuracy [3]. Each set of process parameters, such as product orientation in the working chamber, layer thickness, and method of filling the layer contour, will cause the part structure to look different, resulting in varied values of coefficients such as strength, accuracy, and surface quality. Many scientists have studied the effect of manufacturing process parameters on the mechanical qualities of objects created with FDM technology [4, 5]. Some researchers concentrated on optimizing a certain parameter in respect to a given evaluation criterion, such as process time [6, 7], shape representation accuracy [8, 9], and mechanical properties. The manufacturing process characteristic that most affects product qualities is product spatial orientation in the working chamber [4, 5, 10, 11]. FDM process parameters and product qualities are not thoroughly understood. They have been experimentally determined [4, 5, 12], but their entire properties are still a research problem. This study summarised a series of experiments on the essential parameter of additive manufacturing with FDM technology, product orientation in the working chamber during layer deposition. FDM parts can be "brittle" or "yield point" and fail via thread fracture or layer disjoint [13]. The two behaviours switch orientations [14]. Discuss the most essential PLA quality analysis and characterization methods. The most important PLA characteristics and simplified PLA production routes were reported [15]. The paper discusses a preliminary study that was done to find a general range of transitions between material behaviors. This range was called a critical orientation. Based on the results of tensile, bending, and impact strength tests, the critical orientation problem was outlined. The results of these tests are shown in this paper.

2. Experimental procedures.

2.1. Fused Deposition Manufacturing (FDM).

Fused Deposition Manufacturing (FDM) 3D printing involves layering and fusing materials [16]. FDM is the most versatile, affordable, and popular 3D printing method. FDM builds complicated 3D geometry. This method extrudes heated thermoplastic filaments from the nozzle tip in a semi-molten state and solidifies at chamber temperature. An extrusion nozzle head receives thermoplastic filament from a reel. The nozzle head controls flow and warms material. Stepper motors adjust the extrusion head and flow. The head and build platform move horizontally and vertically, respectively. A microcontroller-based CAM software tool controls this system (Fig. 1). A heated nozzle layers molten polymer on a supporting frame work.

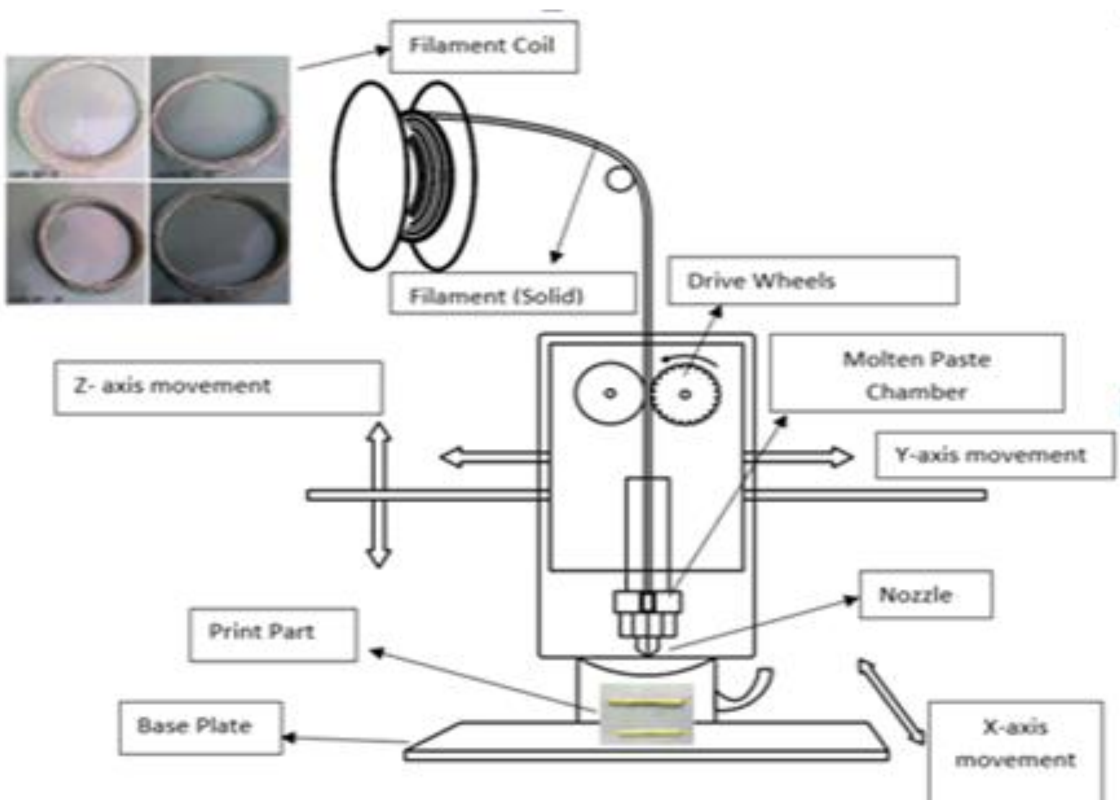


Fig. 1. FDM process

2.2 3D printer machines.

Adroitec Engineering Solutions (P) Ltd., India, provided the 3D printer utilised to create the samples. (See Figure 2). It is based on FDM technology, and after creating a 3D model with computer-aided design (CAD) software, the file must be converted into STL format. The file is then uploaded to the host programme, which turns it into G-code files containing the instructions for creating the final 3D objects. Adroitec Engineering Solutions (P) Ltd., India the PLA filament and squeezes it out through a 0.4 mm nozzle to create a solid object layer by layer. A 0.4 mm nozzle was employed to avoid extruder blockage owing to filler. This technique is known as Fused Filament Fabrication [FFF].

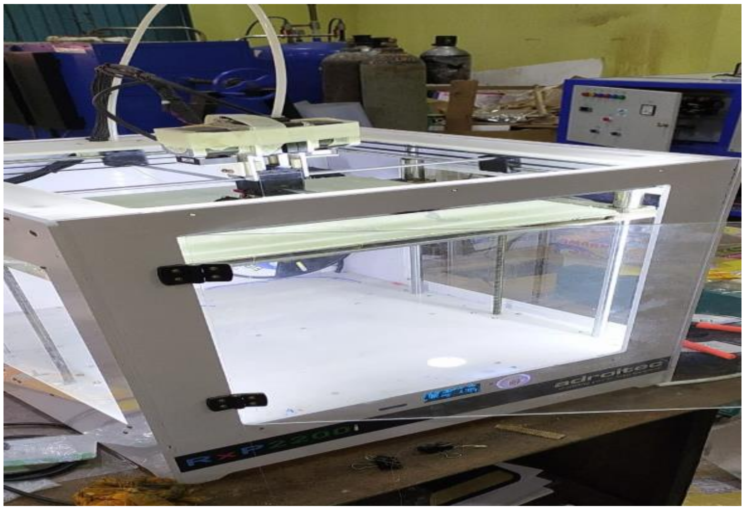
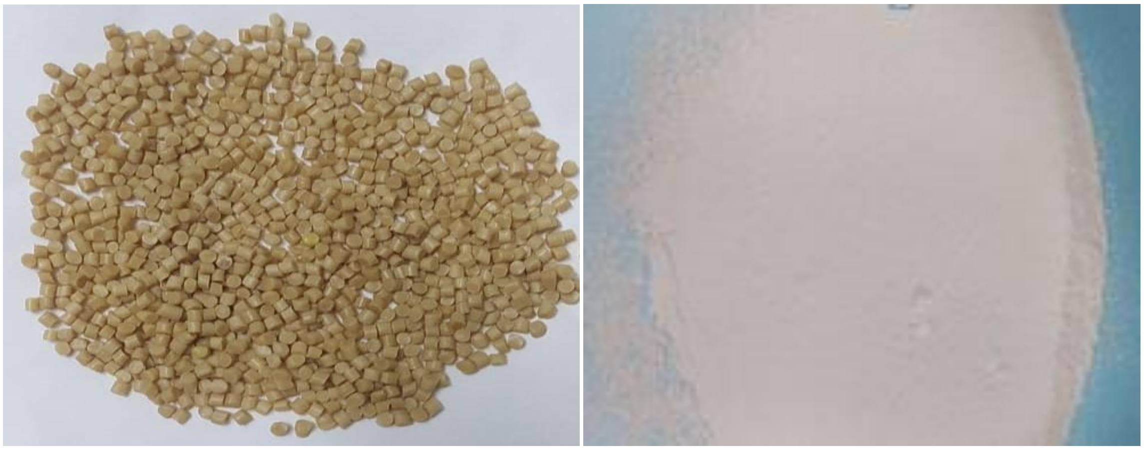


Fig.2. 3D printer (FDM)

2.3. Material.

The PLA was delivered in the form of homopolymer pellets by STALLION Enterprise International Trade Company Rajkot (Gujarat), India. These pellets had a melting point of 120 to 130 °C and a melt flow rate of 7 grammes per minute. The density of the pellets was 1.2 grammes per cubic centimeter. The waste slate powder (density = 2.51 g/cm3) was gathered from a local industry in the hamlet of Multanpura, Madhya Pradesh, India.



(a) (b)

Fig.3. (a) PLA (b) Slate Powder

2.4. Preparations of the Samples.

The ASTM D638 standard was used to make the tensile sample (see Fig. 4). Anyone could print a .STL file of a tensile test sample and send it to the experts for testing. The .STL files were cut up into G-code that a machine could read. After that, each sample was printed by changing settings like the four different SP content 0wt%, 5wt%, 10wt% and 15wt%, four different nozzle temperatures 210°C, 220°C, 230°C, and 240°C , four different raster angle 0°, 30°, 45°, and 90°. And four different printer speed 35mm/s, 4035mm/s, 4535mm/s and 5035mm/s. The other factors, like infill (100%) nozzle diameter (0.4 mm), layer height (0.1 mm), and cooling, don't change. As shown in Fig. 4.

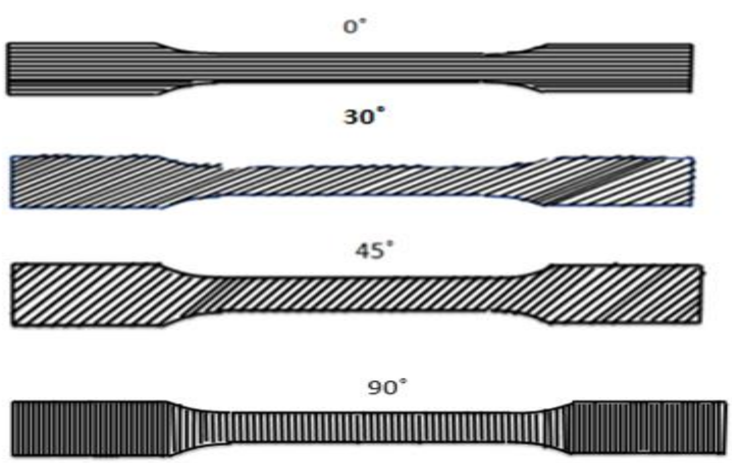


Fig. 4 Deposition Angle of Tensile Test Specimen.

2.5. Tensile Testing.

According to ASTM D638, tensile tests are done on a servo-hydraulic universal testing machine made by HEICO Pvt. Ltd. in Delhi, India, with a movement rate of 2mm/min. Figure 5 shows how the test object is shaped and how big it is. For each combination of print options, the FDM Adroitec machine was used to test four samples. According to the standard EN ISO 527-2:1996, all tests are done at a temperature of 23.2°C. Here, the experiment plan (Table 2) tells us how to set up the factors (Table 1). By making changes to the printing parameters, the tensile strength of 3D-printed parts can be tested. It has been found that the strength of FDM-printed parts is affected by four important printing parameters: the SP content, the nozzle temperature, the raster angle and the printer speed.

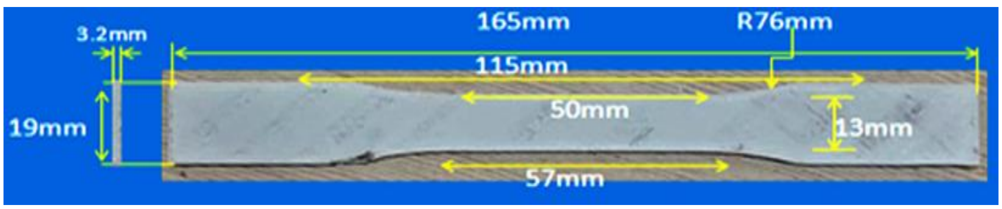


Fig.5. ASTM D638 standard Tensile Test Specimen

3. Selection of process parameters.

Four parameters were used at four levels in this study: SP Content, layer height, nozzle temperature, raster angle and printer speed. Calculating all degrees of freedom (DOFs) is essential for experiment tests and selecting a good orthogonal array. DOF is an important metric since it defines the bare minimum of behavioral requirements.

Table.1. Factor Information.

Factor	Type	Unit	Levels	Values
SP Content	Fixed	%	4	0, 5, 10, 15
Nozzle Temperature	Fixed	°C	4	210, 220, 230, 240
Raster Angle	Fixed	degree	4	0, 30, 45, 90
Printer Speed	Fixed	mm/s	4	35, 40, 45, 50

Table. 2. Experimental plan using L16 orthogonal array.

S.No.	Sp Content (wt%)	Nozzle Temperature(˚C)	Roster Angle(Degree)	Printing Speed mm/s	Tensile strength (MPa)
1	0	210	0	35	30.53
2	0	220	30	40	31.63
3	0	230	45	45	30.85
4	0	240	90	50	29.55
5	5	210	30	45	31.36
6	5	220	0	50	31.15
7	5	230	90	35	30.05
8	5	240	45	40	31.55
9	10	210	45	50	29.05
10	10	220	90	45	29.75
11	10	230	0	40	30.12
12	10	240	30	35	30.10
13	15	210	90	40	27.95
14	15	220	45	35	28.35
15	15	230	30	50	28.05
16	15	240	0	45	29.45

DOF for each parameter equals to the number of levels minus of one [19]. For example, the DOF for a parameter with three levels is two. The right arrays, according to the Taguchi method, are those where the number of tests is at least equal to or greater than the total number of degrees of freedom (DOFs) [20]. This study looked at four parameters at four different levels, so there are a total of fifteen DOFs. The L16 orthogonal array Taguchi method is suggested to cut down on the number of tests. Also, other factors were kept the same, and the way the parameters interacted with each other was not taken into account. Table 1 shows the factors and their values, and Table 2 shows the orthogonal array that was chosen using the Taguchi method. It's very important to note that all of the parameters and their levels were picked to work well with 3-D printing. In terms of outputs, it's clear that mechanical strength is important because it makes printed parts work better. The volume of specimens stays pretty constant, so the density shows how full they are.

4. Results and discussion

4.1 The main effects

The main effect plots are the mean response of each level of parameters connected by a line. A horizontal line presents that there is no effect, while a line with a small deflection from horizontal may importantly affect the response. A stepper slope in a line illustrates the larger magnitude of the main effect. Figure 7 shows the results of this analysis. From figure 7(a), (b), (c) and (d), higher tensile strengths can be obtained by SP content, Raster angle and printer speed respectively. Which provide more adhesion between rasters and between layers respectively. The number of adhesions between layers has a vital role in the final strength of specimens because of local remelting and printing cycle (similar cycle for each layer) repetition. Figure 7(a) indicate that 5wt% slate powder content shows greater tensile strength as compare to other 10wt% & 15 wt%. Figure 7(c) indicates that 0˚ raster angle causes the most strength and 30˚, 45 ˚ results were better than 90˚ because specimens with greater rasters along with their main axis have better tensile strength. In Figure 7(d), the result demonstrates that the highest tensile strength was obtained at 45mm/s printer speed. This is in the middle of used PLA melting temperature range (from 220˚C to 240˚C). This temperature not only provides a suitable viscosity for the best deposition but also leads to the greatest intermolecular fusion between layers.

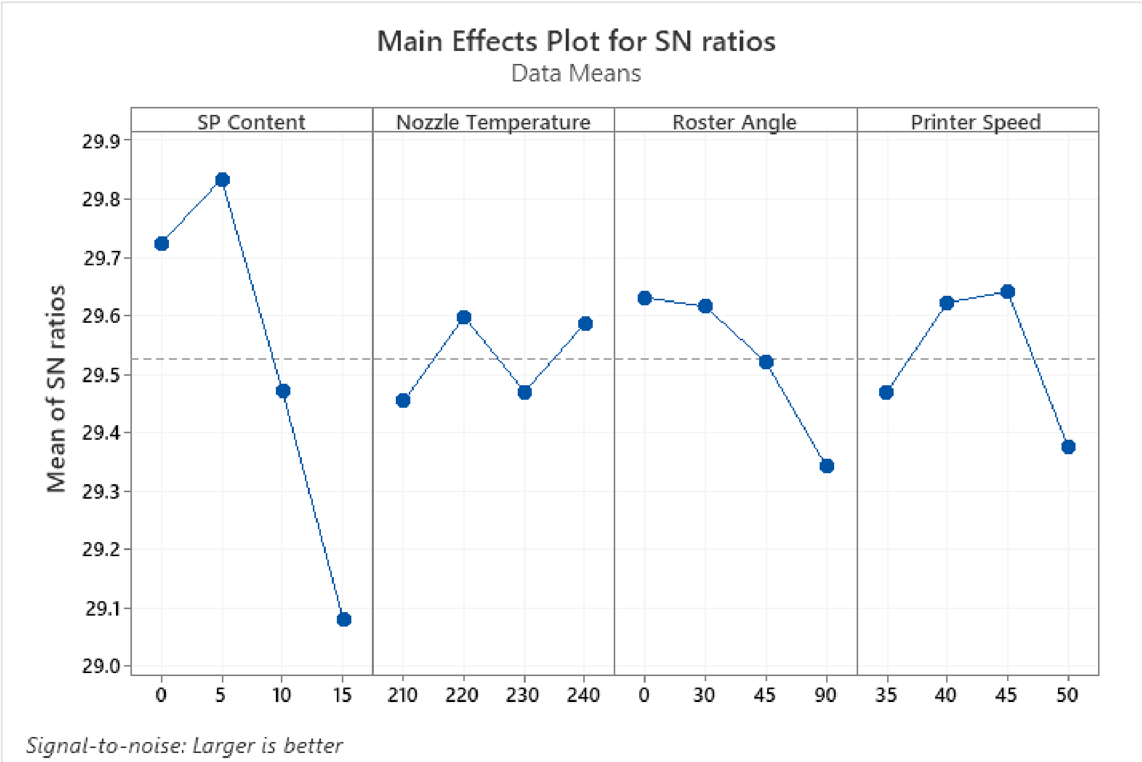


Figure 7. Analysis of main effect for production time: (a) SP content (b) Nozzle Temperature (c) Raster Angle and (d) Printer Speed.

Table.3. Response Table for Signal to Noise Ratios (larger is better)

Level	**SP Content**	**Nozzle Temperature**	**Roster Angle**	**Printer Speed**
1	29.72	29.45	29.63	29.47
2	29.83	29.60	29.61	29.62
3	29.47	29.47	29.52	29.64
4	29.08	29.59	29.34	29.38
Delta	0.75	0.14	0.29	0.27
Rank	1	4	2	3

4.2 Analysis of signal-to-noise ratio

The signal-to-noise ratio (SNR) measures the sensitivity of the quality examined to those uncontrollable factors in the experimental tests. The greater value of SNR is preferable because higher SNR will result in smaller product variance around the target value. The quality characteristic used in this research is "the larger is better" for tensile strength [17].

$$MSD_{(larger\ is\ better)} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \tag{1}$$

$$\frac{S}{N} = -10\log_{10}(MSD) \tag{2}$$

In these relations, MSD represents the mean square deviation, $\mathbf{y_i}$ the output value, n is the number of experiments, and S/N presents the SNR. The S/N ratio acquired for each output is presented in Table 3. It can be realized from table 3 that for tensile strength output, the combination of the parameters and their levels has systematically caused the maximum.

4.3 Analysis of variance

This analysis is a way to determine the contribution of each variable on the outputs value; the relations are as follow [18]

$$SS_{T=\sum_{i=1}^{n} y_i^2 - CF} \tag{3}$$

$$CF = \frac{T^2}{n} \tag{4}$$

Where SS_T is the sum of squares deviation, CF is the correction factor, and T denotes the sum of the output values. To show the effect of each variable on the output value, F index is used as below [19]

$$F = \frac{MS_{\propto}}{MS_e} \quad (5)$$

In this equation, MSα is the mean of squares for each variable and MSe is the mean of squares of error. Table 4 shows the performed ANOVA for the experiments. For tensile strength, SP content makes up the largest proportion at 73.88% on the contrary, nozzle temperature is at the lowest spot with 3.80 %. Noticeably, raster angle and printer speed have a near about percentage (11.67% and 10.65%, respectively).

Table 4. ANOVA for tensile strength.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Contribution (%)**
SP Content	3	1.34241	0.447471	172.58	0.001	73.88
Nozzle Temperature	3	0.06917	0.023055	8.89	0.053	3.80
Raster Angle	3	0.21191	0.070635	27.24	0.011	11.67
Printer Speed	3	0.19341	0.064468	24.86	0.013	10.65
Error	3	0.00778	0.002593	-	-	-
Total	15	1.82467	-	-	-	100

4.4 Slate Powder content effect on FDM process.

The tensile strength of the specimen is raised by incorporating 5 wt.% slate powder content. Firstly, the heat transfer coefficient of a polymer increases with SP content particles, so composite specimens have better cooling, which reduces the possibility of distortion and warpage during the FDM process. Also, metal particles as solid materials can decrease the possibility of shrinkage too. Secondly, the viscosity of composite filaments is reduced by metal particles; therefore, nozzle temperature should be higher in comparison with using pure polymers. Finally, the probability of nozzle clogging is further with composite materials; consequently, larger nozzle diameters are recommended.

5. Conclusion

In the present research, the waste slate powder is utilized as filler with different weight percentages in PLA-based composite by FDM 3-D printer was investigated in order to maximize the tensile strength of the sample. Based on the results and tests, the following optimum conditions were acquired:

- Tensile properties of the 0° raster angle specimens were stronger than the 30˚, 45° & 90˚ raster angle specimens. For tensile strength: SP content 5 wt%, printer speed 45 mm/s.

Finally, the experiments and results were confirmed by the comparison between prediction values and estimation values for each output.

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