International Journal on Recent Technologies in Mechanical and Electrical Engineering (IJRMEE) ISSN: 2349-7947
Volume: 2 Issue: 8 41 - 47

Investigation on the effect of Fused Deposition Modeling Process Parameters on Flexural and Surface Roughness properties of PC-ABS blend

S. Manikandan
A.S. Seshan Kumar, C. Sharma
Department of Mechanical Engineering
PSG College of Technology
Coimbatore, India
s.mani0807@gmail.com, seshankumar@ymail.com ,sharma.ms92@gmail.com

V. Prabhu Raja
Associate Professor
Department of Mechanical Engineering
PSG College of Technology
Coimbatore, India
vpr@mec.psgtech.ac.in

A. Adhiyamaan
Assistant Professor
Department of Mechanical Engineering
PSG College of Technology
Coimbatore, India
adhi0087@yahoo.co.in

Abstract: Rapid Prototyping (RP) is an unconventional process of making physical models by combining several technologies altogether. RP parts are used in many organizations as concept models, functional or semi-functional components, master patterns and direct tooling. Fused Deposition Modeling (FDM) is one of the RP technologies. The mechanical properties of parts produced by FDM are affected by various process parameters. This project concentrates on the effect of process parameters of FDM 900mc machine on mechanical properties such as flexural strength and surface roughness for Polycarbonate-Acrylonitrile Butadiene Styrene **(**PC-ABS**)** blend material. The parameters considered are Contour style, Raster angle, Raster width, and Air gap. Testing is done for the mechanical properties such as flexural strength and surface roughness using the preferred standards. The results obtained were optimized using Taguchi method in order to have better mechanical properties. The results show that raster angle has greater effect on flexural strength. Raster angle of 45°/45° yields higher flexural strength when compared with other parameters considered. Similarly, for surface roughness, contour style is the most significant parameter, where the triple contour style gives better surface finish.

Keywords- *Rapid Prototyping, Fused Deposition Modelling, PC-ABS, Flexural Strength, surface roughness, Taguchi method.*

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I. INTRODUCTION

Rapid prototyping (RP) technique is a time compression engineering process which promisingly minimizes the development time of a product. RP technology produces parts by addition of raw material, unlike other traditional manufacturing process. Way of adding raw material determines the type of RP process [1]. Among various methods, Fused Deposition Modeling (FDM) is one of the prominent methods of RP. FORTUS 900mc FDM machine is developed by Stratasys Inc. as a means of producing solid component from 3D CAD model. Many research works are going on to improve the mechanical properties of FDM made components. The Dynamic mechanical properties like modulus and viscosity of components made of polycarbonate (PC) material were analyzed using frequency sweep experiment under different isothermal temperatures (Adhiyamaan Arivazhagan) [2] Several researches were also done on ABS material to investigate its mechanical properties by optimizing some of the process parameters like conducting experiments on five different build style orientations to achieve good impact resistance (Es. Said et al) [3].

B. H. Lee et al used Taguchi method to obtain the design of experiments for the process parameters like layer thickness, raster angle and air gap and attained the optimum elastic performance of ABS samples made using FDM [4]. RP process has a wide variety of applications and it will play a major role in biomedical field of engineering in the future. ABS M30i is a biomedical material in which S.Dinesh Kumar et al have done a research to investigate its surface roughness by fabricating samples in FDM and optimizing the process parameters by using Taguchi method [5].

PC and ABS blend provides an assemblage of high processability of ABS and splendid mechanical properties of PC like impact and heat resistance [6]. FORTUS 900mc consists of several parameters such as Layer thickness, Build orientation, Contour width, Contour style, Raster angle, Raster width, Air gap, Color and Build temperature. This work emphasizes on the effect of contour style, air gap, raster angle, and raster width on flexural strength and surface roughness (Ra) for the PC-ABS sample fabricated in FDM using Taguchi method.

II. FUSED DEPOSITION MODELLING

FDM is a process where a material is melted to a near liquid state and then deposited as a hot filament which fuses to previously deposited material, building up a physical model, layer by layer as shown in the Fig. 1. The part geometry is fed using a 3-D CAD model which is then converted into a machine understandable format called STL (Stereolithography) file format [7].

Since the component is prepared in FDM by addition of layers the component model is sliced into layers and the layers are defined by Insight software. Slicing is a process in which a mathematical description of a 3-D object is intersected with a series of parallel planes to generate the cross sectional data needed to form layers. After slicing the part is built by Fortus 900mc. The layers are deposited according to the parameter settings that have already been fed and those parameter levels must be within the range of the Stratasys Fortus 900mc FDM machine. Some of the main components of FDM machine are as follows:

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A. FDM Head

Liquefies the thermoplastic modeling material and extrudes it into precise layers that fuse to form the complete material Fig.1 [7].

B. FDM Liquefier

It helps in melting the thermoplastic modeling material to an exact temperature to form the model. It is a part of FDM head [7].

C. FDM Tip

It is the interchangeable nozzle at the end of FDM liquefier. The inside and outside diameters of tips determine the minimum and maximum line widths. Both model and support tips are available. Support materials are needed for complicated shapes to be built by Fortus 900mc FDM machine [7].

D. Canister Bays

Canister Bay consists of model material bays and support material bays along with material drive block for supplying raw filament material into the FDM head as shown in Fig.1 [7].

E. Material Drive Block

Each canister bay has a drive lever to engage and disengage the drive block from canister. Drive block feeds filament from canister to liquefiers. It contains sensors to communicate to system whether material is available to be loaded to liquefier [7].

F. Purge Bucket

Collects model and support filament wastes and debris [7].

G. Gantry Assembly

Gantry assembly is responsible for the head movement in X and Y axes. The head is mounted in Gantry such that only its bottom is protruding into the oven. Gantry and Drive motors are thermally shielded from the oven. Oven is the cabin where part is extruded [7].

H. Platen

Vacuum platen is surface on which parts are built. A plastic build sheet is held on to aluminum platen by vacuum source. Platen has a waffle pattern system in top surface. This allows vacuum to pull across the entire surface of plastic build sheet. Debris screens are placed across the vacuum ports to prevent material particles from entering vacuum lines. [7].

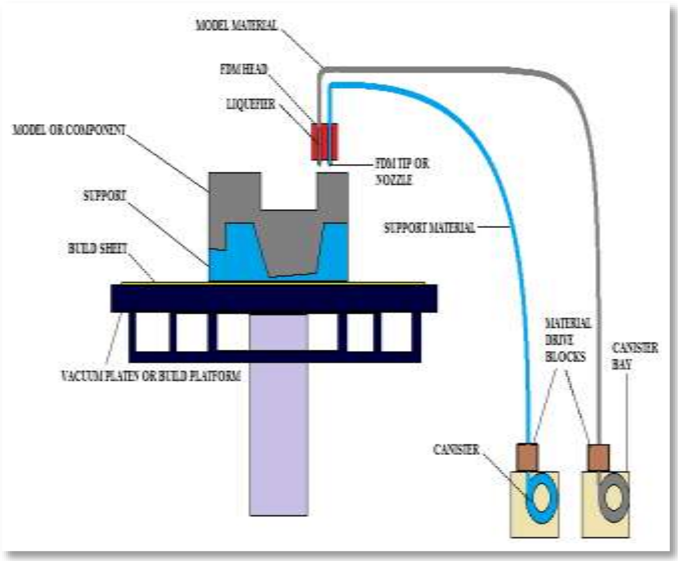

Figure 1. FDM – Working Principle

I. FDM Process parameters

The quality of FDM produced part is highly dependent on various process parameters used in this process. Raster width is the width of the bead deposited on a layer. It is the thickness of the bead (or Road) that the FDM nozzle deposits. It can vary from 0.4064 mm to 0.8314 mm for the Fortus 900mc machine. Raster angle is the angle of the beads deposited with respect to the X axis of the build table. The raster angles which are taken are 45°/45°, 0°/90°, and 30°/60°. 0°/90° is nothing but one layer will be deposited in 0^0 and the other layer in 90^0 like a cross hatch pattern. Air gap is the space between the beads of FDM material. The default is zero, meaning the beads just touch. Air gap values for Fortus 900mc machine ranges from 0.00mm to 0.04mm [7].

Contour is the outermost layer which provides the required shape of the part. Layers of material have to be filled inside the contour. Different types of contour styles are single contour, double contour, triple contour, four contour, five contour and ten contour.

TABLE 1 PROCESS PARAMETER AND LEVELS

LEVELS	PROCESS PARAMETER			
	CONTOUR STYLE	***RASTER WIDTH(mm)***	***RASTER ANGLE***	***AIR GAP(mm)***
1	Single	0.4064	0°/90°	0.04
2	Double	0.6064	45°/45°	0.02
3	Triple	0.8314	30°/60°	0.00

III. DESIGN OF EXPERIMENTS

In this study, design of experiments is conducted with the help of Taguchi method. It uses a special set of arrays called orthogonal arrays that stipulate the way of conducting the minimal number of experiments which could give full information of all the factors that affect the performance parameter.

A. Taguchi method

There are many standard orthogonal arrays available, and these arrays are meant for a specific number of independent design variables and levels. The present work employs L9 orthogonal array where four parameters with three levels are considered as shown in Table 2.

TABLE 2 L9 ORTHOGONAL ARRAY FOR FDM PROCESS PARAMETERS

SAMPLE NUMBER	PROCESS PARAMETER			
	CONTOUR STYLE	*RASTER ANGLE*	*RASTER WIDTH (mm)*	*AIR GAP(mm)*
1	Single	0°/90°	0.4064	0.04
2	Single	45°/45°	0.6064	0.02
3	Single	30°/60°	0.8314	0.00
4	Double	0°/90°	0.6064	0.00
5	Double	45°/45°	0.8314	0.04
6	Double	30°/60°	0.4064	0.02
7	Triple	0°/90°	0.8314	0.02
8	Triple	45°/45°	0.4064	0.00
9	Triple	30°/60°	0.6064	0.04

Nine different combinations of process parameters are framed and for each combination, three samples are considered to have a better accuracy. A total of 27 samples were fabricated in FDM machine and subjected to both surface roughness and flexural testing.

B. Flexural Testing

Flexural test was done based on ASTM standard: ASTM D 790-03 ["Standard Test Methods for Flexural Properties of Unreinforced Plastics and Electrical Insulating materials"]. The recommended specimen dimension is 127 x 12.7 x 3.2mm tested flatwise on a support span, as shown in Fig. 2. The testing was done using Zwick Roell universal testing machine as shown in Fig. 3.

Rate of crosshead motion is calculated by the following equation:

$$R = ZL^2/6d \qquad (1)$$

where R = rate of crosshead motion (mm/min), L = support span (mm), d = depth of beam (mm), and Z = rate of straining of the outer fiber (mm/mm/min). Z shall be equal to 0.01. The rate of crosshead motion is given as 1.36mm/min [8].

The loading nose and supports were aligned in such a way that axes of the cylindrical surfaces are parallel and the loading nose is midway between the supports. The specimen is supported in the center with the long axis of the specimen perpendicular to the loading nose and supports as shown in Fig. 3.

The specimen is loaded by loading nose and is deflected until rupture occurs in the outer surface of the test specimen or until a maximum strain of 5.0% is reached, whichever occurs first.

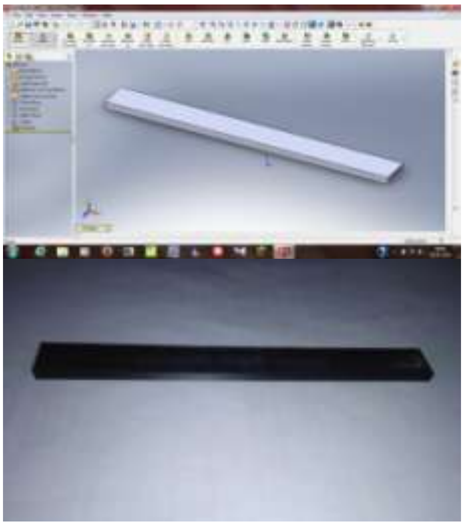

Figure 2. CAD model and fabricated specimen

Figure 3. Flexural Testing

C. Surface roughness Testing

Surface roughness is a measure of the texture of a manufactured component. It is measured by surface roughness Tester TR110. Before testing, it is necessary to select the cut-off length, which can be chosen as 8mm. The instrument is then positioned and the measurement is started. A double tone sounds after a few seconds and the measured value of average

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surface roughness (Ra) is displayed. The instrument consists of a stylus which traces the profile. An integrated sleeve can be slid over the sensor tip in order to protect it when not in use [9].

IV. RESULTS AND DISCUSSIONS

All 27 samples are tested for its flexural strength as well as surface roughness. The results are tabulated and necessary graphs are developed, which are discussed in the following section.

A. Flexural strength

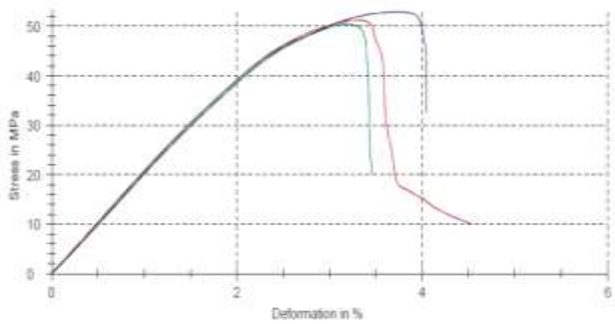
Flexural testing is done for all the samples and the experimental results are given in Table 3.

TABLE 3 FLEXURAL TEST RESULTS OF PC-ABS BLEND SAMPLES

SAMPLE NUMBER	**Number of trials**		
	Trial 1	***Trial 2***	***Trial 3***
1	51.2	50.4	52.8
2	66.2	63.6	63.8
3	62.8	62.1	62.6
4	53.2	51.8	51.7
5	56.1	56.1	55.6
6	54.7	52.8	52.7
7	47.4	46.4	46.9
8	57.1	56.4	55.3
9	49.7	49.7	48.5

All units are in MPa

When the experimental results are plotted as stress – deformation curve for the PC-ABS samples fabricated using FORTUS 900mc, it is observed that FDM process is a very stable process and has high reliability since the strengths of all the specimens of a sample number are tracing similar curves. Two sample graphs are shown in Fig. 4.



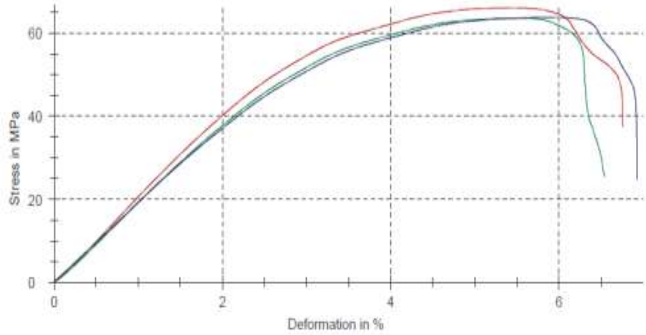


Figure 4. Stress-deformation curve of Flexural Test

The variation of flexural strength across the experiments is shown in Fig. 5. Though the component is manufactured by a single manufacturing process, fluctuations in flexural strength across the experiments could be observed for various process parameters. This clearly shows that the process parameters of FDM affect the flexural strength to a greater extent.

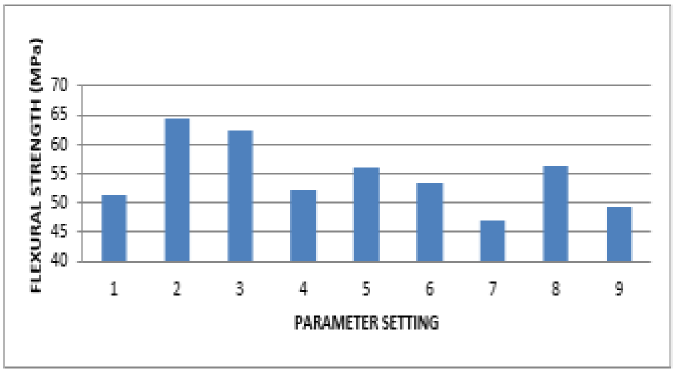


Figure 5. Flexural strength of PC-ABS blend samples for various combinations of FDM parameters.

Taguchi method is employed for analyzing the results of flexural test, by using MINITAB software. The signal to noise ratio provides a measure of the impact of noise factors on performance. The larger the S/N, the more robust the product is against noise. The estimation of S/N ratio is based on experimental objective. It could be Nominal-the-Best, Smaller-the-better and Larger-the-better. In order to obtain higher flexural strength, the condition chosen was Larger-the-better. The S/N ratio can be calculated by using the formula:

S/N ratio = -10*Log10*MSD
MSD = $\sum (1/ y^2)/n$, where y is the property value of the sample.

The mean and S/N ratio values are tabulated and are shown in Table 4.

TABLE 4 S/N RATIO FOR FLEXURAL STRENGTH OF PC-ABS BLEND SAMPLES

SAMPLE NUMBER	MEAN (MPa)	SIGNAL TO NOISE RATIO(S/N)
1	51.5	34.2
2	64.5	36.1
3	62.5	35.9
4	52.2	34.4
5	55.9	34.9
6	53.4	34.5
7	46.9	33.4
8	56.3	35.0
9	49.3	33.9

The mean of S/N ratios were plotted against process parameters as shown in Fig. 6.

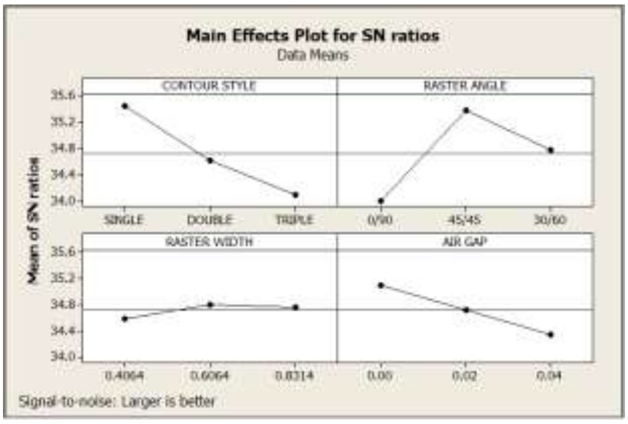


Figure 6. Plot for mean of S/N ratios for Flexural strength

Fig. 6 shows that how each FDM process parameter affects the flexural strength of PC/ABS blend samples. Single contour has the highest flexural strength compared to other contour styles. This can be explained as follows: There are three types of air gaps available in FDM process. They are contour-to-contour, contour-to-raster, and raster-to-raster air gap. A part made of single contour style will have raster-to-raster air gap, contour-to-raster air gap but no contour-to-contour air gap, because of the presence of only one contour. But for other contour styles like double and triple contour, contour to contour air gap will also come into account in addition to other types of air gaps. Moreover, amount of material deposited in the inside region will be less when compared to single contour style.

Fig. 6 also depicts the variations of flexural strength with respect to raster angle. Raster angle 45°/45° has higher flexural strength than 0°/90° and 30°/60°. Since the layers are built in a cross hatch pattern, the angle 45°/45° has equal orientations when compared to other angles. This could be the reason for the angle 45^0 / 45^0 having higher flexural strength.

The variations of flexural strength with respect to raster width are shown in Fig. 6. The higher raster widths like 0.6064 mm and 0.8314 mm have higher flexural strength when compared to raster width 0.4064 mm. This could be because of variation in the amount of material deposited for the respective raster widths. There is not much variation in the flexural strength for the raster width 0.6064 mm and 0.8314 mm.

Fig. 6 implies that air gap of 0.00mm has higher flexural strength because there is no space between beads which are laid. This means all the beads are just touching each other. Air gap 0.02 mm and 0.04 mm have loosely packed structure.

Larger the S/N ratio gives optimum result in Taguchi method. Therefore from the Mean of S/N ratios plot, the larger S/N ratio for the best values of parameters can be obtained. The best parameter setting is given below.

- Contour style = Single
- Raster angle = 45°/45°
- Raster width = 0.6064 mm
- Air gap = 0.00 mm

The parameter setting for obtaining higher flexural strength from S/N ratio is found. The order of significance of each parameter over flexural strength can be found from Response table as shown in Fig. 7

Response Table for Signal to Noise Ratios
Larger is better

Level	CONTOUR STYLE	RASTER ANGLE	RASTER WIDTH	AIR GAP
1	35.44	34.00	34.59	35.09
2	34.62	35.38	34.80	34.72
3	34.09	34.77	34.76	34.34
Delta	1.35	1.38	0.21	0.75
Rank	2	1	4	3

Response Table for Means

Level	CONTOUR STYLE	RASTER ANGLE	RASTER WIDTH	AIR GAP
1	59.50	50.20	53.71	57.00
2	53.86	58.91	55.36	54.94
3	50.82	55.07	55.11	52.23
Delta	8.68	8.71	1.64	4.77
Rank	2	1	4	3

Figure 7. Response Table for Flexural test

The effect of process parameter on flexural strength is determined by its range (delta). Range is ranked from highest value to lowest value; in which rank 1 parameter has largest effect on flexural strength i.e. raster angle has high significance over the flexural strength followed by contour style and then air gap and finally raster width.

B. *Surface Roughness*

Surface roughness values for each specimen measured using surface roughness tester are given in Table 5.

TABLE 5 SURFACE ROUGHNESS TEST RESULTS FOR PC/ABS BLEND SAMPLES

SAMPLE NUMBER	Number of trials		
	Trial 1	*Trial 2*	*Trial 3*
1	16.90	17.12	17.50
2	13.12	14.60	13.02
3	15.82	17.16	14.78
4	14.12	13.99	14.78
5	13.55	13.68	13.15
6	13.29	12.22	13.90
7	10.05	14.92	9.90
8	13.68	15.46	14.54
9	12.12	12.18	14.64

All units are in µm

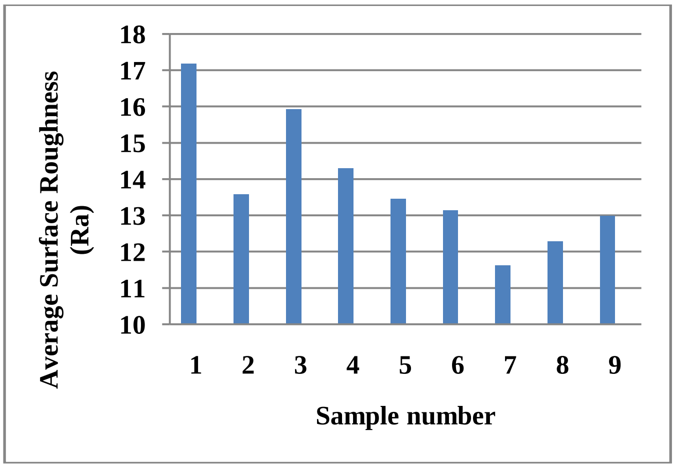


Figure 8. Surface roughnesses for PC-ABS blend samples.

The surface roughness in terms of Ra values for all the nine combinations of parameters are plotted as shown in Fig. 8. It is observed that there are significant variations in the surface roughness values of PC-ABS blend samples for different combinations of FDM process parameter.

S/N ratio for surface roughness values are calculated in MINITAB software using the condition 'smaller the better'. The formula for S/N ratio is,

S/N ratio = -10*Log10*MSD

MSD = $\sum (y^2)/n$, where y is the property value of the sample.

The results of 'mean' and S/N ratios are tabulated and are shown in Table 6.

TABLE 6 S/N RATIO FOR SURFACE ROUGHNESS OF PC/-ABS BLEND SAMPLES.

SAMPLE NUMBER	Mean(µm)	Signal to noise ratio(s/n)
1	17.1733	-24.6980
2	13.5800	-22.6703
3	15.9200	-24.0551
4	14.2967	-23.1072
5	13.4600	-22.5821
6	13.1367	-22.3818
7	11.6233	-21.4780
8	12.2767	-21.8110
9	12.9800	-22.3009

The graph is obtained for the mean of S/N ratio and the process parameters of FDM as shown in Fig. 9

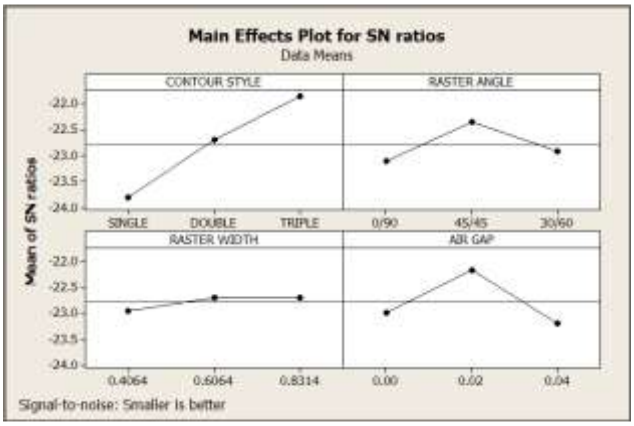


Figure 9. Plot for Mean of S/N Ratios for Ra values

Fig.9 depicts how each process parameter affects the surface roughness property of PC-ABS blend samples. As number of contours increases, Ra value decreases. Triple contour style has less Ra value, thereby yielding good surface finish. Similarly the variations between Ra and raster angle shows that 45°/45° raster angle generates a fine surface finish than 0°/90° and 30°/60° .

From Fig. 9, it can be seen that the raster widths 0.6064mm and 0.8314mm have almost equal levels of surface roughness. Also, the graph shows the influence of air gap on surface finish. Air gap of 0.02mm has least surface roughness value and other air gap values have higher Ra value yielding a poor surface finish when compared to 0.02mm. The stylus undergoes smooth transformation from one bead to other without the effect of valleys just like slipping over the peaks.

The best parameter setting for yielding good surface finish is given below:

- Contour style = Triple
- Raster angle = 45°/45°
- Raster width = 0.6064mm
- Air gap = 0.02 mm

The significance of each parameter over surface roughness in terms of Ra value can be found from the response table as shown in Fig. 10.

Response Table for Signal to Noise Ratios
Smaller is better

Level	CONTOUR STYLE	RASTER ANGLE	RASTER WIDTH	AIR GAP
1	-23.81	-23.09	-22.96	-22.99
2	-22.69	-22.35	-22.69	-22.18
3	-21.86	-22.91	-22.71	-23.19
Delta	1.94	0.74	0.27	1.02
Rank	1	3	4	2

Response Table for Means

Level	CONTOUR STYLE	RASTER ANGLE	RASTER WIDTH	AIR GAP
1	15.56	14.36	14.20	14.16
2	13.63	13.11	13.62	12.78
3	12.29	14.01	13.67	14.54
Delta	3.26	1.26	0.58	1.76
Rank	1	3	4	2

Figure 10. Response table for surface roughness

The order of significance of parameters over surface roughness shows that the contour style has high significance over surface roughness followed by the other parameters.

CONCLUSION

The best combination of FDM process parameters, in order to have good flexural and surface roughness properties are identified for the material PC-ABS Blend. In the direction of having better flexural strength, single contour style, raster angle of 45°/45°, raster width of 0.6064 mm, and air gap of 0.00 mm are the best combinations. Raster angle is the parameter which has the most significant effect on flexural strength of PC-ABS component made by FDM process, when compared with the other parameters taken into account. The best parameter settings to obtain minimum surface roughness is given by triple contour style, raster angle of 45°/45°, raster width of 0.6064 mm, and air gap of 0.02 mm. Contour style is the parameter which has the most significant effect on surface roughness of PC-ABS component made by FDM process, when compared with the other parameters.

The above parameter settings can be used for the fabrication of PC-ABS samples in FDM machine for various applications which focuses on flexural and surface roughness properties of the prototype. The material usage by the FDM machine can be optimized with the help of these parameter settings.

ACKNOWLEDGMENT

The research work was done at PSG College of technology, Coimbatore, Tamil Nadu, India. The samples were fabricated in Stratasys FORTUS 900mc FDM machine available in the TIFAC core at PSG College of Technology. The testing for the flexural strength was done at PSG iTECH Centre of Excellence INDU TECH, Coimbatore, Tamilnadu, India and the surface roughness testing was done in Metrology laboratory of the Department of Mechanical engineering at PSG College of Technology.

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