A robust process optimisation for fused deposition modelling

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Abstract: Rapid Prototyping (RP) technology is being widely used in diverse areas including mould manufacturing. However, the quality of RP parts is significantly affected by the process parameters of the RP machine. This work presents an experimental design technique for determining the optimal quality of a part build by the Fused Deposition Modelling (FDM) process with ABS plastic material. The design investigates (L_9 Taguchi array) the effect of the parameters, contour width, raster width, raster angle and air gap on the dimensional accuracy, form features and surface finish. The experimental results are analysed by using the Analysis of Variance (ANOVA) method.

Keywords: Rapid Prototyping; RP; FDM; ABS plastic; Taguchi; ANOVA.

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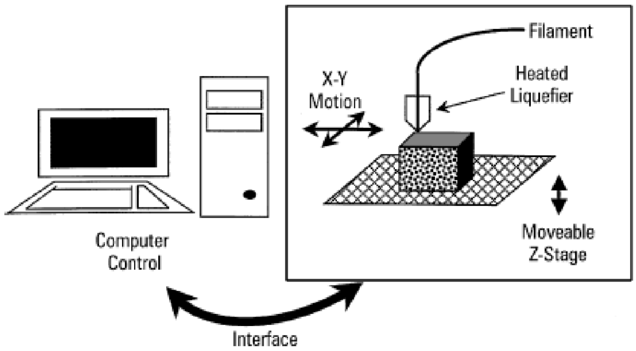
1 Introduction

In order to improve production, industry has tried to apply more computerised automation technology in manufacturing. Recently, the newest manufacturing technology is RP, also referred to as solid freeform fabrication, desktop manufacturing or layered-manufacturing.

The field of RP is a relatively recent result of the Computer-Integrated Manufacturing (CIM) revolution (Burns, 1993). These RP technologies all depend upon an electronic database produced by CAD solid modelling, CT scanning or laser digitising, and other methods, to define a tool path for a net shape (RP parts) manufacturing process. RP processes are additive in nature, in that a three-dimensional (3D) CAD geometry is fabricated by successively layering or adding two-dimensional (2D) slices of the solid. This approach is fundamentally different from the subtractive systems, such as grinding, milling, and drilling, which depend on material removal or subtraction. RP technology plays a role, as a bridge from a general design idea of new products to the products comes true (Chua et al., 2004).

Figure 1 shows a schematic representation of the FDM process. Spooled filaments of 1.75 mm nominal diameter are fed into a heated liquefier, via a set of computer-driven counter-rotating rollers. The liquefier motion is computer controlled in the *X-Y* plane and extrudes material through a nozzle, with deposition onto a fixtureless platform. The fixtureless platform moves in the *Z* direction. The cold filament at the top of the liquefier acts as a piston, creating a positive pressure to extrude the molten material out of the liquefier through the nozzle. The liquid flow, i.e., the filament feed rate into the nozzle, is controlled by the computer. Components are built layer by layer on the platform, and the bonding between neighbouring roads or beads of material takes place due the adhesiveness of the molten material, combined with the re-melting of previously deposited layers.

Figure 1 A schematic of an FDM machine



Materials available for use with the FDM include investment casting wax, ABS plastic and a thermoplastic polyester-elastomer. The P400 ABS material was used in this study. The following additional materials are being considered by Stratasys and others for use with these machines: ABS plastic with varying amounts of chopped glass fibre or glass spheres (Stratasys® Incorporated, 1999), polypropylene with crystalline polymer fibre reinforcement (Gray et al., 1998), elastomers (Elkins et al., 1997) and polymer-bound ceramic and metal powders (McNulty et al., 1998; Pekin et al., 1998).

From theories and experiments, it is known that material properties are directly related with fabrication parameters in the FDM process. It is also known that both material properties and fabrication parameters have a great influence on the mechanical properties and surface qualities for FDM parts (Stratasys® Incorporated, 1999). Often a trial-and-error method is adopted to obtain suitable fabrication parameters to satisfy the demands of specific applications. Default fabrication parameters, recommended by Stratasys for a specific material, do not satisfy the demands of all applications. Using FDM for functional prototyping, it is often important to have good quality in appearance as well as good mechanical properties.

Quality in appearance is mainly defined by dimensional accuracy and surface roughness, while mechanical properties are defined by tensile strength, surface hardness and density. The quality of a prototype is manifested by several parameters. For many engineering applications, dimensional accuracy is an important criterion. In this paper, an attempt is made to obtain optimum process parameters using Taguchi techniques.

2 Literature review

Several attempts have been made in the past to make a systematic analysis of the errors and the quality of the prototypes. Gautham and Henderson (1998) conducted experiments on FDM machine to obtain surface roughness values as a function of orientation and layer thickness and developed decision support software, which allows dynamic colour-coded visualisation of surface quality with respect the two build parameters. Armillotta et al. (1999) conducted an experimental study on the relation between surface finish and layer thickness, orientation, road width and raster angle in the FDM process.

Zhou et al. (1999) conducted experiments on a steriolithography (SLA) RP machine. They have developed a standard sample with 20 different dimensional, geometrical and surface features and suggested the significant factors affecting the quality and accuracy. Diane et al. (1997) conducted an experiment on an SLA machine, whose results conclude that layer thickness and part orientation are important, and they also state that thicker layers would provide a better surface finish with a vertical orientation. Reddy et al. (2006) conducted experiments on Selective Laser Sintering (SLS) RP machine; laser power, scan spacing and part orientation are identified as some of the influencing parameters affecting the part quality in sintering process. Radhakrishnan et al. (2003) have studied the problem of optimisation by primarily considering the direction of orientation of model build-up in a layered manufacturing. They have adopted a genetic algorithm approach to optimise the build orientation.

There are different techniques to determine the optimum process parameters. Taguchi technique is one such method, which has been widely adopted by investigators. Anitha et al. (2001) have studied the applicability of the method to RP problems and found that the results obtained are quite satisfactory. Therefore, the investigators adopted this technique to evolve an optimum process model for FDM.

3 Objectives

This research aims at conducting a scientific and experimental study in improving RP part accuracy through parameter tuning and optimisation of FDM manufacturing processes. The optimisation results or technology obtained from this research can be applied to any other RP machines using similar approaches. The objective of the present study is to conduct a detailed experimental study and to search for interrelationship between the FDM RP product accuracy and the machine parameter set-up, by using Taguchi experimental design and parameter tuning and optimisation techniques. The accuracy of components produced is measured by Coordinate Measuring Machine (CMM) and to achieve a dimensional accuracy of <0.013 mm/mm error and less than 0.005 mm/mm in various form features. The objective function was chosen to be maximisation of the resulting dimensional accuracy. The surface roughness of components produced is measured by the CLA value and to achieve the value of 19 Ra. The objective function was chosen to be minimisation of the resulting surface roughness (Ra) value.

4 Fabrication parameters in FDM process

In FDM, there are about 15 variables to consider prior to a manufacturing process (e.g., layer thickness, road width, air gap, orientation, temperature, raster angle, speed, humidity and wire diameter). Through initial observations and experience with the FDM system, it has been found that although most controllable factors have some effects, a major part of output quality is dictated by a few primary control factors (Armillotta et al., 1999; Gautham and Henderson, 1998) such as contour width, raster width, raster angle and air gap. In the present investigation, we have included these four build parameters as the main factors and examined their effects on dimensional and geometrical accuracy, and surface roughness of the final parts, individually.

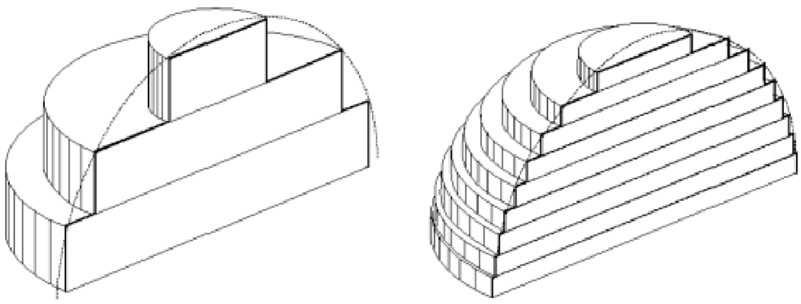
4.1 Layer thickness

It is the thickness of each slice of the part building on the previous layer. It can vary from 0.18 mm to 0.35 mm for FDM process (Stratasys® Incorporated, 1999). A stair-step effect is caused by layer thickness. The comparison of stair-stepping inaccuracies due to thick and thin build layers is shown in Figure 2 (Sabourin et al., 1996). Thus, the surface roughness increases with increase in layer thickness, and dimensional accuracy increases with decrease in layer thickness. Conversely, a lower value of layer thickness will give the better surface finish and good accuracy.

4.2 Road width

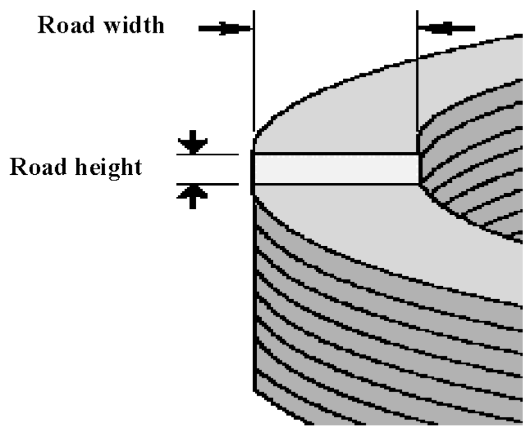
This is the thickness of the bead (or road) that the FDM nozzle deposits. This is shown in Figure 3. It can vary from 0.3 mm to 1.0 mm for the T12 nozzle (Stratasys® Incorporated, 1999). Conversely, medium road width will give the better surface quality for the prototypes.

Figure 2 Comparison of stair-stepping inaccuracies due to: (a) thick build layers poorly approximate complex surfaces and (b) thin layers better approximate these surfaces



Source: Sabourin et al. (1996)

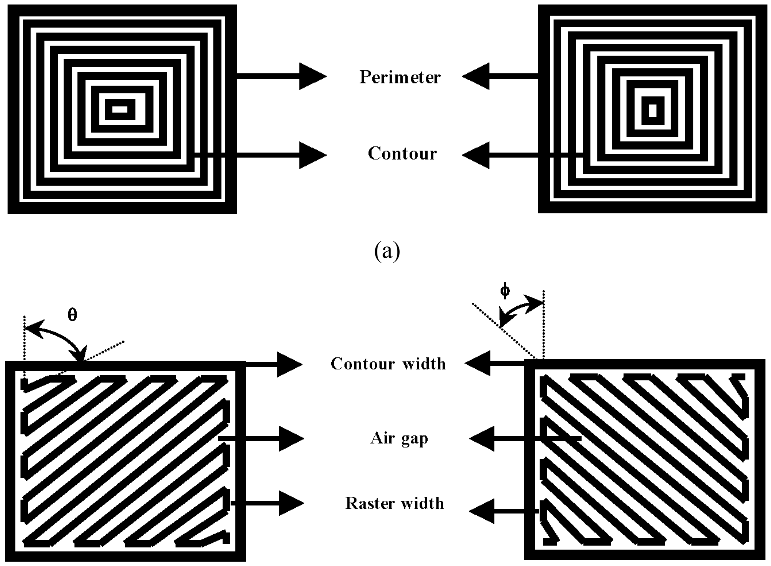
Figure 3 Road width and road height



4.3 Contour width

In FDM process, there are two types of deposition strategies are available: one is contour type deposition, which is shown in Figure 4(a), and the other one is raster-type deposition, shown in Figure 4(b). Contour width is the width of the contour tool path that surrounds each of the part cures. Using at least one contour fills every path curve. This is shown in Figure 4(b).

Figure 4 (a) Contour deposition and (b) raster deposition



(a)

(b)

4.4 Raster width

It is the tool path width of the raster pattern used to fill interior regions of the part curves. This is shown in Figure 4(b).

4.5 Raster angle

It is the angle made by the raster with the *X*/*Y* axis. This is shown in Figure 4(b).

4.6 Air gap

This is the horizontal space between the beads of FDM material. This is shown in Figure 4(b). The default is zero, meaning that the beads just touch (Stratasys® Incorporated, 1999). It can be modified to leave a positive gap, which means that the beads of material do not touch. This results in a loosely packed structure that builds rapidly. It can also be modified to leave a negative gap, meaning that two beads partially occupy the same space. This results in a dense structure, which requires a longer build time.

4.7 Speed

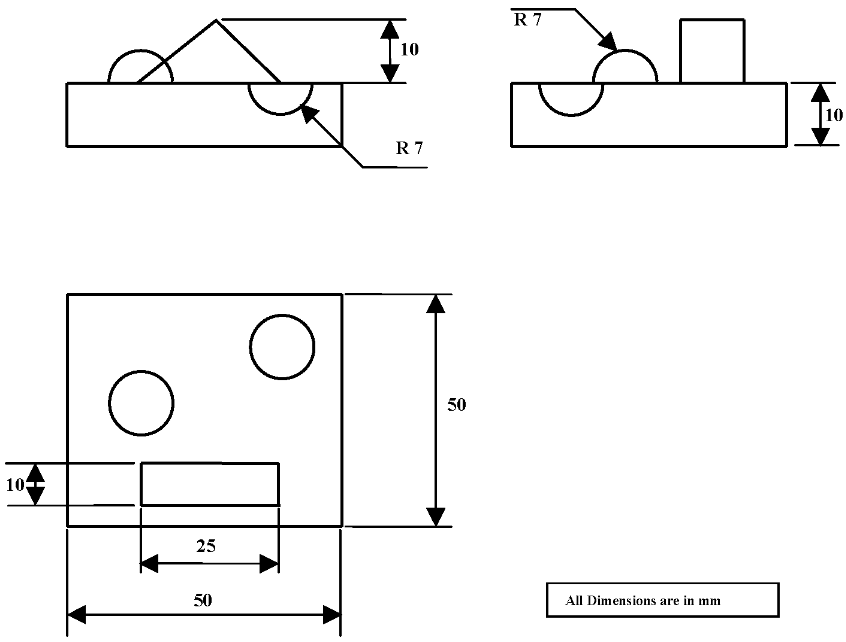
This is the rate that the FDM head moves in thousandths of meter per second. It can be varied (Stratasys® Incorporated, 1999). Conversely, medium speed will give the better surface quality for the prototypes.

5 Quality of the FDM parts

5.1 Part geometry

In order to properly define accuracy, a standard sample needs to be designed to represent some common dimensional, geometric features and surface roughness for FDM part quality evaluation. The designed part is depicted in Figure 5.

Figure 5 Specimen used for the experiment



5.2 Part accuracy responses

Minimum deviation between fabricated part dimension and CAD model dimension was selected as one of the part accuracy criteria. To measure the deviation, each axis (X, Y and Z) was studied separately. For finding deviation of each axis, length (X), width (Y) and height (Z) values of the fabricated parts were measured using the Mitutoyo BH303 CMM. Then, deviations from CAD model dimension were calculated as the error percentage. For example, deviation in the Z-axis was calculated through equation (1).

$$E_z = (Z - 10)/10 \times 100 \tag{1}$$

where Z is the measured height of the fabricated part.

5.3 Surface quality response

Laser scanning systems are used to produce high-precision surface-quality evaluation. Shellabear (1999) performed an extensive surface-quality comparison between many commercial RP systems. For surface-quality measurement, he used a Zeiss Laser Scanning Microscope (LSM). In this research, the samples of each trial are tested for surface roughness using the Taylor–Hobson Surtronic-3P apparatus, by adjusting a cut-off length of 2.5 mm.

6 The design of experiment

6.1 Matrix experiment design

Taguchi's method is a quality-control method, where the system of interest is harder to model mathematically, or it is cross-linked with quite a few of factors and levels. The main advantage of Taguchi's method is that the design of parameters and variance analysis and the optimal parameters of process can be scientifically analysed. Taguchi's method emphasises the notion of using two types of design variables in a study. These factors are control and noise factors (Walpole et al., 1998; Krottmaier, 1994). Control factors are variables that can be controlled in both the experiment and the process. Noise factors are variables that may or may not be controlled in the experiment but cannot be controlled in the process (or not controlled well in the process). The goal of robust parameter design is to choose the levels of the control variables that are most robust to changes in the noise variables.

The most important advantage of Taguchi's method is not the possible reduction of the number of experiments to a minimum, but the ability to represent graphically the combinations of parameters and their n-dimensional forms. The focused factors and their levels of targeted system have to be decided first in Taguchi's method of experimental design. We can use Taguchi's orthogonal array table to quickly collocate the parameter disposition table of focused factors and their levels.

ANOVA of Taguchi's method with the experimental results is then carried out to find out the influence for each factor. The Signal-to-Noise ratio (S/N ratio) is the formation of summary statistics at each combination in the control array. It is used to quickly identify the degree of the influence with the different factor levels and the noise factors that affect the experimental result. That is, the S/N ratio is an objective index to measure the stability of quality. If S/N ratio is larger, the quality of the experiment becomes nicer with this combination of factors and levels set-up. Typically, there are three S/N ratios:

- *Minimise response or Smaller the Better characteristic (SB)*. The S/N ratio is as in equation (2). If the characteristic of the quality is smaller, the target extreme value will be zero.

  $$S/N = -10 \log[1/n \, \Sigma y_i^2] \quad (2)$$

  where y_i is the export (output) value, i is from 1 to n.

- *Maximise response or Bigger the Better characteristic (BB)*. The *S*/*N* ratio is as in equation (3). If the characteristic of the quality is larger, the target extreme value will be unlimited.

  $$S/N = -10 \log [1/n\ \Sigma 1/y_i^2] \quad (3)$$

  where y_i is the export (output) value, *i* is from 1 to *n*.

- *Achieve target or Nominal the Best characteristic (NB)*. The *S*/*N* ratio is as in equation (4). The characteristic of the quality is a target value.

  $$S/N = 10 \log [u^2/\sigma^2] \quad (4)$$

  where

  $$u = 1/n\ \Sigma y_i \quad (5)$$

  and

  $$\sigma^2 = 1/(n-1)\ \Sigma(y_i - u)^2 \quad (6)$$

  where y_i is the export (output) value, *i* is from 1 to *n*.

In this presented study, one of the main objectives is to optimise the process parameters for a FDM RP system. The focused process parameters include contour width, rater width, raster angle and air gap of made-up ABS plastic. Generally, the inaccuracy of RP parts seldom happens in the *X*- and *Y*-direction. The *Z*-axis dimension of the part may be the major source of dimensional inaccuracy because of improper process parameters (Jacobs, 1992). Achieve target or nominal the best (NB) analysis model of Taguchi's method was used in this study. The target form error value of the specimens is 0.08 mm, and the surface roughness value is 19 Ra.

6.2 Experimental set-up

The recommended process parameters for the FDM system from RP maker are available. However, the quality of RP parts made using these parameters was unsatisfactory in our experience. An experimental set-up was developed to conduct this study of the process optimisation by utilising Taguchi's experimental design. Four control factors, that each has three levels (shown in the Table 1), were selected and collocated by the L_9 (3^4) orthogonal array of Taguchi's method. Table 2 shows the layout of experimental design, including building time (in minutes) and model and support materials consumption (in grams). RP parts were built up for each combination of parameters, and the output data and building time were recorded down for each test run. The above conditions necessitate a 3^4 experiment. That is, $3^4 = 81$ factor combinations are necessary to cover all possibilities. If the orthogonal arrays are used, the number of factor combinations can be reduced to nine without neglecting one of the main effects.

Table 1 Process parameters and their levels

Parameter	*Units*	*Level 1*	*Level 2*	*Level 3*
Contour width	mm	0.406	0.456	0.506
Raster width	mm	0.406	0.456	0.506
Raster angle	deg.	0	45	90
Air gap	mm	0	0.0125	0.025

Table 2 L_9 Orthogonal array for the experiment

Exp. no.	*Contour width* (mm)	*Raster width* (mm)	*Raster angle* (deg.)	*Air gap* (mm)	*Build time* (min.)	*Model material* (gm)	*Support material* (gm)
1	0.406	0.406	0	0	49	26.37	1.43
2	0.406	0.456	45	0.0125	59	26.37	1.41
3	0.406	0.506	90	0.025	47	25.47	1.41
4	0.456	0.406	45	0.025	61	25.91	1.41
5	0.456	0.456	90	0	49	26.24	1.41
6	0.456	0.506	0	0.0125	47	25.86	1.43
7	0.506	0.406	90	0.0125	50	25.94	1.41
8	0.506	0.406	0	0.025	47	25.53	1.43
9	0.506	0.506	45	0	58	26.87	1.41

7 Experimental results

In this study, we analysed the measurement of form errors and surface roughness of RP parts, and adopted the N.B. model of Taguchi's method as a means to optimise process parameters for FDM system. Table 3 shows the measured data for the experiment. The react tables of *S*/*N* ratio, sensitivity and ANOVA table can be generated from Table 3. Tables 4–9 show the *S*/*N* react tables, sensitivity react tables and ANOVA tables for the experiment.

Table 3 Test result for form errors and surface roughness of the part

Exp. no.	*Circularity deviation* (mm)	*Sphereness of external sphere deviation* (mm)	*Sphereness of internal sphere deviation* (mm)	*Surface roughness of top surface of the base* (Ra)	*Surface roughness of triangular surface* (Ra)
1	0.650	0.137	0.045	19.57	27.60
2	0.122	0.191	0.111	21.03	28.60
3	0.047	0.138	0.029	24.57	31.63
4	0.118	0.161	0.035	22.03	29.93
5	0.277	0.213	0.077	23.1	27.27
6	0.067	0.213	0.029	20.87	29.40
7	0.239	0.152	0.024	23.33	27.50
8	0.211	0.179	0.024	24.80	32.47
9	0.034	0.083	0.011	19.53	26.56

Table 4 React table of *S*/*N* ratio (signal-to-noise ratio) for form errors and surface roughness

Exp. no.	*Circularity deviation*	*Sphereness of external sphere deviation*	*Sphereness of internal sphere deviation*	*Surface roughness of top surface of the base*	*Surface roughness of triangular surface*
1	1.74226	24.97518	34.84127	27.88002	35.38262
2	17.48363	24.33149	4.97430	35.39139	46.33351
3	11.41074	25.31585	18.87530	28.03443	29.86372
4	17.02672	47.25405	23.87217	60.03723	38.86640
5	16.72315	19.29525	10.96737	35.84837	33.53897
6	12.66168	19.29525	18.87530	34.17270	46.14024
7	22.23402	32.44679	16.18825	34.06193	34.78150
8	31.42364	29.19225	16.18825	27.26342	27.45980
9	10.68469	15.21285	11.61908	27.74335	30.54558

Table 5 React table of sensitivity for form errors and surface roughness

Exp. no.	*Circularity deviation*	*Sphereness of external sphere deviation*	*Sphereness of internal sphere deviation*	*Surface roughness of top surface of the base*	*Surface roughness of triangular surface*
1	–3.74417	–17.26558	–26.93575	25.83181	28.81818
2	–18.27280	–14.37933	–19.09354	26.45678	29.12732
3	–26.55804	–17.20241	–30.75204	27.80810	30.00198
4	–18.56235	–15.86348	–29.11863	26.86029	29.52213
5	–11.15040	–13.43240	–22.27018	27.27224	28.71370
6	–23.47850	–13.43240	–30.75204	26.39044	29.36694
7	–12.43204	–16.36312	–32.39577	27.35829	28.78665
8	–13.51435	–14.94293	–32.39577	27.88903	30.22964
9	–29.37042	–21.61843	–39.17214	25.81404	28.46491

Table 6 React table of each factor and level for form errors and surface roughness, *S*/*N* ratio. The underlined values denotes as the largest values for the each group

Factors name	*Levels*	*S/N ratio for circularity*	*S/N ratio for sphereness of external sphere*	*S/N ratio for sphereness of internal sphere*	*S/N ratio for surface roughness of top surface of the base*	*S/N ratio for surface roughness of triangular surface*
Contour width (A)	0.406	10.21221	24.87417	*19.56362*	30.43528	37.19328
	0.456	15.47051	*28.61485*	17.90494	*43.35276*	*39.51521*
	0.506	*21.44740*	25.61729	14.66519	29.68957	30.92896

Table 6 React table of each factor and level for form errors and surface roughness, *S/N* ratio. The underlined values denotes as the largest values for the each group (continued)

Factors name	*Levels*	*S/N ratio for circularity*	*S/N ratio for sphereness of external sphere*	*S/N ratio for sphereness of internal sphere*	*S/N ratio for surface roughness of top surface of the base*	*S/N ratio for surface roughness of triangular surface*
Raster width (B)	0.406	13.66766	*34.89200*	*24.96723*	*40.65973*	*36.34351*
	0.456	*21.87680*	24.27299	10.70997	32.83439	35.77743
	0.506	11.58570	19.94131	16.45656	29.98349	35.51652
Raster angle (C)	0	15.27586	24.48756	*23.30161*	29.77204	36.32755
	45	15.06501	*28.93279*	13.48851	*41.05732*	*38.58183*
	90	*16.78930*	25.68596	15.34364	32.64824	32.72807
Air gap (D)	0	9.71670	19.82776	19.14257	30.49058	33.15572
	0.0125	17.45977	25.35784	13.34595	34.54201	*42.41842*
	0.025	*19.95370*	*33.92071*	*19.64524*	*38.44502*	32.06331

Table 7 React table of each factor and level for form errors and surface roughness, sensitivity

Factors name	*Levels*	*S/N ratio for circularity*	*S/N ratio for sphereness of external sphere*	*S/N ratio for sphereness of internal sphere*	*S/N ratio for surface roughness of top surface of the base*	*S/N ratio for surface roughness of triangular surface*
Contour width (A)	0.406	–16.19085	–16.28244	–25.59377	26.69890	29.31582
	0.456	–17.73041	–14.24276	–27.38028	26.84099	29.20092
	0.506	–18.43893	–17.64149	–34.65456	27.02045	29.16040
Raster width (B)	0.406	–11.57870	–16.49739	–29.48338	26.68346	29.04232
	0.456	–14.31251	–14.25155	*–24.58650*	27.20602	29.35689
	0.506	–26.46898	–17.41774	–33.55874	26.67086	29.27794
Raster angle (C)	0	–13.57819	–15.21363	–30.02785	26.70376	29.47159
	45	–22.06852	–17.28708	–29.12810	26.37704	29.03812
	90	–16.71349	–15.66597	*–28.47266*	27.47954	29.16744
Air gap (D)	0	–14.75418	–17.43880	–29.45936	26.30603	28.66560
	0.0125	–18.06111	–14.72495	*–27.41378*	26.73517	29.09364
	0.025	–19.54491	–16.00294	–30.75548	27.51914	29.91792

Table 8 ANOVA results for form errors

Column	*Factors*	*DOF*	*Sum of squares*	*Variance*	*Percentage contribution*
Circularity of hole					
1	Contour width (A)	2	0.02600	0.01300	8.94700
2	Raster width (B)	2	0.12300	0.06150	42.32600
3	Raster angle (C)	2	0.07160	0.03580	24.63800
4	Air gap (D)	2	0.07000	0.03500	24.08800
5	Error	0	0	–	–
6	Total	8	0.29060	0.03630	100
Whereness of external sphere					
1	Contour width (A)	2	0.00525	0.00262	38.04300
2	Raster width (B)	2	0.00446	0.00223	32.31880
3	Raster angle (C)	2	0.00157	0.00078	11.37680
4	Air gap (D)	2	0.00258	0.00129	18.69560
5	Error	0	0	–	–
6	Total	8	0.01380	0.00173	100
Sphereness of internal sphere					
1	Contour width (A)	2	0.00242	0.00121	33.91390
2	Raster width (B)	2	0.00352	0.00176	49.30650
3	Raster angle (C)	2	0.00040	0.00020	5.64950
4	Air gap (D)	2	0.00079	0.00039	11.12990
5	Error	0	0	–	–
6	Total	8	0.00715	0.00089	100

Table 9 ANOVA results for surface roughness

Column	*Factors*	*DOF*	*Sum of squares*	*Variance*	*Percentage contribution*
Top surface of the base					
1	Contour width (A)	2	1.07166	0.53833	3.39436
2	Raster width (B)	2	3.52040	1.76020	11.15041
3	Raster angle (C)	2	12.32540	6.16270	39.03910
4	Air gap (D)	2	14.65446	7.32723	46.41611
5	Error	0	0	–	–
6	Total	8	31.57193	3.94649	100
Triangular surface					
1	Contour width (A)	2	0.35650	0.17825	1.07059
2	Raster width (B)	2	2.00810	1.00405	6.03045
3	Raster angle (C)	2	3.36956	1.68478	10.11902
4	Air gap (D)	2	27.56516	13.78258	82.77993
5	Error	0	0	–	–
6	Total	8	33.29933	4.16241	100

8 Analysis and discussion

8.1 Estimation of factor effect

In the following analysis, an attempt was made to find the condition for target value for form errors and surface roughness. Based upon the achieved target analysis of Taguchi's method, the signal-to noise ratio (*S*/*N* ratio) (see equations (4)–(6)) is a summary statistic representing the ratio of mean (u) and variance. The sensitivity adjusts the mean of output quality values to the target value. These two values are the way to determine the significant factors in optimisation process. In the analysis for the experiments, the values of *S*/*N* ratio and sensitivity were calculated as follows. In order to determine the significant factors for optimisation, the variance has to be decreased.

From Table 6, choose the factors with the biggest numbers of *S*/*N* as candidate of parameters combination (the underlined data in Table 6), that is, A3B2C3D3 for circularity, A2B1C2D3 for sphereness of external sphere, A1B1C1D3 for sphereness of internal sphere, A2B1C2D3 for surface roughness of top surface of the base and A2B1C2D2 for surface roughness of triangular surface.

In Table 8, for circularity, the contribution of factor *A* (8.947%) is very small, which means the level of factor *A* affected the variance least, similarly for sphereness of external sphere, the contribution of factor *C* (11.3768%) and for sphereness of internal sphere, the contribution of factor *C* (5.6495%). In Table 9, for surface roughness of the top surface of the base, the contribution of factor *A* (3.39436%) is very small, which means the level of factor *A* affected the variance least, similarly for surface roughness of the triangular surface, the contribution of factor *A* (1.07059%). Therefore, the level of factors has to be promoted in order to decrease the variance. Then the sensitivity(s) was examined as follows:

The estimated value, s_{opt}, is as for circularity: A1B1C1D3

$$s_{op} = s_{A1} + s_{B1} + s_{C1} + s_{D3} - 3s_{ave} = -16.649636 \tag{7}$$

and the ideal value, s_{TA}, is as

$$s_{TA} = 10 \times \log m^2 = 10 \times \log (0.08)^2 = -21.9382, \tag{8}$$

where m is the target value.

Thus,

$$S = (s_{TA} - s_{opt}) \text{ is } -5.2885643. \tag{9}$$

Since S (–5.2885643) is negative, the adjusted s for A3 becomes –23.727494 (= –18.43893 – 5.2885646). However, the value for A3 is the smallest number among the group of factor *A* in Table 7 (out of the range in these levels of factor *A*). Hence, it is not necessary to do any adjustment of A3 after comparing react table in Table 7. Therefore, the most optimal process parameters combination is likely A3B2C3D3 for circularity.

Similarly, the values of *S*/*N* and sensitivity were calculated in the procedures of process optimisation by using Taguchi's method (see Tables 6 and 7) for all the remaining features (sphereness and surface roughness). From Table 6, for the sphereness of the internal sphere A1B1C1D3 (the largest *S*/*N* ratios for each factor) was selected as the possible parameters' combination. From the ANOVA in Table 8, the contribution of factors *C* and *D* are very small. Hence, the factors *C* and *D* have to be adjusted in order to decrease the variance. $S(= s_{TA} - s_{opt})$ was calculated as 6.293668. Necessitated adjustment was made as follows: C1 (–30.02785) to C3 (–28.47266), D3 (–30.75548) to D2 (–27.41378), and B1 (–29.48338) to B2 (–24.5865). As a result, the most factors combination is likely A1B2C3D2 for sphereness of internal sphere (see Table 7).

To analyse the data from the experiment, a regression analysis was used to develop a quantitative model relating the factors. The regression equations for circularity, sphereness and surface roughness in terms of process parameters are given in equations (10)–(12).

$$Y_{\text{circularity deviation}} = 0.7212 + 1.0887 \times B - 0.0083 \times C - 4.3333 \times B^2 + 0.00012 \times C^2 \quad (10)$$

$$Y_{\text{spherenesss}} = -7.6597 + 17.7019 \times A + 17.0923 \times B - 0.0013 \times C - 19.6 \times A^2 - 18.8 \times B^2 + 1.3394 \times 10^{-4} \times C^2 - 214.4 \times D^2 \quad (11)$$

$$Y_{\text{surface roughness}} = 27.6 - 0.04211 \times C + 93.2 \times D + 427.16 \times 10^{-6} \times C^2 + 4064 \times D^2 \quad (12)$$

where Y is the response (accuracy/surface roughness); A is contour width, B is raster width, C is raster angle and D is air gap.

Typical relationships between the circularity and process parameters are illustrated in Figure 6, using the MATLAB 6.0 software (Biran and Breiner, 1995). It shows the variations of circularity with raster angle and road width. Similarly, the relationships between the sphereness and part surface roughness and process parameters are illustrated in Figures 7 and 8.

From these analyses, we were able to reach the conclusion of the main factors and best set-up of the build parameters for dimensional, form features and surface roughness. Such findings are summarised in Table 10, in which we also list the suggested setting level of the main factors for achieving the best results.

Figure 6 The part circularity deviation with respective process parameters

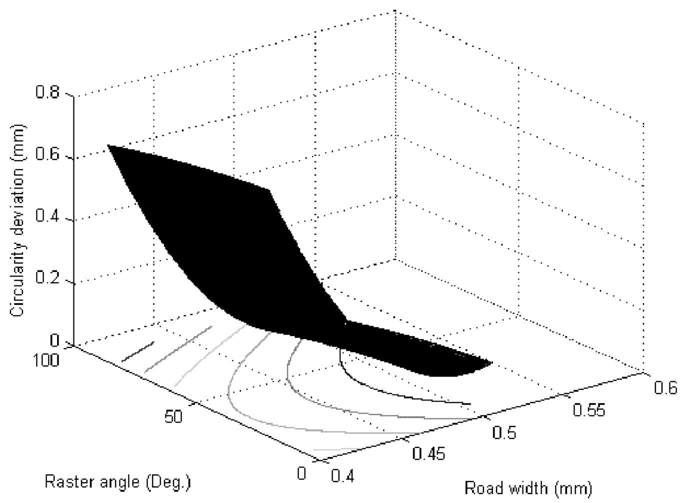


Figure 7 The part sphereness with respective process parameters

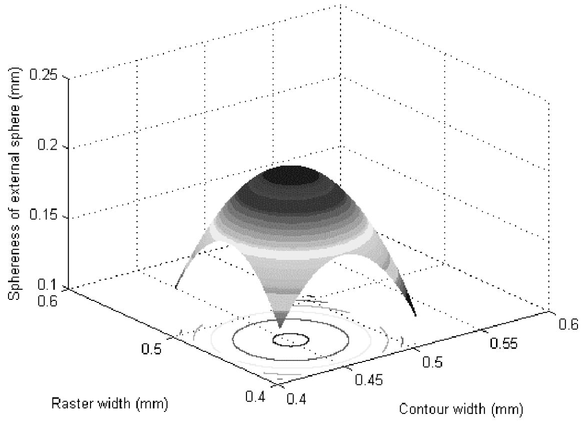


Figure 8 The part surface roughness with respective process parameters

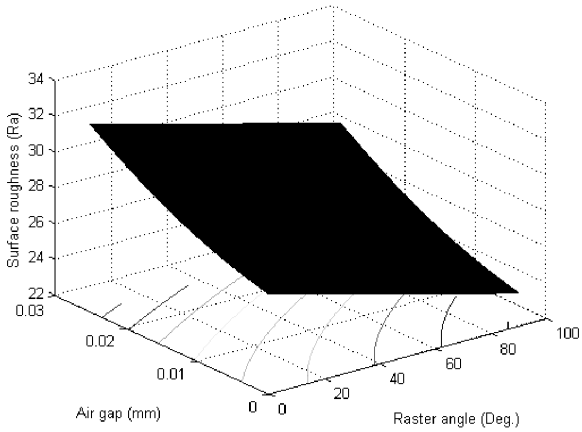


Table 10 Summary of main factors and the best setting for dimensional, geometry and surface roughness features

Group name	*Description*	*Major factors and best settings*
Dimensional accuracy		
Horizontal *X*/*Y* dimensions	Length	Raster width has the largest effect. Level I is the best
Vertical *Z* dimensions	Thickness	Raster width has the largest effect. Level I is the best
Geometric forms		
Circularity	Circularity of hole	Raster width has the largest effect. Level II is the best
Sphereness	Sphereness of external sphere	Contour width and raster width both are significant. Level II of contour width and level I of road width are the best
Sphereness	Sphereness of internal sphere	Contour width and raster width both are significant. Level II of contour width and level II of raster width are the best

Table 10 Summary of main factors and the best setting for dimensional, geometry and surface roughness features (continued)

Group name	*Description*	*Major factors and best settings*
Surface quality		
Surface roughness	Top surface of the base	Raster angle and air gap both are significant. Level II of raster angle and level III of air gap are the best
Surface roughness	Triangular surface	Raster angle and air gap both are significant. Level II of raster angle and level II of air gap are the best

9 Conclusion

A detailed study of the most important four build parameters that affect the dimensional, form features and surface roughness of the FDM parts fabricated by ABS plastic (P400) material on FDM Maxum RP machine, namely, the contour width, raster width, raster angle and the air gap, was performed in the present investigation. A sample component was used for testing the quality. To reduce the large amount of the total number of experiments required, the study employs the Taguchi L_9 orthogonal array for setting up the different combination of the respective control factors, each at three different levels. Out off the four parameters studied, the raster width and contour width contribute significantly for the part accuracy and form features, and air gap and raster angle contribute significantly for surface roughness. The Taguchi's technique helped in identifying the optimum input process parameters. The best settings of the parameters for dimensional, form features and surface roughness were found. Using the ANOVA analysis technique, we were able to identify the factors that are most significant in affecting the quality of the part. It is noted that, although the conclusions derived from the present investigation are all based on the FDM RP machine, the same experimental set-up and analysis techniques can be readily applied to different RP technologies, and the corresponding best setting of the various control parameters can be obtained accordingly. Some other design and manufacturing features were not considered. These may not respond in the same way as the features identified. This would be worth in our future study.

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