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Analysis on fused deposition modelling performance

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Abstract: Fused deposition modelling (FDM) is one of rapid prototyping (RP) technologies which uses an additive fabrication approach. Each commercially available FDM model has different types of process parameters for different applications. Some of the desired parts require excellent surface finish as well as good tolerance. The most common parameters requiring setup are the raster angle, tool path, slice thickness, build orientation, and deposition speed. The purpose of this paper is to discuss the process parameters of FDM Prodigy Plus (Stratasys, Inc., Eden Prairie, MN, USA). Various selected parameters were tested and the optimum condition was proposed. The quality of the parts produced was accessed in terms of dimensional accuracy and surface finish. The optimum parameters obtained were then applied in the fabrication of the master pattern prior to silicone rubber moulding (SRM). These parameters would reduce the post processing time. The dimensional accuracy and surface roughness were analyzed using coordinate measuring machine (CMM) and surface roughness tester, respectively. Based on this study, the recommended parameters will improve the quality of the FDM parts produced in terms of dimensional accuracy and surface roughness for the application of SRM.

Key words: Rapid prototyping (RP), Fused deposition modelling (FDM), Dimensional accuracy, Surface roughness
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1 Introduction

Rapid prototyping (RP) and rapid tooling (RT) technologies have become the focus for product development in recent years. The adaptation of RP (currently known as layered manufacturing (LM)) is crucial in RT, either as a direct or indirect technique. Some of the RP parts will be used as a master pattern for tooling applications. The critical evaluation for the RP product as the master pattern is to produce good dimensional accuracy as well as surface finish. In this study, the optimum parameters obtained will be applied in the fabrication of the master pattern prior to room temperature vulcanized silicone rubber moulding (SRM).

The nature of silicone rubber mold duplicates whatever kind of surface condition that the master pattern presents. Therefore, the master pattern made by fused deposition modelling (FDM) must have an acceptable surface finish and dimensional accuracy. This study is to investigate the capability of the FDM Prodigy Plus (Stratasys, Inc., Eden Prairie, MN, USA) to produce parts by applying different process parameters available on the machine. Anitha *et al.* (2001) and Ahn *et al.* (2009) proved that layer thickness is the most influencing parameter for the surface finish of LM. In general, a thinner layer will generate a smoother surface finish. However, Ahn *et al.* (2009) presented that the values of surface roughness depend on different angles of the parts. In addition to layer thickness, other process parameters should be applied to maximize the part quality. The process parameters can contribute to a better product and reduce the post-processing work.

The surface finish and dimensional accuracy are vital in molding and parts assembly. Magrab (1997) highlighted the close relationship between the surface roughness and tolerance of a product. The tolerance should be at least ten times the value of the average surface roughness. However, the dimensional and geometrical tolerance also depends on the types of LM processes. Grimm (2003) stated that the deviation of the FDM Prodigy Plus is 0.60% on average while 0.3 mm deviation for *z* axis. In addition, Nooraini (2006) mentioned the accuracy precision of Prodigy Plus is ±0.127 mm.

Many studies of FDM were performed in an attempt to make suggestions on how to improve the quality of parts. Sun *et al.* (2008) mentioned that the thermal factor affects the quality of bonding. Han *et al.* (2002) and Sun *et al.* (2008) also suggested that deposition speed and its movement are influenced by a parts geometry. The deposition speed affects the surface and layers of the FDM part. There were also factors of road width, air gap, and raster angle used to enhance the strength (Lee B.H. *et al.*, 2005; Lee C.S. *et al*., 2007). Therefore, the initiative made by different authors and geometrical-shape issues are the basis of this study.

2 Fused deposition modelling Prodigy Plus

FDM is the solid-based RP process that is widely used in design and product development processes. It is a process of building the part layer by layer, from bottom to top by heating thermoplastic wire. The basic equipments of FDM involve drive wheels (to drive the filament from its cartridge into heater), a heater and liquefier (to melt the filament), a tip (nozzle that remove/extrude out the filament), a platform (the base where the filament is deposited), and a piston (to move the platform at *z* axis). The filament is extruded in a semi-molten state and in a thin ribbon form. The thin ribbon shapes also confirm the bonds of filaments at each layer (Liou, 2008). The extruded filament which is deposited onto the platform is recognized as a ‘road’ (Grimm, 2003; Bellini *et al.*, 2004). A road will be quickly solidified after being stacked by another layer of road on the platform. The road that deposited earlier, which will be stacked by the latter road, is called a substrate.

The FDM technology was established in the late 1980s while the model FDM Prodigy Plus was developed during several series of models (such as FDM Vantage, FDM Maxum, and FDM 3000) in the late 1990s. The FDM Prodigy Plus is a suitable concept application (Chua *et al.*, 2003). The feed material used by this equipment is the thermoplastic ABS (P400), both for parts and supports. Insight™ software is the medium for this machine to plan and generate its geometrical model and support structure, called tool path. The support structure of the model is removed using the WaterWorks™ solution.

3 Methodology

The performance investigation of FDM involves the designing and fabricating of the test model using FDM. The design of the test model is developed based on an objective to study the capability of FDM machine to produce the desired shapes. Six test models were built with different sets of processing parameters. The methodology is divided into three major steps: (1) design of test model; (2) process parameters; and, (3) measurement of dimension and surface roughness.

3.1 Design of test model

The design of test model contains a variety geometrical shapes and sizes that are commonly available on plastic parts. The geometrical representation of test model was generated by SolidWorks (3D computer-aided design (CAD)) as shown in Fig. 1. The CAD data were then converted into standard triangular language (STL) format. The fabrication for the build of the model and its support structures were generated automatically by Insight software.

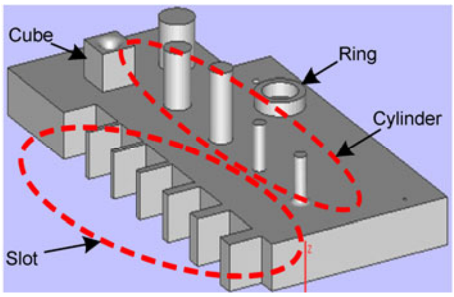


Fig. 1 Computer-aided design (CAD) of test model

The selection of design shapes for test model had been made by referring to the previous studies in RP (Mahesh *et al*., 2004), RT (Hanumaiah and Ravi, 2007), and SRM (Rahmati *et al.*, 2007). The features were also being varied by different sizes (Table 1).

Table 1 Features in the test models

Feature	Number of features
Slot (SL)	6
Cube (CB)	1
Cylinder (CL)	5
Ring (RG)	1

3.2 Process parameters in FDM Prodigy Plus

The basic parameters that commonly being studied for FDM are layer thickness, road width, air gap, and built style or direction. Some may require fine surface finish for assembly purposes and some may not. FDM Prodigy Plus provides several parameters for users to obtain the desired parts.

Based on the application and the requirements, there are three different values of layer thickness that can be selected by users as shown in Table 2. On the other hand, there are two options of visible surface: normal and fine. However, the fine visible surface offers more tool path setups than the normal one. With the tool path setup, the contour width and internal raster are believed to be among influencing parameters that affect the desired performance, such as formation of small cylinders and slots. Thus, the fabrication of FDM parts was made by applying three parameters: layer thickness, contour width, and internal raster. Each parameter was varied by two levels. Six test models were built as shown in Table 3. However, the selection of the fine visible surface parameter was kept constant for every test model since it is the desired criterion.

Table 2 Available layer thickness (formally known as slice height) in FDM Prodigy Plus

Thickness (mm)	Purpose
0.3302	Draft
0.2540	Standard
0.1778	Fine

Table 3 Test model and the varied parameters

Model	Layer thickness (mm)	Contour width (mm)	Internal raster (mm)
Test 1	0.1778	0.3048	0.5048
Test 2	0.2540	0.5048	0.3048
Test 3	0.1778	0.5048	0.5048
Test 4	0.1778	0.3048	0.3048
Test 5	0.2540	0.5048	0.5048
Test 6	0.1778	0.5048	0.3048

3.3 Measurements of dimension and surface roughness

The dimension of each test model was compared to the CAD/nominal dimension. The results were accessed in *x*, *y* and *z* axes. The measurements were taken for each size of slot (SL1–SL6), cube (CB), and diameters of cylinders (CL) and ring (RG). The tolerance for *x* and *y* axises is ±0.127 mm (Nooraini, 2006). Meanwhile, for *z* axis, the measurement tolerance was 0.3 mm as referred to Grimm (2003).

The measurement of dimensional accuracies was performed using a touch-probe type coordinate measuring machine (CMM) (LH40, Wenzel, UK). Every feature was measured five times and averaged. Ten or more touch points were taken to measure the diameter or roundness of the cylinder. The measurements of the cylinders were also being made by divided into three regions (upper, middle, and lower) in order to observe the uniformity of each cylinder (Fig. 2a).

Besides, the surface roughness of the every test model was measured using a portable surface tester (Mitutoyo SJ-301, Mitutoyo Corporation, Kanagawa, Japan). The surface roughness was measured at the horizontal and vertical corners (Fig. 2b). This is to distinguish the influence of different parameters at every corner and for shape evaluation purposes.

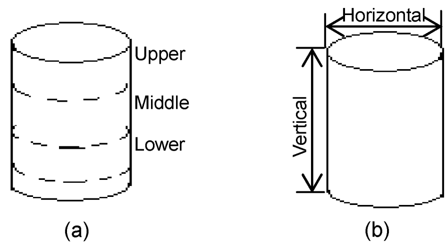


Fig. 2 Example of measurement of surface roughness (a); (b) the regions to inspect the roundness of a cylinder

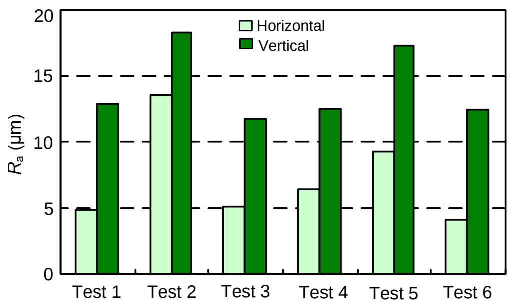


Fig. 3 Average roughness (R_a) of every test model

4 Results and discussion

4.1 Dimensional accuracy

Table 4 shows the width dimension of the SL feature. Some SLs of test models exceeded the tolerance value (0.127 mm), especially when they are approximately 2 mm and below. This can be seen clearly from Test 4. Test 6 does not exceed the precision values. For example, its SL4 is within the range of tolerance.

Table 4 also depicts the width or thickness deviation of ribs or RG. It can be seen that the deviation values become worse when fabricating the circular shape of RG. This is because the nominal thickness of RG is also 2 mm. The smallest deviation values are from Tests 6 and 2.

Moreover, Table 4 portrays the height deviation values of CLs. From the result, it shows that every test model is within the range of 0.3 mm of deviation. However, Test 1 has the least deviation while Test 6 has the most deviation. It also shows that there is inconsistency in shape of the CLs. It was found that the feature is not fine from a cylindricity view point. From Table 5, it was found that most of the diameters for cylinders from every test model were close to nominal dimensions at the lower regions. The results are listed in Table 5 for CLs with diameters of 10 mm and 7.5 mm.

4.2 Surface roughness

As predicted, the thin layer had produced a smoother surface than the thick layer, whether it was measured vertically or horizontally. Fig. 3 indicats that every horizontal surface is better than vertical surface. This scenario proved that the up-facing surface (horizontal) will always better than the

Table 4 Deviations of different features in different test models

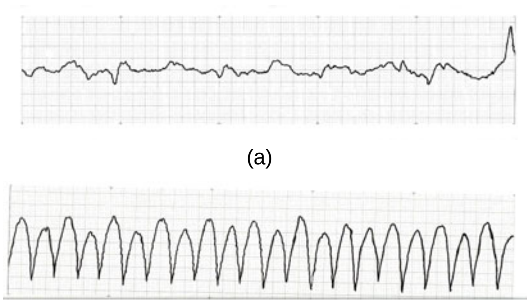
Feature	Nominal	Test 1		Test 2		Test 3		Test 4		Test 5		Test 6	
		Actual	Dev	Actual	Dev	Actual	Dev	Actual	Dev	Actual	Dev	Actual	Dev
Width (mm)													
SL1	5.0	4.9612	0.0388	5.0576	0.0576	4.8763	0.1237	4.9840	0.0160	4.9743	0.0257	4.8865	0.1135
SL2	4.0	4.0155	0.0155	4.1036	0.1036	4.0148	0.0148	4.2120	0.2120	4.0975	0.0975	3.9530	0.0470
SL3	3.0	3.1104	0.1104	3.1240	0.1240	3.0690	0.0690	3.2250	0.2250	3.1067	0.1067	2.9589	0.0411
SL4	2.0	2.0773	0.0773	2.1333	0.1333	2.0842	0.0842	2.1600	0.1600	2.1054	0.1054	1.9641	0.0359
SL5	1.5	1.6186	0.1186	1.6526	0.1526	1.6314	0.1314	1.7420	0.2420	1.6358	0.1358	1.4734	0.0266
SL6	1.5	1.6461	0.1461	1.6614	0.1614	1.6440	0.1440	1.6920	0.1920	1.6197	0.1197	1.4783	0.0217
Thickness (mm)													
RG	2.0	3.8156	1.8156	3.8728	1.8728	3.7972	1.7972	3.9080	1.9080	3.9357	1.9357	3.7699	1.7699
Height (mm)													
CL1	10	9.9170	0.0830	9.9143	0.0857	9.9381	0.0619	9.8050	0.1950	10.1077	0.1077	9.8013	0.1987
CL2	12	12.0250	0.0250	12.0110	0.0110	12.0660	0.0660	12.0000	0	12.1230	0.1230	11.8826	0.1174
CL3	15	15.0470	0.0470	15.0460	0.0460	15.0710	0.0710	14.9956	0.0044	15.1076	0.1076	14.7841	0.2159
CL4	10	10.0810	0.0810	9.8918	0.1082	9.9489	0.0511	9.8393	0.1607	10.0579	0.0579	9.7188	0.2812
CL5	10	9.9129	0.0871	9.9043	0.0957	9.8810	0.1190	9.8919	0.1081	10.0833	0.0833	9.7370	0.2630
CB	8	7.9593	0.0407	7.8493	0.1507	7.9859	0.0141	7.9010	0.0990	8.0624	0.0624	7.9209	0.0791

Dev: deviation

Table 5 Roundness of two cylinders from every test model (mm)

Model	Roundness of CL1			Roundness of CL2		
	Upper region	Middle region	Lower region	Upper region	Middle region	Lower region
Nominal	10	10	10	7.5	7.5	7.5
Test 1	9.7485	9.7568	9.7533	7.2311	7.1970	7.1999
Test 2	9.8018	9.7972	9.8325	7.2619	7.2735	7.3530
Test 3	9.7938	9.7866	9.8316	7.2925	7.2162	7.3467
Test 4	9.7345	9.7058	9.7525	7.2440	7.1850	7.4006
Test 5	9.8117	9.8220	9.8535	7.2761	7.2691	7.3330
Test 6	9.7710	9.7839	9.8013	7.2538	7.2281	7.2931

down-facing surface (vertical). This is due to the formation of elliptical curves or fillet on the down-facing surface during layer-bonding. The general surface profile is depicted in Fig. 4. There were four test models, Tests 1, 3, 4, and 6, which showed good surface roughness and all of them were from the same layer thickness parameter (0.1778 m). When measured vertically and horizontally, it was found that the best surface roughness measurements were obtained during Tests 3 and 6.



(a)

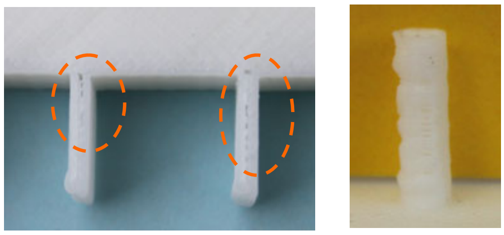
(b)

Fig. 4 General surface profile of (a) horizontal surface and (b) vertical surface

The effect of layer thickness, contour width, and internal raster to the roughness can also be seen with naked-eye observation, especially when viewing the small cylinder. For example, the diameter of CL4 of Test 1 is 3.5 mm. Its surface was measured but the value obtained was unreliable since it was too coarse and wavy. The surface of the cylinder became rougher and worse when the sizes were smaller. This means that residual stress is severe to smaller features. It is believed that surface condition would more prevalent when the diameter of the feature is about 2 mm. Error on the cylinder formation or part distortion, has been described by Zhang and Chou (2008) and it is known as residual stress. There are three factors of the residual stress: thermal gradient, speed of deposition and part geometry (Han *et al.*, 2002; Sun *et al.*, 2008). However, the deposition speed, which also related to the part geometry, is not the controllable factor in this experiment.

Contour width and internal raster have a significant effect on the quality of the part. The effect of internal raster can be observed in Fig. 5a. It was observed that tiny holes existed at the SL feature due to a larger internal raster value (0.5048 mm). The smaller internal raster value (0.3048 mm) can aid the formation of the shape by filling the small area optimally and with fewer holes.

Meanwhile, the smaller contour width produced a poor shape on small cylinders. This can be seen in Fig. 5b. The contour width is very important for the outer shape of the cylinder. When the contour width is too thin, it was easily affected by heat, i.e., from chamber and tip.



(a) (b)

Fig. 5 The small holes occurred at Test 3 which used bigger Internal Raster than Test 4 (a); the small cylinder of Test 1 (b)

Small contour width will be easily affected by the high temperature, which causes re-melting of the substrate. The wider contour will help to create a good formation of the part geometry since it can sustain the heat gradient. On the other hand, the error formation on small cylinders can be reduced when a thicker contour width is applied. It helps the deposition process since the filaments, which have a larger area of contact, become more easily bonded to each other.

5 Conclusions

Experiments were conducted in order to find the effect from variable FDM parameters which can produce desired test models that are suitable for SRM. There are some conclusions from this study:

1. The FDM machine is less accurate when making circular shape as significant deviation, ranging from 0.1–0.2 μm radial distances occurred. This is because that the gantry mechanism constraints the movement of the deposition head.

2. From the comparison of the nominal to actual test models, the best dimension for a feature to be built with FDM Prodigy Plus in x, y directions is 2 mm and above. This is applied to almost all types of shapes (i.e., slot, cube, cylinder, and ring). The

dimensions less than 2 mm will cause to deviate from its accuracy (0.127 mm). Meanwhile, almost all features are within tolerance when measured in *z* axis (deviation of 0.3 mm).

3. In making small parts, which require a good surface finish and appearance, it is recommended to apply appropriate values of contour width and internal raster, besides applying thin layer and fine visible surface finish. This study showed that both of these parameters can aid in the bonding quality between layers and lead to better surface finish.

4. Parameters applied onto Test 6 are decided to be the best parameter setup in fabricating a master pattern using FDM Prodigy Plus for SRM application, since it produced parts or features that are dimensionally within tolerances, and generated the best surface finish.

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