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DIMENSIONAL ACCURACY AND SURFACE ROUGHNESS OF PART FEATURES MANUFACTURED BY OPEN SOURCE 3D PRINTER

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ABSTRACT

This paper investigates the effectiveness and the accuracy of open source 3D printer of Mendel Max and Kossel Mini which the additive manufacturing technique of Fused Filament Fabrication (FFF) was implemented. A benchmark of the 3D printer test model was designed based on critical features of AM process i.e. hemispheres, cube, cylindersand slots. The benchmark was produced by both machines using variation FFF parameters of layer height and infill density. In addition, the material of FFF was varied between PLA and ABS for each test. The dimensional accuracy of the part features were measured by the nominal dimension of the part using Profile Projector DS600. In addition, TR200roughness tester was used to measure the surface roughness. The result shows that for dimensional accuracy results, Mendel Max machine has a lower deviation result compared to Kossel machine. Furthermore, PLA filament gives better result compare to ABS filament in term of surface quality finishing for both machines. The result shows that for both 3D printer machines, the quality and accuracy of the part features are better when the layer thickness is 0.178 and20% ofinfill density.

Keywords: dimensional accuracy, low cost 3D printer, FFF, FDM, additive manufacturing.

1. INTRODUCTION

Dimensional accuracy and surface quality of a production part remains major issue in the manufacturing engineering process. The need to have a very accurate parts or features that resembles as close as possible to the original design is decisive and it will influence how the product will be wholly accepted and approved for distribution to the end-users. In 3D printing process, where different technology exists such as Fused Filament Fabrication (FFF) / fused deposition modelling (FDM), Selective Laser Sintering (SLS) and Laminated Object Manufacturing (LOM), the dimensional accuracy and surface quality for each of the process will be unique. They are subjected to the limitation of the machine itself; the materials, the environment, the user etc. On the other hand, the retail price of open source 3D printer machine becomes affordable for consumer to purchase. However, consumer may face problem to choose which is the best 3D printing machine around. Furthermore question remains whether the open source 3D printer will be able to produce complex part features in term of dimensional accuracy and surface roughness comparable to the industrial or high-end 3D printing machine.

FFF is the most common used 3D printer techniques in the world [1]. The recent growth of open source 3D printer is mainly due to this technology alone since it is simple to use and regarded as an eco-friendly machine. FF Fallows fabrication of objects or prototypes by heating thermoplastic filament and extrudes through its nozzle and by built up the sequence in layer by layers process. Although the process is simple and automated, the dimensional accuracy and the quality of the end product sometimes frustrated consumer which lack the knowledge of engineering process and the drawback of FFF process. Furthermore consumer may be unfamiliar with the process parameter and the material of FFF, thus this might limit the user to machine control of 3D printer.

Dimensional accuracy and surface roughness of part features fabricated by FFF machine has been studied by several researchers for several purposes. Sudin M.N.*et al.* [2] investigates the dimensional accuracy of FFF/FDM machine, FDM 400MC Machine and found out that the machine is less accurate in producing a circular shape part such as cylindrical, sphere and hole. Bakar *et al.* [3] examines the limitation of FDM Prodigy Plus in term of dimensional accuracy and surface quality using simple benchmark consists of multiple features with various process parameters. Dyrbus [4] study the dimensional accuracy of part features. The study showed that the FDM able to obtain dimensional accuracy of 0.1mm and 0.4°. For open source 3D printer, Dixit *et al.* [5] investigates the influence of the process parameter by comparing FDM machine and low cost 3D printer. Galantucci *et al.* [6] used design of experiment method to improve dimensional accuracy on rectangular test specimens, minimizing changes in length, width and height for both industrial 3D printing system and an open-source one. While Habeeb *et al.* [7] study the tensile strength and porosity of open source FFF machine and claim they are acceptable and comparable to those from mid-range commercial manufacturer. In addition, improvement in dimensional accuracy and surface roughness of open source 3D printer has been reported in [8-12].

Thus the dimensional accuracy and surface roughness of open source FFF is one of the main issues in 3D printer study. This will help a clear understanding for consumer and researcher to identify potential application especially for open source 3D printer.

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2. METHODOLOGY

2.1 Benchmark of part features

The benchmark of part features is designed with various geometrical sizes and shapes based on simplification benchmark from [2-3]. The benchmark is proposed as shown in Figure-1 and the detail dimension is shown in Figure-2. It consists of 2 hemispheres (HP1 & HP2), 1 cube (CB), 5 cylinders (CL1 – CL5) and 6 slots (SL1 – SL6). The part features is limited to this features due to critical performance of circular shape .In addition, the size area for both FFF machines are limited to include a lot of features.

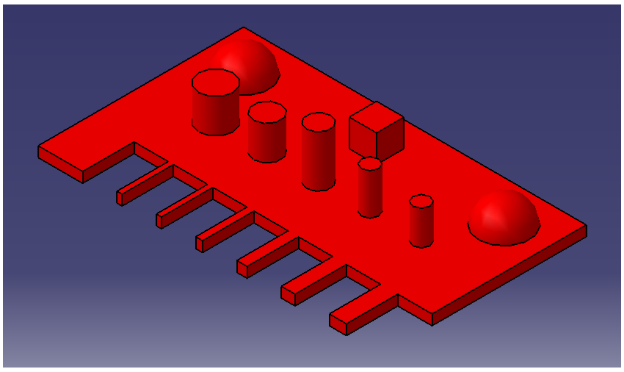

Figure-1. Selected features drawn by solid modeling software.

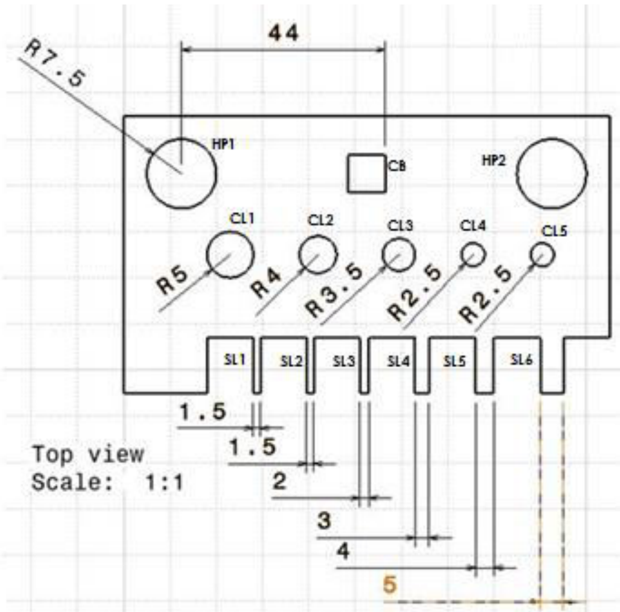

Figure-2. Selected features drawn by solid modeling software.

2.2 Part features fabrication

The model was prepared by solid modelling software CATIA V5. Then the digital file was transferred and sliced by using Repetier Hosts software. Two open source FFF machine, Mendel Max and Kossel Mini Pursa i3 were used to fabricate all 4 set of the model.

The parameter settings of the infill density and layer thickness are varied as shown in Table-1. This is to investigate whether the parameters have any influence to the dimensional accuracy or surface roughness of the part. In addition, layer temperature and printing speed was set to 190 ºC and 40 mm/s respectively and with no additional support structure based on [13]. In addition, the model was varied by the filament materials of ABS and PLA.

Before the printing process began, the printing platform was prepared by mixed acetone and ABS and spread onto the printing area of printing platform [14]. Afterwards, both of FFF machines built and fabricate the model. Overall, a total of 16 models were fabricated using both machines.

Table-1.FFF Process parameters

Set	**Layer thickness** (mm)	**Infill density** (%)
1	0.178	20
2	0.178	30
3	0.254	20
4	0.254	30

2.3 Measuring the dimension of part features

After the printing process was completed, the dimensions of part features were measured via Profile Projector DS600. The linear dimensions were measured at three different points and the average measurements were calculated. The dimensions were compared to the nominal dimension to obtain the dimensional accuracy. For slots (SL), the measurements were taken for the width of the features. While for cylinders (CL) and cube (CB), the measurements were taken for the height of the features. While for surface roughness, a handheld roughness tester, TR200 was used. The surface roughness, R_a was measured at three different points at both vertical and horizontal direction and the average measurements were calculated.

3. RESULTS AND DISCUSSIONS

3.1 Result of part features accuracy in mendel max

The data measurements for all 4 sets (variation of layer thickness and infill density) using Mendel Max 3D Printer are shown in Table-2(a) for ABS and Table-2(b) for PLA. The deviation for each measurement were calculated and presented in bar graph to aid understanding.

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Table-2(a). Deviations of the different features in different test sets using Mendel Max 3D Printer for ABS.

	Features	Nominal	ABS			
			Set 1	Set 2	Set 3	Set 4
Width (mm)	SL1	1.5	1.724	1.691	1.619	1.603
	SL2	1.5	1.759	1.722	1.585	1.512
	SL3	2	2.297	2.381	2.156	2.113
	SL4	3	3.338	3.224	3.092	2.981
	SL5	4	4.453	4.044	4.087	4.030
	SL6	5	5.437	5.106	5.235	5.071
Height (mm)	CL1	10	10.160	10.330	10.120	10.180
	CL2	10	10.110	10.290	10.150	10.150
	CL3	15	15.260	15.310	15.770	15.260
	CL4	12	12.290	12.370	12.420	12.250
	CL5	10	10.330	10.340	10.530	10.360
	CB	8	8.138	8.083	8.135	8.097

Table-2(b). Deviations of the different features in different test sets using Mendel Max 3D Printer for PLA.

	Feature	Nominal	PLA			
			Set 1	Set 2	Set 3	Set 4
Width (mm)	SL 1	1.5	1.694	1.597	1.713	1.436
	SL 2	1.5	1.688	1.571	1.616	1.563
	SL 3	2	2.176	2.062	2.257	2.051
	SL 4	3	3.183	3.054	3.227	3.043
	SL 5	4	4.258	4.106	4.264	4.095
	SL 6	5	5.239	5.056	5.294	5.057
Height (mm)	CL 1	10	10.360	10.370	10.170	9.927
	CL 2	10	10.330	10.240	10.200	9.953
	CL 3	15	15.150	15.170	14.990	14.030
	CL 4	12	12.030	12.080	11.960	12.090
	CL 5	10	10.140	10.300	10.100	10.140
	CB	8	8.045	8.021	7.965	7.854

For SL in Figure-3, Set 1 has the highest deviation for Mendel Max 3D printer using ABS material compared to the lowest deviation in Set 4.Whereas in Figure-4 there is no clear pattern for CL and CB. In Figure-5, Set 1 and Set 3 has the highest deviation for Mendel Max 3D printer using PLA material compared to the lowest deviation in both Set 3 and Set 4. In Figure-6, there are also no pattern exist for CL and CB for PLA material. Thus this shows that the Slab features produced by Mendel Max are influenced by the process parameters. In this case, a high deviation occurs in SL when the layer thickness and infill density is low. In term of material, generally Mendel Max using ABS has higher deviation compares to the machine using PLA. This might be due to the ABS easily influenced by the heat and therefore easily to warp and gives higher deviation to the measurement [14].

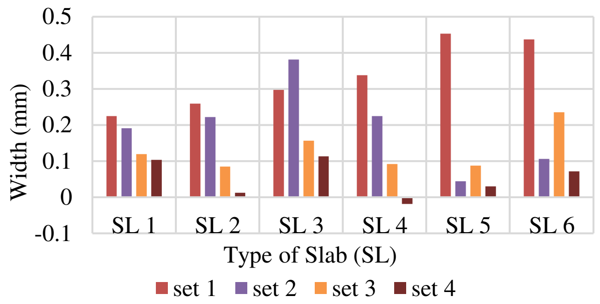

Figure-3. Deviation of width of Slab (SL) for Mendel Max 3D printer using ABS material.

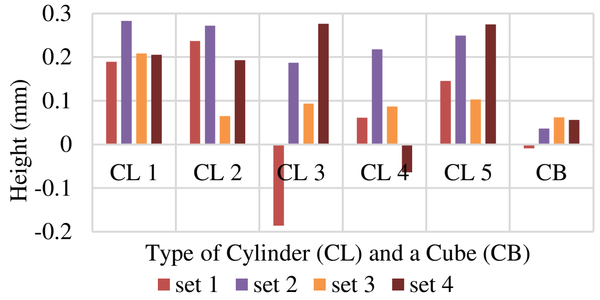

Figure-4. Deviation of width of Cylinder (CL) for Mendel Max 3D printer using ABS material.

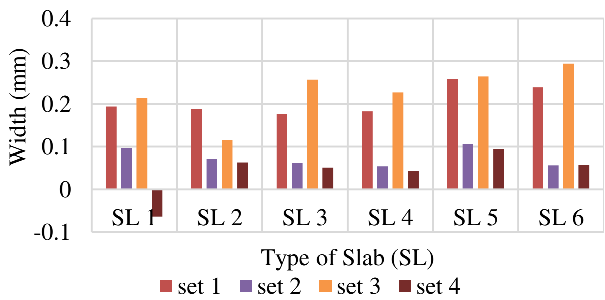

Figure-5. Deviation of width of Slab (SL) for Mendel Max 3D printer using PLA material.

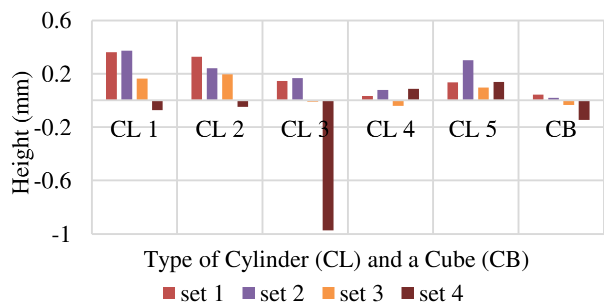

Figure-6. Deviation of width of Cylinder (CL) for Mendel Max 3D printer using PLA material.

3.2 Result of part features accuracy in Kossel Mini

The data measurements for all 4 sets (variation of layer thickness and infill density) using Kossel Mini 3D Printer are shown in Table-3a for ABS and Table-3b for

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PLA. The deviation for each measurement were calculated and presented in graph.

Table-3(a). Deviations of the different features in different test sets using Kossel Mini 3D printer.

	Feature	Nominal	ABS			
			Set 1	Set 2	Set 3	Set 4
Width (mm)	SL 1	1.5	2.078	1.763	1.808	1.705
	SL 2	1.5	2.229	1.671	1.775	1.682
	SL 3	2	2.545	2.293	2.518	2.255
	SL 4	3	3.736	3.352	3.578	3.266
	SL 5	4	4.605	4.421	4.738	4.453
	SL 6	5	5.755	5.533	5.679	5.521
Height (mm)	CL 1	10	10.160	10.330	10.120	10.180
	CL 2	10	10.110	10.290	10.150	10.150
	CL 3	15	15.260	15.310	15.770	15.260
	CL 4	12	12.290	12.370	12.420	12.250
	CL 5	10	10.330	10.340	10.530	10.360
	CB	8	8.138	8.083	8.135	8.097

Table-3(b). Deviations of the different features in different test sets using Kossel Mini 3D printer.

	Feature	Nominal	PLA			
			Set 1	Set 2	Set 3	Set 4
Width (mm)	SL 1	1.5	1.552	1.529	1.602	1.567
	SL 2	1.5	1.545	1.512	1.587	1.586
	SL 3	2	2.085	2.027	2.079	2.081
	SL 4	3	3.087	3.052	3.086	3.063
	SL 5	4	4.146	4.072	4.137	4.082
	SL 6	5	5.109	5.075	5.113	5.061
Height (mm)	CL 1	10	10.370	10.240	10.180	10.240
	CL 2	10	10.270	10.270	10.130	9.883
	CL 3	15	15.260	14.940	14.920	15.010
	CL 4	12	12.150	12.010	11.910	11.920
	CL 5	10	10.210	10.240	10.100	10.230
	CB	8	7.992	7.980	7.945	7.974

For SL in Figure-7, Set 1 has the highest deviation for Kossel Mini 3D printer using ABS material compared to the lowest deviation in Set 4. This is the same pattern with Mendel Max machine. Whereas in Figure-8 there is also no effect of process parameters for CL and CB. In Figure-9, there has a higher deviation for Set 3 for all SL but the result for others are no clear indication which is the best. In Figure-10, there are also no pattern exist for CL and CB for PLA material. Thus this shows that the Slab features produced by Kossel are slightly influenced to the layer thickness and infill density. Similarly, Kossel mini machines using ABS has higher deviation compares to the machine using PLA.

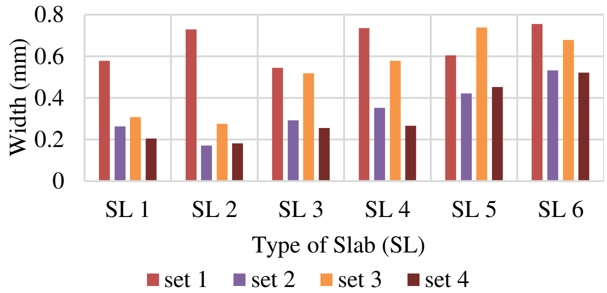


Figure-7. Deviation of width of Slab (SL) for Kossel 3D printer using ABS material.

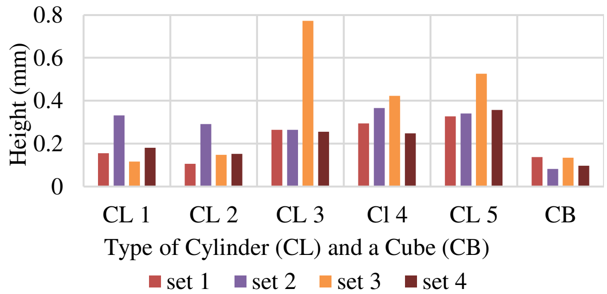


Figure-8. Bar graph of height of Cylinder (CL) for Kossel (ABS).

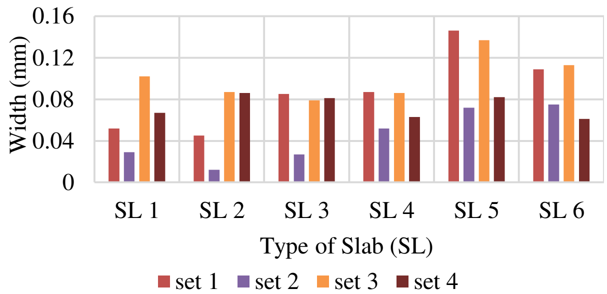


Figure-9. Bar graph of height of Cylinder (CL) for Kossel (PLA).

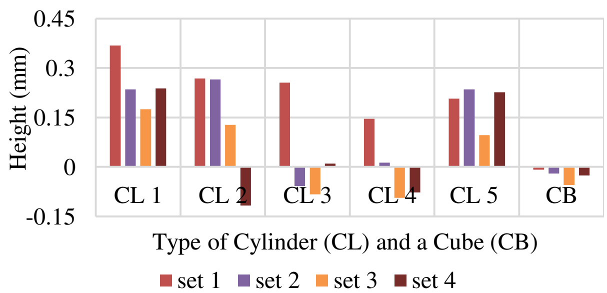
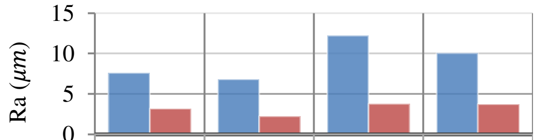


Figure-10. Bar graph of height of Cylinder (CL) for Kossel (PLA).

3.3 Comparison of surface roughness

The result for surface roughness for Mendel Max is presented in graph in Figure-11 and Figure-12. While for Kossel Mini the result is shown in Figure-14 and Figure-14. For Mendel max using ABS in Figure-12, Set 2 has the lowest surface roughness for both horizontal and vertical direction while set 3 gives higher result. This is also similar to the machine using PLA material in Figure-12. On the other hand, the surface roughness for Kossel also has the same pattern as Mendel Max shown in Figure-13 and Figure-14. As the result of for the comparison between the two machines, it is observed that Mendel Max machine is the better as it portrays generally lower surface roughness.

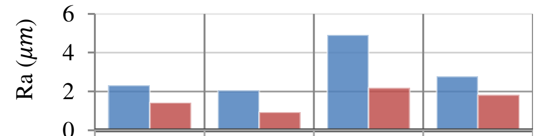


	Set 1	Set 2	Set 3	Set 4
Vertical	7.615	6.807	12.219	10.073
Horizontal	3.212	2.253	3.806	3.762

Set of Experiments

Vertical Horizontal

Figure-11. Bar graph of roughness test for Mendel (ABS).

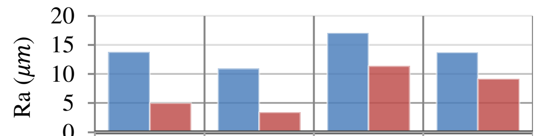


	Set 1	Set 2	Set 3	Set 4
Vertical	2.319	2.053	4.903	2.774
Horizontal	1.428	0.928	2.179	1.818

Set of Experiments

Vertical Horizontal

Figure-12. Bar graph of roughness test for Mendel (PLA).

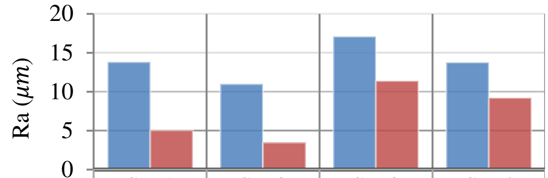


	Set 1	Set 2	Set 3	Set 4
Vertical	13.805	10.946	17.059	13.735
Horizontal	5.029	3.458	11.371	9.194

Set of Experiments

Vertical Horizontal

Figure-13. Bar graph of roughness test for Kossel (ABS).



	Set 1	Set 2	Set 3	Set 4
Vertical	13.805	10.946	17.059	13.735
Horizontal	5.029	3.458	11.371	9.194

Set of Experiments

Vertical Horizontal

Figure-14. Bar graph of roughness test for Kossel (PLA).

CONCLUSIONS

Based on the result, it can be concluded that most of the part features were capable to be built using both open source 3D printer. The 3D printer process parameters influence the dimensional accuracy of Slab features and surface roughness for both Mendel Max and Kossel Mini machines. Generally for lower layer thickness of 0.178 and higher infill density of 30% gives better results. Comparison between the two machines shows that Mendel Max performed better in terms of dimensional accuracy and surface roughness although both machine has similar price range.

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