EFFECT OF PART FEATURES ON DIMENSIONAL ACCURACY OF FDM MODEL

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ABSTRACT

This research investigates the dimensional accuracy of parts produced using the additive manufacturing method of Fused Deposition Modelling (FDM). The fabrication of parts was carried out based on the standard value of process parameter of Stratasys FDM 400MC machine. Parts with four common features of products in different sizes were fabricated in FDM machines using Acrylonitrile Butadiene Styrene (ABS) material. Then, the linear dimension of each part feature was measured with a Coordinate Measurement Machine (CMM) that was repeated for three times. The accuracy of the fabricated part feature was computed by subtracting the nominal dimension of the part (CAD model) with the measured dimension of FDM model. An analysis of sixteen different dimensions of the part feature was identified that parts dimension had a significant effect on the dimensional accuracy of FDM model. In addition, it was found that FDM machine is less accurate in producing a circular shape part such as cylindrical, sphere and hole as the majority of them are out of the machine's tolerance.

Keywords: dimensional accuracy, FDM, part features, additive manufacturing.

1. INTRODUCTION

Dimensional accuracy is vital in any manufacturing process as it is an indication of how close a basic dimension of fabricated parts with the dimension of the ideal product (nominal dimensions). In the sand casting process, the design and generation of the pattern are an important activity in the pre-casting process as it acts as a replica of the final product. Thus, any defect in the pattern will affect the quality of the final product. To achieve a high-quality cast product, casting defects such as dimensional inaccuracy is one of the obstacles to the metal casting industries. To overcome this defect, metal casting industry is shifting from traditional methods of producing patterns, i.e. machining, curving to the more advanced method which is by applying rapid prototyping (RP) technology.

A pattern made of RP such as Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS) is strong enough to replace the traditional wooden patterns [1]. Yet, the dimensional accuracy of any rapid prototype pattern relies on many process parameters such as air gap, layer thickness, raster angle and contour width, and results can vary from part to part or day to day. Thus, consideration must be given to the issues such as the time frame in which measurements are taken, axis to be measured and environmental exposure. The FDM machine developed and manufactured by Stratasys, is available in a number of series, including FDM Maxum, FDM Titan, FDM Vantage and Prodigy Plus 400MC. FDM offers functional prototypes with ABS, PA, polycarbonate and other materials. These thermoplastics are extruded as a semi-molten filament, which is deposited on a layer-by-layer basis to construct a prototype directly from 3D CAD data [2].

Dimensional accuracy of part fabricated by FDM machine has been investigated by several researchers for many reasons. Bakar *et al.* [3] investigated the capability of the FDM Prodigy Plus (Stratasys, USA) to produce parts by applying different process parameters available on the machine. The investigation was based on the capability of FDM machines to produce the common design features of the plastic part. Dimensional accuracy and surface quality were investigated in the study. Dyrbuś [4] carried out an investigation to determine the dimensional errors and surface roughness of the elements made with FDM method. The study focused on the influence of the form of elements (linear and angular dimensions, curvatures) to the accuracy and surface roughness of prototypes. The results of the study showed that FDM method is able to obtain dimensional accuracy of linear dimensions and angle accuracy about 0.1 mm and 0.4° respectively.

Singh *et al.* [5] investigated the effect of part placement (X and Y direction) in the building of dimensional accuracy and mechanical properties of the parts, produced by using SLS process. Nancharaiah et al. [6] investigated the effect of the process parameters; layer thickness, road width, raster angle and air gap on the surface finish and dimensional accuracy. The experiments were designed based on Taguchi's design of experiments with three levels for each factor. The results were statistically analyzed to determine the significant factors and their interactions. They found that layer thickness and road width affecting greatly on both; surface quality and part accuracy whereas raster angle have a small effect. Besides that, air gap has a great effect on dimensional accuracy, but small effect on surface quality.

Rapid prototyping (RP) is a technology that produces physical models by selectively solidifying ultraviolet (UV) sensitive liquid resin using a laser beam. These models can be formed using various techniques. A study was undertaken by Murugesan *et al.* [7] compared the dimensional accuracy and surface details of three prototype models with a 3D STL (standard template

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library) image. They used the STL file to produce three different rapid prototype models, namely; model 1- fused deposition model (FDM) using ABS (Acrylonitrile butadiene styrene), model 2 - Polyjet using a clear resin and model 3-3-dimensional printing (3DP) using a composite material. Measurements were carried out at various anatomical points. For surface detail reproductions the models were subjected to scanning electron microscopy (SEM) analysis. They found that the dimensions of the model created by Polyjet were closest to the 3D STL virtual image followed by the 3DP model and FDM. SEM analysis showed uniform, smooth surface on Polyjet model with adequate surface details.

Nizam *et al*. [8] studied the dimensional accuracy of the skull models produced by Rapid prototyping technology using stereolithography apparatus (SLA). Eight linear measurements were repeatedly made between identified landmarks in each of the original skull and its replica model using an electronic digital caliper. Each of the linear measurements was repeated 5 times and the average was taken to determine the absolute difference and percent difference between the original skull and its replica model. The overall absolute difference between the four human adult skulls and its replica models was 0.23 mm with a standard accuracy of 1.37 mm. The percent difference was 0.08% with a standard accuracy of 1.25%. The degree of error established by this system seems affordable in clinical applications when these models are used in the field of dental surgery for surgical treatment planning.

Pennington *et al.* [9] investigated the dimensional accuracy of parts produced using the rapid prototyping method of fused deposition modelling (FDM). Parts with six features common to products were created on a Stratasys FDM2000 out of acrylonitrile butadiene styrene (ABS) measured with a coordinate measurement machine and digital micrometers. An analysis of 12 different dimensions on parts produced using FDM identified that part size, the location of the work envelope, and envelope temperature had a significant effect on the dimensional accuracy of FDM.

Gregorian *et al*. [10] investigated the present in-plane accuracy of a particular FDM machine using the benchmark “User Part” shows the effect of optimizing Shrinkage Compensation Factors (SCF) on the accuracy of the prototype parts. The benchmark parts were built on the FDM-1650 prototyping machine and a total of 46 measurements were taken on the X and Y planes using a Brown & Sharpe Coordinate Measuring Machine (CMM). The data were then analyzed for accuracy using standard formulas and statistics, such as mean error, standard accuracy, residual error, error, etc. The optimal SCF for the FDM-1650 machine was found to be 1.007 or 0.7%. The dimensional accuracy study is important in determining how accurate the FDM is and this could lead to the understanding the possible application of FDM for pattern generation in the casting process. Thus, this project investigates the dimensional accuracy of parts produced using the additive manufacturing method of Fused Deposition Modelling (FDM). This research was carried out based on the following research question: Are the part feature and its size influence the dimensional accuracy of FDM model?

2. METHODOLOGY

2.1 Developing 3D models of part features

The CAD model of the part features was generated using CATIA V5 solid modelling software as shown in Figure-1. Then, this model was converted into a standard triangular language (STL) format for the fabrication using the FDM 400MC machine. It was sliced into a series of closely spaced in horizontal planes. FDM 400mc uses Insight™ software to import STL files which automatically slices the file, generates the necessary support structures and material extrusion paths or allows the user to manually manipulate any of the model/support structures and/or tool paths. The sliced model and supports were then converted into a Stratasys modelling language (SML) file, which contains actual instruction code for the FDM machine tip to follow specific tool paths, called roads. Then, the SML file was sent to the FDM machine as a build file and fabrication of the part begins. There were no adjustments made to process parameter prior to, or during, the study that would improve the overall accuracy or the quality of a feature. In total, four common parts features, namely; hole, slot, cylinder and sphere with three to five different dimensions were fabricated in this study. Table-1 summarise the detail dimension of each part features.

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Table-1. Signature and dimension of the part feature.

Hole	Diameter (mm)	Slot	Width (mm)	Cylinder	Diameter (mm)	Sphere	Diameter (mm)
HL1	5	SL1	4	CL1	5	SP1	15
HL2	10	SL2	8	CL2	8	SP2	20
HL3	15	SL3	12	CL3	10	SP3	30
HL4	20	SL4	16	CL4	20		
		SL5	20				

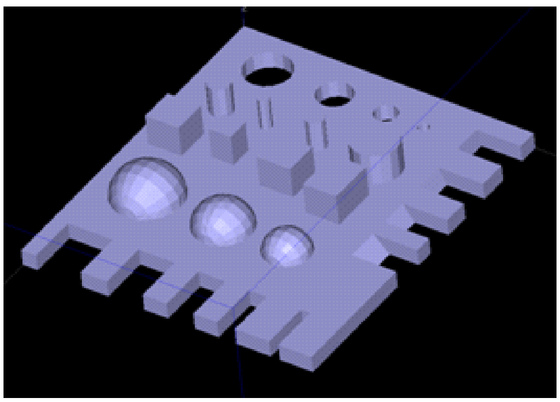

Figure-1. The 3D modelling of parts features.

Figure-2. The FDM model of part features.

2.2 Part features fabrication using additive manufacturing process

In the pre-processing step, the STL file format is prepared to build the RP model, the parameter such as raster orientation, layer thickness, and air gap was set on the machine to build the model. The RP model was built by using the FDM 400MC machine with a working envelope of 355 x 254 x 254 mm. To avoid the influence of FDM process parameters on the accuracy of rapid prototyping models, all the part features were constructed with standard parameters. In this study, the standard size of nozzle, T16 was used to build the model. Table 2 shows the FDM process parameters used in the study. Layer by layer deposition of ABS plastic material supplied in a form of the filament wire through an extrusion head was used to build the model. Finally, the model was cleaned from any unintended material for the linear dimensional measurement. Figure 2 shows the fabricated model of part features.

Table-2. FDM process parameters.

Process parameter	Value
Layer thickness	0.254 mm (standard)
Slice	0.25 mm
Road width	0.51 mm
Delta angle	90°

2.3 Measuring the dimension of part features

The FDM model was measured via Coordinate Measuring Machine (CMM) with a touch probe, model LH40 manufactured by Wenzel with accuracy 5μm as shown in Figure-3. The linear dimension of part features was measured at three different points and averaged. The dimensions were compared to the nominal dimension to get the dimensional accuracy. The results were accessed in the x-axis. According to Nooraini [11] the tolerance in the x-axis is 0.127 mm.

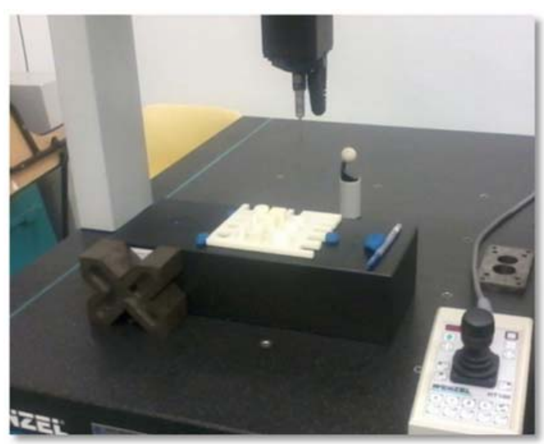

Figure-3. Measurement of part features by using the CMM.

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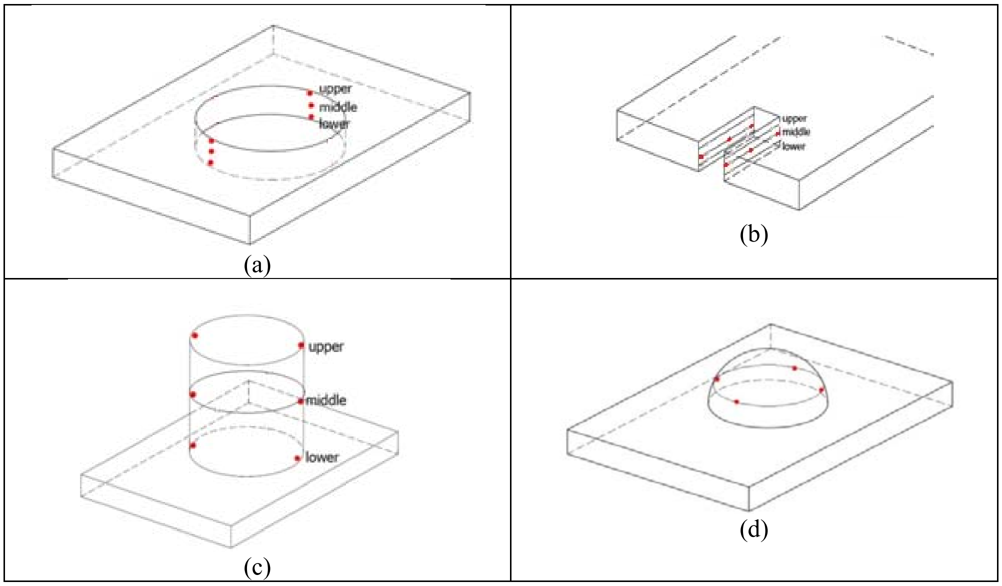

Figure-4. (a) Points of measurement for hole (b) and slot (c) cylinder (d) and sphere.

3. RESULTS

The result of nominal dimension is obtained from the CAD model and the actual dimensions are obtained from FDM model. The average values of an actual dimension are measured to know the accurate dimension of the samples. Then, the dimensional accuracy was calculated using a formula. In general, the accuracy of the hole increases when the diameter of the hole is increased. The highest accuracy of the hole is 99.00% at HL4 (Ø20mm) and the lowest is 93.21% at HL1 (Ø5mm). All the four actual sizes of the hole are smaller than its nominal values (negative deviation), but all the dimensional deviations of holes are exceeding the standard tolerance of the FDM machine which is ±0.127mm.

Five slots with different sizes (4, 8, 12, 16 and 20mm) were fabricated using the FDM machine. The highest accuracy of the slot is 99.97% at SL5 and the smallest is 99.03% at SL1. The result shows that the dimensional accuracy of the slot increases when the width of the slot increased. The actual dimension of the slot with width dimensions of 4mm and 8mm is smaller than the nominal value (negative deviation), meanwhile the slot with the width dimension of 12, 16 and 20mm is larger than the nominal value (positive deviation). However, all the dimensional deviation of the slot is within the tolerance value of the FDM machine (±0.127mm).

The largest dimensional accuracy of the cylinder is 99.18% at CL4 and the smallest is 94.98% at CL1. The result shows that the dimensional accuracy of the cylinder increase as the diameter of the cylinder increased. All the actual dimension of the cylinder below the nominal value of the cylinder diameter (negative deviation) and all of them exceeds the standard tolerance of the FDM machine which is ±0.127mm.

For the sphere, the dimensional accuracy is within the limit of the FDM machine tolerance value of the sphere with a diameter of 25mm. The dimensional accuracy exceeds the tolerance value for the sphere with the diameter of 20mm and 30mm. Based on the results, the highest accuracy occurs when the diameter of the sphere is 25mm. The summary of results is as in Table-2.

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Table-3. Dimensional accuracy of the part features of different sizes.

Part feature		Nominal value	Actual diameter (mm)			Average of actual diameter (mm)	Deviation (mm)	Dimensional accuracy (%)	Remarks
			1	2	3				
Hole	HL 1	Ø5mm	4.6603	4.66	4.6606	4.6603	-0.3397	93.21%	Exceed tolerance
	HL 2	Ø 10mm	9.7412	9.7415	9.741	9.7412	-0.2588	97.41%	Exceed tolerance
	HL 3	Ø 15mm	14.763	14.7626	14.7633	14.763	-0.2370	98.42%	Exceed tolerance
	HL 4	Ø 20mm	19.7997	19.7995	19.7999	19.7997	-0.2003	99.00%	Exceed tolerance
	SL 1	4 mm	3.9445	3.9443	3.9944	3.9611	-0.0057	99.03%	Within tolerance
	SL 2	8mm	7.9615	7.9613	7.9614	7.9614	-0.0386	99.52%	Within tolerance
	SL 3	12mm	12.0177	12.0175	12.0177	12.0176	0.0176	99.85%	Within tolerance
	SL 4	16mm	16.0326	16.0322	16.0324	16.0324	0.0324	99.80%	Within tolerance
	SL 5	20mm	20.0051	20.005	20.0052	20.0051	0.0051	99.97%	Within tolerance
Cylinder	CL1	Ø5mm	4.7492	4.7489	4.7493	4.7491	-0.2509	94.98%	Exceed tolerance
	CL 2	Ø8mm	7.6891	7.6893	7.6887	7.689	-0.3110	96.11%	Exceed tolerance
	CL 3	Ø10mm	9.7307	9.7305	9.7307	9.7306	-0.2694	97.31%	Exceed tolerance
	CL 4	Ø20mm	19.8361	19.8359	19.8362	19.8361	-0.1639	99.18%	Exceed tolerance
Sphere	SP1	Ø20mm	19.6561	19.656	19.6561	19.6561	-0.3439	98.28%	Exceed tolerance
	SP2	Ø25mm	25.0885	25.0883	25.0886	25.0885	0.0885	99.65%	Within tolerance
	SP3	Ø30mm	29.4997	29.4997	29.4996	29.4997	-0.5003	98.33%	Exceed tolerance

4. CONCLUSIONS

Based on the accuracy analysis, the FDM machine is less accurate in fabricating the circular shape such as a sphere, cylinder and hole as its dimension have exceeded the tolerance value (±0. 127mm) of FDM machine. The machine can produce a high accuracy of square shape parts such as slot as all of them are within the tolerance limit of the FDM machine (above 99% accuracy). In conclusion, for fabricating a circular shape part, the nominal value must be set, over sizes than the intended dimension as to compensate its negative dimensional deviation. However, the exact value is dependent on the compensation factor of a particular part feature, but it is out of the research scope. Since the dimensional accuracy of FDM part is influenced by process parameters, the significance process parameters need to be determined and optimized prior to fabrication of the test model as to obtain the highest performance of the FDM machine. It can be said that part features and its dimension will influence the dimensional accuracy of FDM parts.

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