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Analysis of Shrinkage Compensation Factor (SCF) of FDM uPrint SE for Accuracy Enhancement

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Abstract: This paper scrutinizes the shrinkage of a component manufactured using Additive Manufacturing (AM) and emphasizes mainly on the change in dimensions of a AM component after printing. The physical model can be easily manufactured by having the CAD data in STL format for real time AM. However, deviation of product size in CAD model transforming to physical model will be existing due to the deformation of the material mainly because of shrinkage. So here an analysis is carried out to find the optimal shrinkage compensation factor (SCF) of the part manufactured by Fusion Deposition Modelling (FDM) machine which uses ABS P430 as the base raw material. To achieve the latter a suitable model part is considered taking all the dimension and geometrical constraints which are essential for finding SCF and through regression analysis with the help of Co-ordinate Measuring Machine (CMM) and Solid Works modeling, SCF is calculated. Based on the experimental study, dimensional accuracy of the part significantly improved after applying the SCF value of 0.068% which is assumed to be constant in all directions.

Keywords: Rapid prototyping, Additive manufacturing, Shrinkage Compensation factor (SCF), Accuracy in RP, Fused deposition modeling (FDM)

1. Introduction

Additive manufacturing (AM) is the emerging technology for manufacturing prototypes of functional parts with complex geometry which is like a boon for the industry/ R&D people to produce parts relatively in lesser time and with the ability to visualize the geometry. The AM technology is letting the user to produce complex geometries like prosthetics and implants which can be accomplished by having the scan file in. STL format which is supported in AM machine [1].

The prototypes tend to substantially inspect and detect errors during the design stage, allowing further to compute the mass properties of assemblies and subassemblies [2]. But the manufacturing time is comparatively lower depending upon the size and complexity of the geometry when compared to the traditional manufacturing processes. The layer by layer nature of the process enables the user to produce complex geometries without increasing the cost of production. This technique was developed in the year 1980, since that time it's been revolutionary in the manufacturing field [3].

One of the major benefits of AM is to make geometries with near perfect strength-to-weight ratios as functional performance for real time applications in automobiles, aircrafts industries and can be very useful for presenting design in client presentations, bid proposals and regulation certification [4][2]. Less manufacturing and maintenance costs is required for lighter products but the material used in FDM are thermoplastics which may affect on the environment. In

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economical point of view weight plays a crucial role in success of the industry. The weight can be achieved by reducing the part weight during the design stage itself by considering other factors which effects the latter [5].

The most important challenge for any manufacturing industry is to maintain the accuracy of the prototypes produced by AM technology. However, they tend to change from one phase to another phase therefore the parts have relatively smaller dimensional change when compared with the design dimensions [2]. This may create difficulties during the assembly process because of the poor accuracy of the technology and they tend to warp or shrink from its designed dimensions imposing the user to prototype the parts several times in order to get the component with preferred dimensions or slightly inaccurate parts.

1.1 Dimensional Accuracy

Dimensional accuracy of a component represents the degree of agreement between the manufactured dimension and its designed specification [6]. Dimensional accuracy of the AM parts is quite an obstacle preventing it to be employed in primary production process [7]. The parts prepared with extrusion AM processes namely FDM depends on the product design parameters and filament properties but aesthetics being one of the considerations, properties of the finished part can play a challenging role in the applications where fit and form is significant. [8]

AM manufactured parts have poor accuracy and surface roughness in comparison with the conventional machining operations [9]. Tong et al (2008) observed in a study to improve the accuracy of an AM process, and stated about two common methodologies to be followed. The first one is the "Error avoidance", which tends to remove the source of an error and the second one is "Error compensation", which attempts to withdraw the effect of an error without eliminating its source. A lot of research [10-16] was conceded in the past for improving the accuracy of the Rapid Prototyping (RP)/AM parts which falls under the first methodology "Error avoidance" and focused on the different features of the RP process. These include correction of data file, improvement of slicing technique, generation of support structure, planning of tool path, and optimization of build orientation etc. and a good process planning can greatly enhance the degree of accuracy of the machine to some range, but current RP technology is still producing parts with substantial errors, to diminish the errors, resulting error compensations are used [17].

Some of the researchers have dedicated their research efforts to improve the accuracy of RP technology by eliminating the STL format, errors are also under investigation such as NURBS and direct slicing methods [16]. Part build time and output accuracy also significantly affected by many factors. However, only few selected parameters are controlled by the users. These controllable parameters appear to be easy to change, but minor changes in the parameter values will have a diverse effect on the output. Additionally, changing the combination of levels or factors turns into a predicting game which will give the user an indication after numerous trials of experimentations what settings should be opted for different circumstances [16].

1.2 Shrinkage (SCF)

The shrinkage is always found to have a diverse effect on the part accuracy in AM among all kinds of errors, during thermal cycles the material unveils the shrinkage which differs from material to material. The Fused Deposition Modelling (FDM) parts always exhibits shrinkages because of the latter reason. During the data interpretation the shrinkage can be compensated by finding the shrinkage compensation factor (SCF) after calibrating the shrinkage experimentally [18]. This comes under the first methodology "Error Compensation" the purpose of SCF is to compensate the source of error not eliminate those [17], here the users are allowed to set a SCF before manufacturing the part which will be different for different directions to fix the shrinkage effect [19].

The SCF can be found by producing the stock test samples and arriving for a linear relationship between the nominal dimension and produced dimensions but while dealing with the latter fundamental assumptions is usually made. That is shrinkage is orthotropic and the shrinkage compensation scaling factors are constant for all X, Y and Z dimensions [18]. Therefore, finding the SCF will provide optimal accuracy of rapid prototypes manufactured in industries. Here an analysis is carried out using one of AM machine FDM in relation to SCF. The following section provides an outline of FDM process that's used in this work.

1.3 Fused Deposition Modelling (FDM)

Fused Deposition modelling machine (FDM uPrint SE), built by Stratasys is a solid based rapid prototyping technology introduced in the year 1992 which is the global leader of installed RP Systems, shipping 44% of industrial RP systems in the world [9]. In this research it was used for fabricating the prototype and the build volume is 8×6×6 inches capable of producing hard solid complex prototypes which can be used in variety of applications. ABS P430 filament of diameter 1.78 mm is used in this FDM technology.

The filament is heated above its melting point temperature and extruded through the nozzle on to the build tray and the platform is lowered every time in order to form a new layer on top of the previous layer to build the solid prototype. Here the 3D Model created in any one of the CAD software saved in the Stereo Lithography format STL (Surface Tessellation Language) is exported to software (CatalystEx) which is specially developed for handling the STL file and also it is interfaced with the FDM for producing final prototype.

The CatalystEx program uses an algorithm to slice the three-dimensional body into two dimensional layers then the FDM Machines downloads the model data as an SML (Stratasys Machine Language) file [20]. The machine extrudes a thin film of thermoplastic material (ABS P430) through the heated nozzle on to the build tray as layer by layer in the X-Y plane. Every slice will have equal height.

To produce each layer the extrusion head fills the outline of the layer first and then fills according to the raster. The raster fill type is of straight-line segments which are linked together and uniformly spaced. Each layer will be fused before another layer is laid on the previous one and solid model will be created. The ABS P430 is a thermoplastic which is durable enough as like of production parts. Its advantages are impact resistance, high tensile strength, heat resistant, chemical resistant, and scratch resistant and its downsides are limited weather resistance, low resistance to solvent [20].

2. Methodology/ Fabrication

In order to examine the build precision of the prototyping machine, an RP part was manufactured in the FDM uPrint SE which covers the extent of build platform and allowing for the measurements of the parts in all the three directions. This specific part (Fig.1) was chosen since it holds: (1). independent surfaces, (2). a variety of balanced measurements and (3). virtually equal number of inside and outside dimensions. These three features provide the necessary data for performing measurements. This is certainly, for the reason it reduces the bias on specific measurements, and provides the critical details for producing the part [2].

2.1 The Printing Process

The steps involved in printing are as given below:
  i.   Conversion of SOLIDWORKS file into STL format
  ii.   Selection of Part Orientation
  iii. Feeding of parameters to the printer using CatalystEx
  iv.   Post-processing

Support material: The orientation with the least amount of support material consumed is highly beneficial. The estimated time for manufacturing the prototype and material consumption is listed in table 1.

Table 1 - CatalystEx output data

Estimated Build Time	3hr 50 min
Model Material Volume	101600 mm^3
Support Material Volume	5735.472 mm^3
Number of Layers	286

2.2 Post-processing

The printed part is allowed to cool to room temperature after which the water-soluble support material (SR-30) is removed by immersing the component in a bath containing NaOH solution. After complete dissolution of the support, the component is removed and allowed to dry.
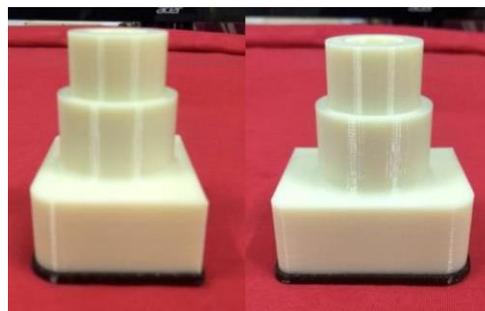

Fig. 1 - (a) Printed Component- side view; (b) Printed Component- front view

2.3 Dimensional measurement

After post-processing, the component is blow-dried to remove any traces of moisture present. The component is measured for variations in dimensions. Since, the component has both linear and curved contours, precise and accurate measurement is required. The most suitable machine to measure all component dimensions is the Co-ordinate Measuring Machine (CMM) as shown in Fig 2.

Fig. 2 - Accurate Spectra CMM during measuring dimensions

Balloon numbers (1 to 20) shown in the figure 3 gives the dimensional values taken with respect to the reference planes. These dimensions with balloon numbers were considered to be the most critical dimensions that are needed for calculating the shrinkage factor.
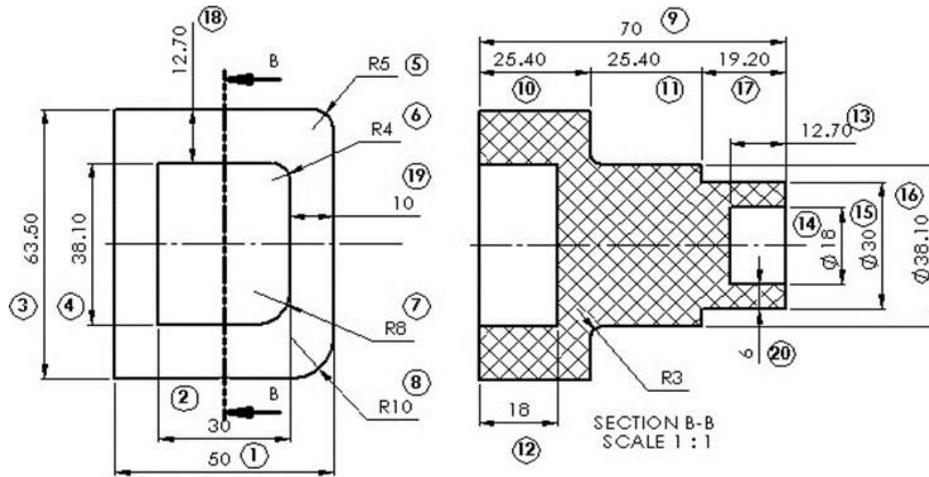

Fig. 3 - Ballooning of dimensions

These balloon numbers were taken based on the geometrical profiles. In connection to the geometrical profiles, dimensions such as inside and outside radius, inner and outer diameters, length and inner bore, etc. values are taken. A set of 20 balloon numbers were considered for this paper.

Table 2 describes about the balloon numbers measured in CMM. The deviations were observed and identified that most of the dimensions had deviated from the nominal value. This was mainly due to the shrinkage and moisture content of the component occurred during the phase change and post processing respectively. For example, if we consider balloon number 1, has a deviation of -0.112 mm from its nominal dimensions of 50 mm, but if we consider radius dimensions, that is balloon number 5,6,7,8 has increased from its nominal dimensional values of R5, radius R4, radius R8 and radius R10 mm respectively. So, to overcome all these deviations, calculation of Shrinkage Compensation Factor (SCF) is significant.

Table 2 - Measured CMM Values

Balloon No	Nominal Dimension (mm)	CMM Value (mm)	Deviation (mm)	% of Deviation
1	50	49.888	-0.112	-0.224
2	30	30.233	0.223	0.776
3	63.5	64.052	0.552	0.869
4	38.1	38.238	0.138	0.362
5	R5	5.162	0.162	3.240
6	R4	4.639	0.639	15.975
7	R8	8.1335	0.1335	1.668
8	R10	10.264	0.264	2.64
9	70	70.356	0.356	0.508
10	25.4	25.457	0.057	0.224
11	25.4	25.573	0.173	0.681
12	18	18.056	0.056	0.311
13	12.7	12.793	0.093	0.732
14	Ø18	17.960	-0.04	-0.222
15	Ø30	29.849	-0.151	-0.503
16	Ø38.1	37.925	-0.175	-0.459
17	19.20	19.338	0.138	0.718
18	12.7	12.560	-0.14	-1.102
19	10	9.850	-0.0456	-1.5
20	6	6.547	0.547	9.116

3. Shrinkage Compensation Factor - Calculations

To calculate the SCF, 15 measurements were taken in the X and Y plane. These measurements were given as input into an Excel program and from these points, 7 outside and 8 inside dimensions were calculated as shown in figure 4. After obtaining this data, statistical equations were used to determine the overall accuracy of the part.
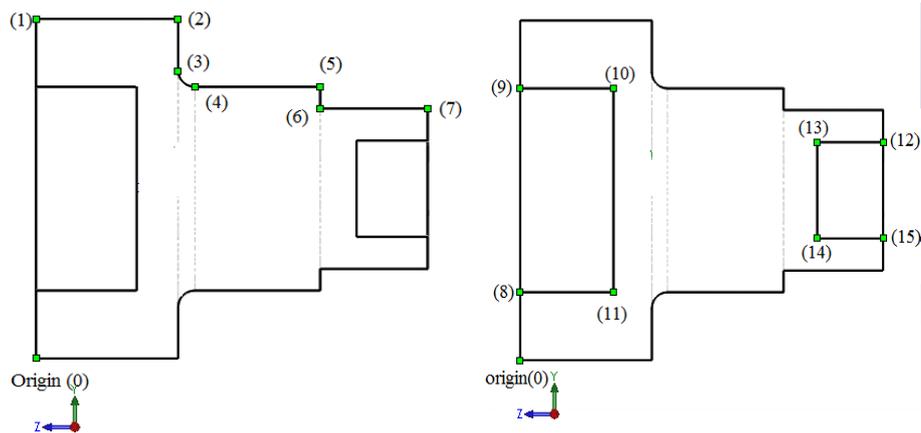

Fig. 4 - Representation of Inside and Outside Dimensions in SolidWorks

3.1 Error

First the dimensional data is converted to the differences relative to the CAD dimensions. The error in each of the dimensions is calculated by,

$$Actual\ error = (a - c)$$

Where 'a' is the measured dimension and 'c' is the CAD Dimension.

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3.2 Slope

Many statistical data analysis computations were derived from the 8 inside dimensions and 7 outside dimensions. The slope of the best-fit regression line of actual error vs. ideal dimension was calculated to get an idea of the accuracy of the part and to determine the new SCF. The slope is determined by,

$$Slope = (\frac{(7+8)\times(A+B) - (C-D)\times(E-F)}{constant}) \qquad [2]$$

Where,

A = Σ (Inside Ideal Dimension) *(Error)

B = Σ (Outside Ideal Dimension) *(Error)

C = Σ (Outside Ideal Dimension)

D = Σ (Inside Ideal Dimension)

E = Σ (Error Outside Dimensions)

F = Σ (Error Inside Dimensions)

The constant is determined by,

$$Constant = ((7+8)\times((\Sigma G^2)+(\Sigma H^2)) - (\Sigma(H)-\Sigma(K))\times(\Sigma(M)-\Sigma(K))) \qquad [2]$$

Where,

G = Inside Measured Dimension

H = Outside Measured Dimension,

K = Inside Ideal Dimension,

M = Outside Ideal Dimension.

3.3 Measurement of dx and dy:

This process of finding the slope, constant, and intercept is performed for both the x and y dimensions and the two results are averaged at the end. The measurement of dx and dy for both inside ideal, inside actual, outside ideal and outside actual dimensions done using solid works measurement tool as shown in figure 5.
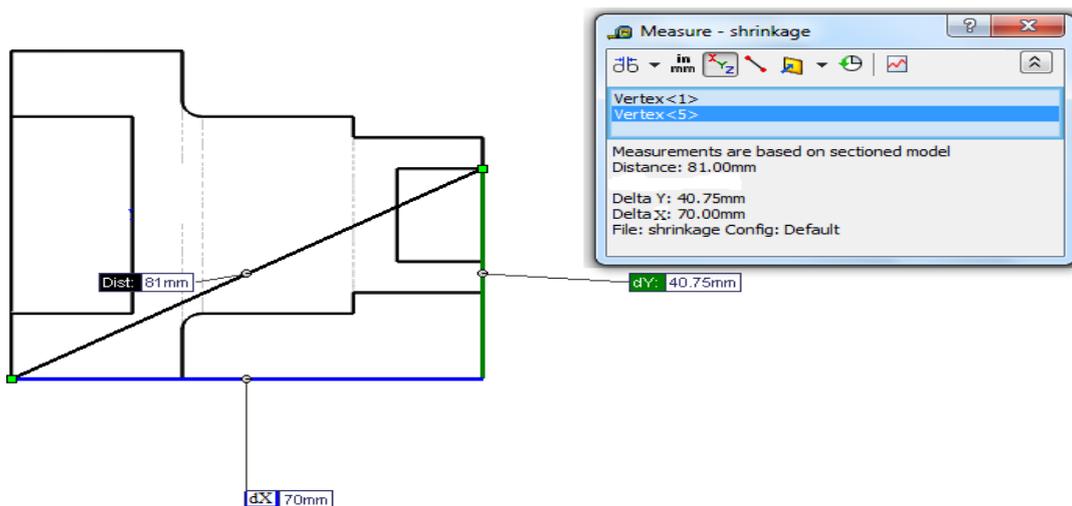

Fig. 5 - Representation of measuring dx and dy using solid works measure tool

The below table 3 describes about the measurements like inside, outside measured dimensions and inside, outside ideal dimensions required for calculating the constant values along the X and Y plane which were measured using CMM. In later stage these parameters are used for calculation of optimum value of SCF.

Table 3 - Calculation of constant on X plane and Y plane

G	G²	H	H²	K	M
0	0	0	0	0	0
0	0	25.46	648.2116	0	25.4
18.06	326.1636	25.46	648.2116	18	25.4
18.06	326.1636	28.46	809.9716	18	28.4
70.37	4951.937	51.03	2604.061	70	50.8
57.67	3325.829	51.03	2604.061	57.3	50.8
57.67	3325.829	70.37	4951.937	57.3	70
70.37	4951.937	-	-	-	-
	ΣG² =17207.86	ΣH = 251.81	ΣH² =12266.45	ΣK =290.6	ΣM =250.8

Constant (X) = 440570.808

G	G²	H	H²	K	M
12.56	157.7536	64.05	4102.403	12.7	63.5
51.49	2651.22	64.05	4102.403	50.8	63.5
51.49	2651.22	54.15	2932.223	50.8	53.8
12.56	157.7536	51.15	2616.323	12.7	50.8
41.01	1681.82	51.15	2616.323	40.75	50.8
41.01	1681.82	46.95	2204.303	40.75	46.75
23.05	531.3025	46.95	2204.303	22.75	46.75
23.05	531.3025	-	-	-	-
	ΣG² =10044.19	ΣH = 378.45	ΣH² = 20778.28	ΣK = 254	ΣM = 375.9

Constant (Y) = 447166.595

Table 4 describes about the measurements like inside, outside ideal dimensions and inside error, outside error dimensions required for calculating the slope along the X and Y plane and these parameters are used for calculation of optimum SCF value in the later stage.

$$\text{Average Slope} = ((-0.0052566-0.0081059)/2) = -0.00668125$$

Finally, the SCF is derived. The SCF is an indication of the numerical percentage of how small or large the user part is compared to the actual CAD dimensions. The SCF equation incorporates the initial shrinkage compensation factor, which was used in the beginning of the build process and the calculated SCF is constant for all the three directions. The equation to determine the SCF is,

$$\text{New SCF} = ((1 - (\text{Slope})) \times (1 + \text{SCF(X)OLD})) \qquad [2]$$

$$= 1 - (1 - (-0.00668125)) \times (1 + 0)$$

$$\text{New SCF} = 0.00668 \text{ (or) } 0.668\%$$

Table 4 - Calculation of slope along X plane and Y plane

Inside ideal dimension dx	Error	dx * error	Outside ideal dimension dx	Error	dx * error
0	0	0	0	0	0
0	0	0	25.4	-0.06	-1.524
18	-0.06	-1.08	25.4	-0.06	-1.524
18	-0.37	-6.66	28.4	-0.06	-1.704
70	-0.37	-25.9	50.8	-0.23	-11.684
57.3	-0.37	-21.201	50.8	-0.23	-11.684
57.3	-0.37	-21.201	70	-0.37	-25.9
70	-0.37	-25.9	-	-	-
D = 290.6	F = -1.6	A = -101.942	C=250.8	E = -1.01	B = -54.02

Slope (X) = -0.0052566

Inside ideal dimension dy	Error	dy * error	Outside ideal dimension dy	Error	dy * error
12.7	0.14	1.778	63.5	-0.55	-34.925
50.8	-0.69	-35.052	63.5	-0.55	-34.925
50.8	-0.69	-35.052	53.8	-0.35	-18.83
12.7	0.14	1.778	50.8	-0.35	-17.78
40.75	-0.26	-10.595	50.8	-0.35	-17.78
40.75	-0.26	-10.595	46.75	-0.2	-9.35
22.75	-0.3	-6.825	46.75	-0.2	-9.35
22.75	-0.3	-6.825	-	-	-
D=254	F=-2.2	A=-101.388	C=375.9	E=-2.55	B=-142.94

Slope(Y) = -0.0081059

4. Results

The intention of the work is to find out the ideal shrinkage compensation factor (SCF) of the part produced through FDM machine for manufacturing the most precise parts. The calculated SCF should be applied in the interfacing software's of the RP machine for compensating the accuracy of parts after shrinkage. The figure 6 shows the comparison between the measured CAD dimensions versus actual dimension of FDM produced part.
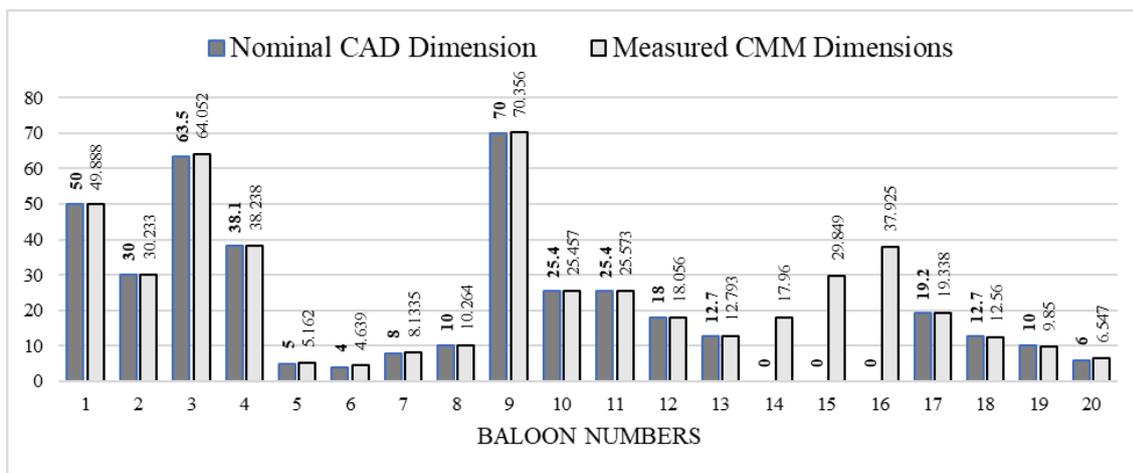

Fig. 6 Comparison between the Nominal CAD dimensions and Measured CMM Dimensions

Using the CMM. These errors were revealed due to the shrinkage issue in the FDM U print SE. The application of SCF value in the interfacing software yielded parts with higher accuracy than before.

5. Conclusion and Recommendations:

As the focus of this research was to come up with an optimal shrinkage compensation factor for FDM Uprint SE) and manufacture an accurate part. From the examined data, the best SCF for the FDM Uprint SE found to be which is constant in all directions:

$$SCF = 0.00668, \text{ or } (0.668\%)$$

In future further improvement in accuracy of AM parts can accomplished by changing temperature and build speed during the build process and these parameters can aid in reducing the amount of warpage that the part undergoes due to the amount of time its exposed to heat [2]. Additionally, the user should able to give inputs in both X and Y directions in the machine interfacing software rather than giving only one common input for all directions [2].

As the machine (FDM uPrint SE) used in this work for prototyping has fixed layer thickness of 0.254 mm that means the nozzle diameter cannot be changed therefore this will have greater effect on the accuracy of the part building along the Z direction compared to the X and Y directions [21].The identified error can be fixed by having an FDM machine with a possibility to change the layer thickness, temperature and build speed or STL file optimization. On assumption the parts with round off dimension with reference to the layer thickness can greatly improve the accuracy of the part but nominal dimension values have to be sacrificed, so the addition of all these inputs will let us to produce an accurate part that is further closer to its desired dimensions.

Lastly, the support material that is presently in practice with this 3D printer must be altered since it is hard to eliminate. Support material with water soluble characteristics would save valuable post processing time in cleaning and removing it.

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