MULTI OBJECTIVE OPTIMISATION OF BUILD ORIENTATION FOR RAPID PROTOTYPING WITH FUSED DEPOSITION MODELING (FDM)

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Abstract

The ability to select the optimal orientation of build up is one of the critical factors since it affects the part surface quality, accuracy, build time and part cost. Various factors to be considered in optimisation of build orientation for FDM are build material, support material, build up time, surface roughness and total cost. Experiments were carried out and results are analysed for varying build orientation for primitive geometries like cylinder. An appropriate weighting factor has been considered for various objective functions depending on the specific requirement of the part while carrying out multi-objective optimisation. These analyses will help process engineers to decide proper build orientation.

1. INTRODUCTION

The main advantages of Solid Freeform Fabrication (SFF) processes are that they don't require any part specific tooling and completely automated. In Fused Deposition Modeling (FDM) a three dimensional CAD model of the part is sliced into layers and the numerical data on the geometry of layers is then fed into the fabrication unit, which builds each layer sequentially until the entire part is fabricated.

SFF processes are conducive to the concept of distributed design and manufacturing where in process providers will list their constraint on website and designers will perform manufacturability analysis for their design. This helps in reduction time for redesign when manufacturing constraints are violated.

Until recently SFF processes were primarily used for creating prototype parts. Increasingly SFF processes are being considered for creating functional parts. In such applications, SFF can either be used for creating tooling i.e., patterns for casting, low volume molds, etc. or directly creating the functional part itself. In order to create defect free functional parts, it is extremely important to fabricate the parts with the best part build orientation within allowable dimensional and geometric tolerances.

Fused deposition modeling (FDM) is a rapid prototyping (RP) process that fabricates parts layer by layer by deposition of molten thermoplastic material (ABS) extruded from a nozzle. A proprietary software, Quickslice, processes the STL file to create the slices and roads and commands the FDM machine to generate layers of specified thickness and road width from the nozzle of a liquefier head. In general, the outer perimeter of the layer is laid down first, after which fill roads are created to fill the solid areas inside each layer. The types of fill patterns available are the raster, the contour or a combination of both. The layers are deposited continuously at any part build orientation to build the part bottom up. Geometric accuracy of components is one of the most important quality characteristics in layered manufacturing processes on which most rapid prototyping (RP) techniques are based. Layered manufacturing is an approximate fabricating process in which the final geometric error of the physical part is affected, not only by the approximation technique used, but also by the fabrication process.

In spite of the many potential advantages of layered manufacturing (LM), however, the surface quality of the fabricated 3D object is inferior to that of the general NC machined part.

This is due to the stair stepping effect, which comes from stacking layers with some level of thickness. This effect is prominent on the inclined surfaces of the fabricated parts. Also, most LM technologies utilize support structures to prevent deflection when stacking the layers. After detaching the supports from the part in the post-process, many support removal burrs remain on the surface of the part. That is, the stair stepping effect and support removal burrs are the main causes of poor surface quality in LM parts. In order to improve the surface quality of the LM processed part, many attempts have been made to select the best build orientation. Conventional manual finishing such as hand grinding has mainly been used because it is simple and quick.

In addition, Cobb et al. [1] proposed using more efficient finishing techniques such as abrasive blasting, barrel tumbling, and vibration finishing. Also, Williams and Melton [2] developed a finishing process for SL processed parts using abrasive flow machining (AFM). Statistical analysis was used to determine the effect of the AFM finish according to media grit size, media pressure, build orientation and other variables. The result showed that the main improvements were achieved with one or two AFM cycle. However, these machining approaches are inevitably harmful to the original part boundaries, and excessively time consuming. Also, theoretical researches using the attributes of the LM process have been done. Reeves and Cobb [3] presented a mathematical model of the surface roughness of SL processed parts as a design tool for determining optimum build orientation and planning post-process finishing operations in order to reduce inherent surface deviations. Lang et al. [4] considered surface quality, build time, and support structure to illustrate desirable fabrication orientation in SL. Criteria for dealing with the three factors was proposed. The surface quality is estimated by maximizing or minimizing the area of non-stepped surfaces. Alexander et al. [5] proposed methods to calculate the cost and orientation of parts and demonstrated how these two problems were associated. They analyzed the orientation problems and the cost model with SL and FDM processed parts from a general point of view, so that the solution could be applied to a broad spectrum of LM processes. Rattanawong et al. [6] developed a part-build orientation system for RP by considering the volumetric errors encountered in parts during the building process. The technique applied a primitive volume approach, which considered that complex parts were constructed from a combination of basic primitive volumes. The system displayed the volumetric errors graphically and recommended the best orientation to minimize these errors for the entire part. Thrimurthulu et al. [7] proposed an approach that could determine the optimum part deposition orientation for enhancing part surface finish and reducing build time in the FDM process. They formulated a single optimization problem by adding two objectives, average part surface roughness and build time, after weighting them to represent preferences. In calculating average surface roughness, a stochastic model was used by approximating the layer edge profile as parabola. Also, the average roughness value of the downward facing surface was approximated by 1.2 times. Byun and Lee [8] presented a methodology about determination of the optimal build direction for different RP processes using multi-criterion decision making. They considered surface roughness, build time, and part cost as criterion in determining the optimal orientation. The multi-criterion decision making was preformed by simple additive weighting method. In most of these researches, the optimal fabrication direction is determined by priority among surface accuracy, build time, and support structure for a specific LM. Even when surface accuracy is a priority, calculations of surface roughness is performed by simple or approximated expressions. That is, actual roughness distribution factors such as the support removal burrs and material property are not considered in determining fabrication direction. Also, examples and applications for comparative simple geometry CAD model have been mainly presented. As mentioned above, excessive roughness of the LM processed part surface due to support material removal brings about a crucial weak point in practical application. In general LM, post-machining process to improve the surface quality is the most time consuming except for part building process. However, it is difficult to find some specific attempt which theoretically deals with the post-machining minimization in LM.

The aim of the present study is developing the decision support system to help the user or designer for choosing the optimal build up direction of a part. The best orientation is calculated considering four major factors : Accuracy, Surface quality, Build time, and part cost. To choose the best orientation, the orientations are ranked according to the scores of orientations. The scores are obtained using the simple additive weighting method

METHODOLOGY

Chung et. al [9] presents a multi object approach for determining the optimal part building orientation. Part accuracy is used as the primary objective while build time is used as a secondary. The optimal orientation is chosen in the value of the primary objective function is maximized. If the values in the other orientations are within a certain range from the maximum as specified by the user the secondary objective, build time is considered. The build time is estimated from the no. of slices made for a part. Frank & Fadell [10] proposed an expert systems that considers surface finish, build time and support generation. Hur & Lee[11] developed an algorithm to calculate the staircase area, additionally, the total build time and volume of support structure were calculated. The optimal part orientation is determined based on the user's selections of primary criteria. Allen & Dutta [12] describe a method that determines orientation of an object with minimal support structure. If two orientations required equals surface areas of contact, the orientation with a lower center of mass would be chosen.

Pham et.al [13] considered part cost, build time, problematic features, optimally orientated features and support volume. By multiplying score of each candidate by the weights assigned intuitively for each criterion, the orientation with the highest score selected has the desirable build up direction. Masood et.al [14] developed an algorithm to calculate the amount of volumetric error caused by slicing a CAD model. Xu et.al [15] considered build in accuracy as one of the criteria that includes the sum of the staircase volume the oversize volume under the overhang area and trapped volume. He has given more emphasis on build cost. This paper builds the model with accuracy consideration in addition to above criteria.

Mathematical Model

Surface roughness (Ra) is measured using Mitutoyo Handy surf. It has been observed that there is a gap between deposited road if the build orientation is in between 70 & 90 degree angle build orientation. The surface profile clearly indicated that the geometry of build edge profiles can be approximated as parabola. However the surface profile around 90 degree build orientation is idealized as a semicircle instead of parabola. Hence the surface roughness in the range of ($70^\circ \leq \theta \leq 90^\circ$) is calculated by assuming linear variation between these values. The measured values of surface roughness is found to be following a stochastic model where in surface roughness is directly proportional to thickness of the slice and inversely proportional to $\cos\theta$ with a proportional constant of 70. However surface roughness value for 90 deg. Is assumed to be ($112^* t$) where t is the slice thickness.

Cylindricity is considered as the major factor for considering accuracy of cylinder which is used as part in this work, Cylindricity is a condition where all points on the surface of a cylinder are equidistance from the axes. Unlike circularity, the cylindricity tolerance applies to circular and longitudinal elements at the same time[16]. Cylindricity is a composite form tolerance that simultaneously controls circularity, straightness of a surface, and taper of cylindrical features.

The build time, build material requirement and support material requirement is taken directly from FDM machine log file. The approximate part cost for each orientation can be estimated using the equation.

Total cost = (Machine hr. cost/min * Build up time) + (Build material * Build material cost)
+ (Support material * Support material cost)

In the present case Machine hr cost = $10 / hr
Build material cost = $ 0.2169 / cc
Support material cost = $ 0.1735 /cc.

To determine the best alternative based on conflicting criteria's are considered. Each criterion is assigned with a weight. A final appraisal score A_i for each ith alternative is computed by multiply the jth criterion importance weights.

The Build time factor, total cost factor, roughness factor and fit & form factor are obtained by calculating the average value for each of the criteria and by dividing build time, total cost, roughness and cylindricity for each build orientation with the average value

The preference is then ordered according to the score. The alternative that has the lowest score is chosen as the best. The weighting factor ratio for each is used to indicate the relative importance of four criteria's in a specific application.

W_1, which represents weighting factor for form accuracy is more important than other criteria is normalized as {0:0.1:0.4:0.5}

W_2 which represents weighting factor for surface quality is more important than other criteria is normalized as {0.05 : 0.15 : 0.5 : 0.3}.

W_3, which represents weighting factor for total cost is more important than other criteria is normalized as {0.2 : 0.6 : 0.1 : 0.1}.

W_4 which represents weighting factor for production rate is more important than other criteria is normalized as {0.8 : 0.2 : 0 : 0}.

RESULTS & DISCUSSION

Cylinder of 20mm diameter was fabricated using Fused deposition Rapid prototyping machine (FDM SST) with varying orientation angle 0 to 90 degree at 5 degree interval. The dimensions and accuracy are measured with Mitutoyo coordinate measuring machine (CMM), The surface roughness is measured with Mitutoyo Handy surf. The experimental results are used to calculate the number of layers, total cost, build time, build material requirement, support material requirement, surface roughness and accuracy for varying build orientation at 5 degree interval. The results are depicted graphically and also in form of table.

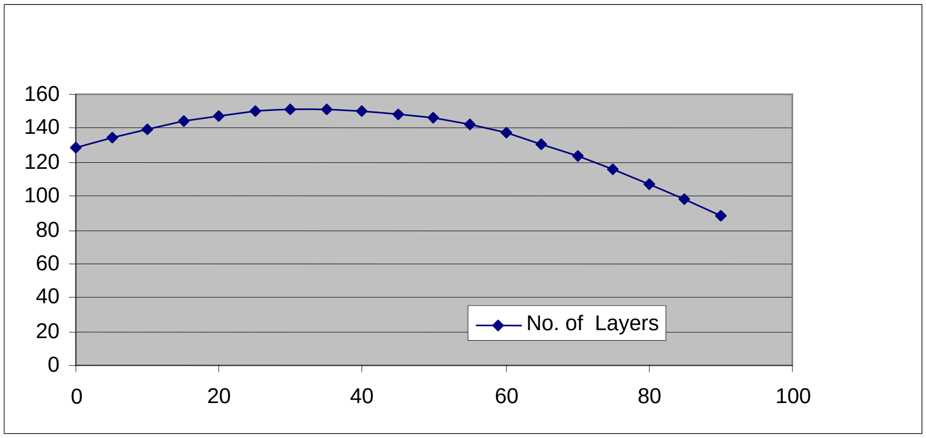

Fig.1. Number of layers Vs Build orientation angle

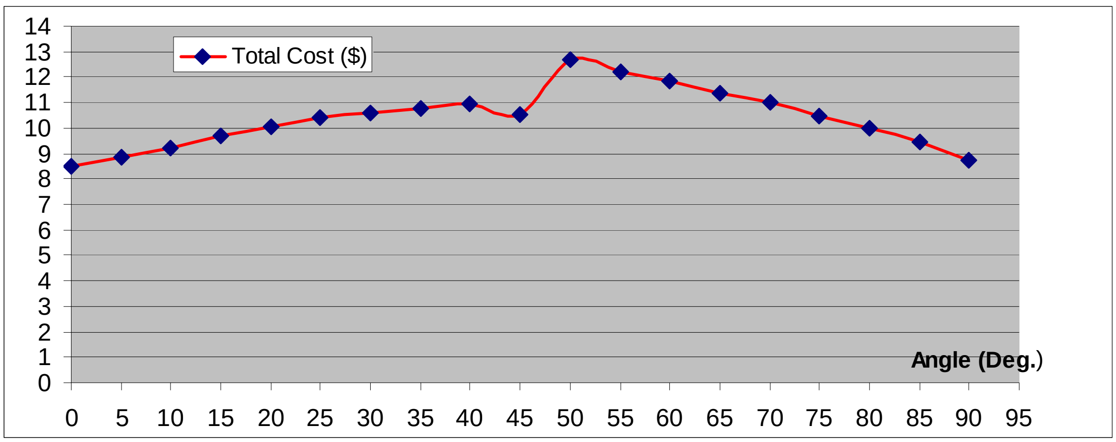

Fig 2. Variation of total cost with Build orientation angle

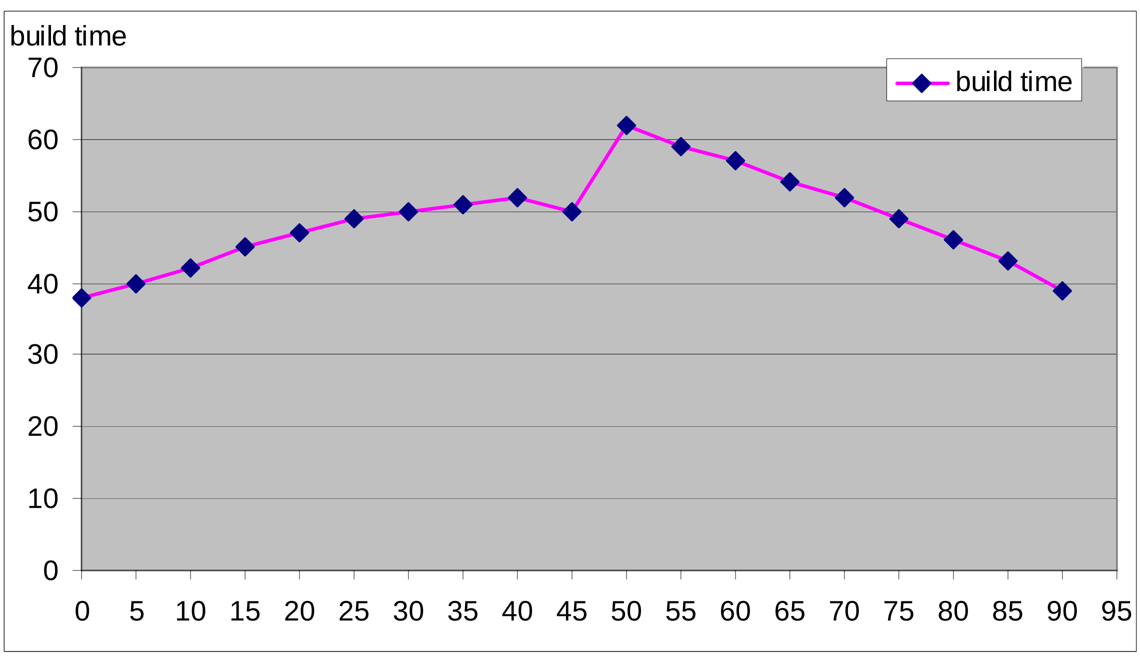

Fig.3. Build Time Vs Build orientation angle

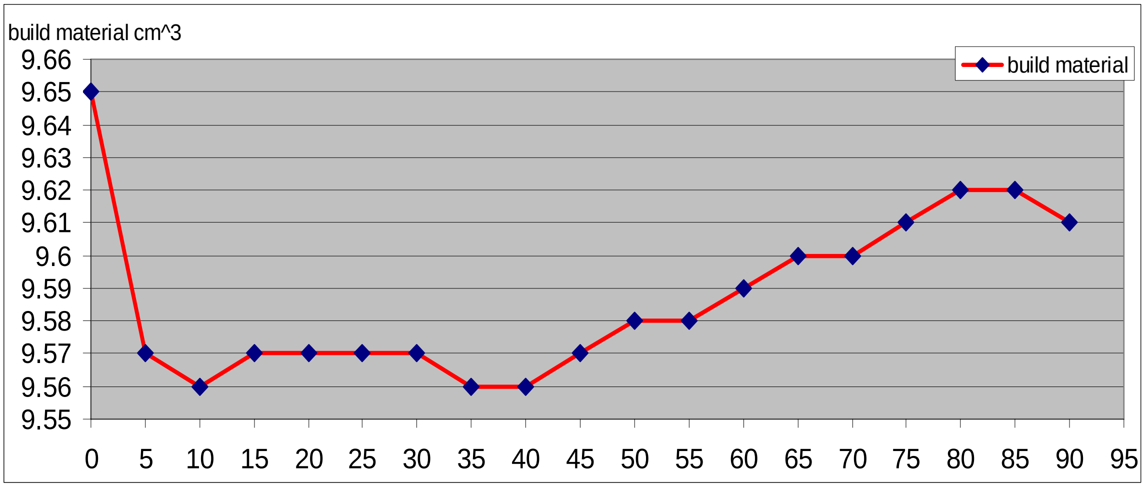

Fig.4.Build Material Vs Build orientation angle.

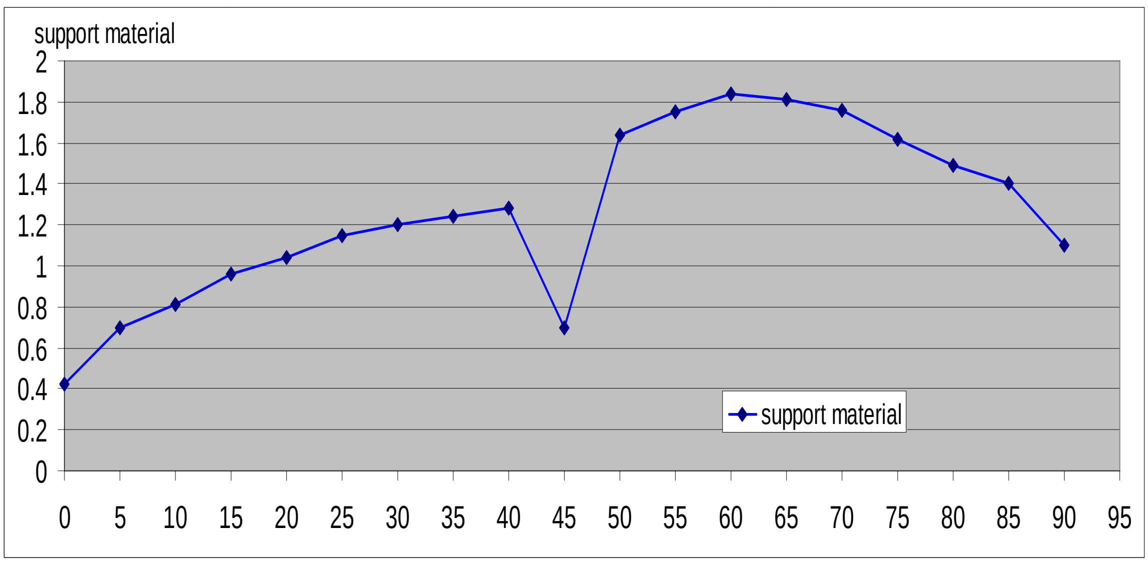

Fig.5. Support Material Vs Build orientation angle.

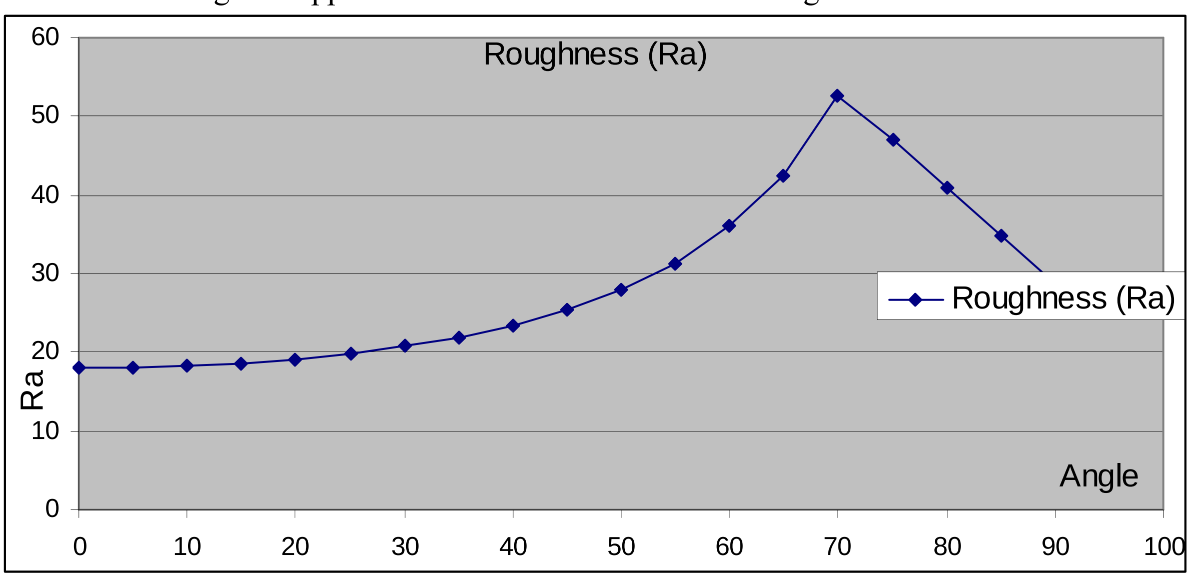

Fig.6. Surface roughness Vs Build orientation angle.

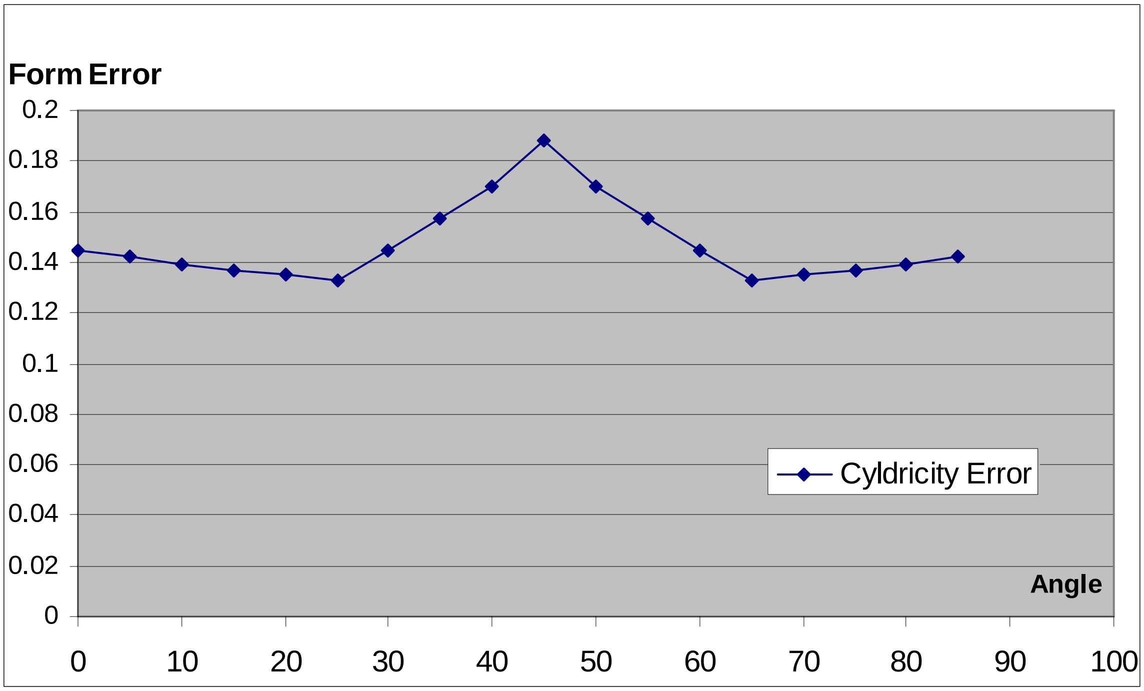

Fig.7. Accuracy Vs Build orientation angle.

Angle (Deg)	No. of Layers	Build Time (Min)	Build Mat cm3	Support Mat cm3	Total cost ($)	Roughness (Ra) micron	Form accuracy (Cylindricity) (mm)
0	129	38	9.65	0.42	8.49017	17.98828	0.145
5	134	40	9.57	0.7	8.84865	18.0569923	0.142
10	139	42	9.56	0.81	9.19652	18.2657782	0.139
15	144	45	9.57	0.96	9.72146	18.6228378	0.137
20	147	47	9.57	1.04	10.0669	19.1427277	0.135
25	150	49	9.57	1.15	10.4169	19.847871	0.133
30	151	50	9.57	1.2	10.5912	20.7710766	0.145
35	151	51	9.56	1.24	10.7617	21.9596351	0.157
40	150	52	9.56	1.28	10.9345	23.4820318	0.17
45	148	50	9.57	0.7	10.5153	25.4392695	0.188
50	146	62	9.58	1.64	12.6601	27.9847958	0.17
55	142	59	9.58	1.75	12.1768	31.3616091	0.157
60	137	57	9.59	1.84	11.8593	35.97656	0.145
65	131	54	9.6	1.81	11.3569	42.5638966	0.133
70	124	52	9.6	1.76	11.0160	52.5942122	0.135
75	116	49	9.61	1.62	10.4969	46.9075	0.137
80	107	46	9.62	1.49	9.97942	40.815	0.139
85	98	43	9.62	1.4	9.46576	34.7225	0.142
90	88	39	9.61	1.1	8.75138	28.63	0.143
Average	133	48.7	9.588	1.258	10.384	28.691	0.147

Table 1. Numerical values of parameters at different Build orientation angle

Angle	B.T F	T C F	R F	F&F F	Form Accuracy	Surface Quality	Total Cost	Production rate
0	0.780541	0.8175	0.6267	0.9850	0.82499	0.7705	0.807839	0.7879
5	0.821622	0.8521	0.6291	0.9646	0.81926	0.7728	0.83497	0.8277
10	0.862703	0.8856	0.6364	0.9442	0.81528	0.7774	0.861974	0.8672
15	0.924325	0.9361	0.6488	0.9307	0.8185	0.7902	0.904514	0.9266
20	0.965406	0.9694	0.6669	0.9171	0.8222	0.8023	0.933144	0.9662
25	1.006487	1.0031	0.6915	0.9035	0.8287	0.8176	0.962683	1.0058
30	1.027027	1.0199	0.7237	0.9850	0.8840	0.8617	0.988228	1.0256
35	1.047568	1.0363	0.7651	1.0665	0.94297	0.9103	1.014485	1.0453
40	1.068108	1.0529	0.8181	1.1548	1.0100	0.9669	1.04271	1.0650
45	1.027027	1.0125	0.8863	1.2771	1.0944	1.0295	1.02932	1.0241
50	1.273514	1.2191	0.9750	1.1548	1.08937	1.0805	1.199185	1.2626
55	1.211892	1.1726	1.0927	1.0665	1.0876	1.1028	1.161871	1.2040
60	1.170811	1.1420	1.2535	0.9850	1.1081	1.1521	1.143238	1.1650
65	1.109189	1.0936	1.4830	0.9035	1.1543	1.2320	1.116687	1.1060
70	1.068108	1.0608	1.8325	0.917	1.2976	1.4039	1.12508	1.0666
75	1.006487	1.0108	1.6344	0.930	1.2201	1.29836	1.064308	1.0073
80	0.944865	0.9609	1.4221	0.9442	1.1370	1.1857	1.00221	0.9480
85	0.883243	0.9115	1.2098	0.9646	1.0574	1.0752	0.941017	0.8889
90	0.801081	0.8427	0.9975	0.9997	0.98311	0.9651	0.865591	0.8094

Table 2. Scores of orientation for FDM.

The above Table 2 indicates that zero degree build orientation is optimal value for total cost and build time and surface quality aspects. However 10 degree orientation is the optimal value for form accuracy criteria. The variation in form accuracy and surface quality between 0˚ to 25˚ is not so significant and user may select any one of its value for optimal results. However total cost and production rate are sensitive even within 0 to 15 deg build orientation. The weight criteria changes with type of product, its features and dimensions, form accuracies etc. The big difference in surface roughness for the orientation of zero degree & 90 degree is attributed to vertical faces or the horizontal facets whose roughness is critically zero.

It is proposed to carry out the present study for bench mark products which are complex in nature or having different features on different faces/edges.

Virtual simulation of rapid prototyping parts will help in reducing the number of physical prototype to produce parts. The designer may conveniently relies and validate the intended part before coming to manufacture. Orienting a part with minimum z height will result in fewer slices, and hence, a reduction in built time. However surface accuracy improves with smaller thickness of the slice which may increase built time. Hence a proper trade off decision has to be taken in optimization of product design. A highly curved surface needs a smaller tolerance value for better surface quality and form accuracy. This results in an increased number of facets, and hence, the file size, which may have to be compromised with the accuracy of part surface. The average cusp height represents the mean of the linear deviation of all the facets and it is one way of representing dimensional error. Volumetric deviation which can be evaluated by summing up of all the volumetric errors for each layer gives the overall volumetric deviation. Theoretically speaking volumetric deviation is measure of the surface accuracy. However the average cusp height which can be evaluated easily is an universal phenomenon for measuring the surface accuracy. The orientation that gives minimum cusp height is the preferred orientation of the part for minimum build time while achieving good surface finish.

The form accuracy for curved objects has to be taken up as profile accuracy rather than conventional form accuracies like straightness, circularity, flatness, cylindricity etc.

CONCLUSION

1. A mathematical model was developed after validating the theoretical values of surface roughness with measured values. This helps in reducing experimental work and improves possibilities of virtual simulation of rapid prototyping parts.
2. Multi criterion decision making can help rapid prototyping users in selecting the best build up direction of the part and create optimal process planning.

FUTURE WORK

Post process error includes process, shrinkage and warpage errors, warpage is another kind of inaccuracy caused by uneven distribution of heat energy and resultant binding force. Shrinkage error is mainly due to shrinkage losses during the solidification of the part. Development of mathematical models for warpage and shrinkage errors using thermodynamics and binding force models may enhance the overall surface and form accuracy of the prototypes.

ACKNOWLEDGEMENT

The Authors wish to express their gratitude to The Director, National Institute of Technology Warangal for permitting us to carry out the work and also permitting us to present the paper at 18th SFF International Symposium at University of Texas Austin.

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