Experimental Investigation of Surface Roughness for Fused Deposition Modeled Part with Different Angular Orientation

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Abstract: Fused deposition modelling (FDM) is a filament based rapid prototyping system which provides fabricated real parts with multiple production-grade materials, such as ABS-M30, PC, PPSF and PC-ABS blend. Fused deposition modelling technology, essentially fabricates parts via layer manufacturing process. More complex 3D physical models can be efficiently fabricated by this technology without any geometric limitation; a remarkable reduction in production life cycle has been achieved. However, due to the nature of Layer Manufacturing process, stair case effect is unavoidable which results in poor surface finish. In this paper, the surface roughness of a model having surfaces at different angles is analyzed to understand the effect of different angled surfaces on the surface roughness of the FDM modelled part.

Keywords: Angular Orientation, FDM, Layer Manufacturing, Stair Case Effects

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1 INTRODUCTION

FDM (Fused Deposition Modeling) method is usually used to make prototypes developed by S. Scott Crump in the late 1980s and was commercialized in 1990 [1]. FDM is commonly used for modeling, prototyping, and production applications. Similar with most other additive manufacturing processes FDM works on an "additive" principle by laying down material in layers. A plastic filament is unwound from a coil and supplies material to an extrusion nozzle which can turn on and off the flow. The nozzle is heated to melt the material and can be moved in both horizontal and vertical directions by a numerically controlled mechanism, directly controlled by a CAM software package. The model or part is produced by extruding small beads of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle [2].

Nomenclature

Φ	angle of rotation (degrees)
α	build orientation (degrees)
F	ratio of supported area to total area of the part
t	layer thickness (mm)
Ra	surface roughness value (µm)
Ra Avg	average surface roughness value (µm)
Ra-Max	maximum surface roughness value (µm)
Ra-Min	minimum surface roughness value (µm)
h	exit diameter of the FDM tip (mm)

In all FDM processes, the solid model of a component to be produced is first created in CAD environment and is sliced before transferring the data to the FDM machine. Figure 2 shows the process chain of FDM process. The FDM 400mc™ from Stratasys allows you to manufacture real parts in-house with multiple production-grade thermoplastics, such as Acrylonitrile Butadiene Styrene-M30, Polycarbonate, Poly Propylene SulFone and Polycarbonate- Acrylonitrile Butadiene Styrene blend. FDM 400mc is a user configurable high-performance workhorse, ideal for creating real parts for conceptual prototypes through direct digital manufacturing. FDM 400mc specifications are shown in Table 1.
The areas of application are closely related to purpose of prototyping and consequently the material used. The key benefits of FDM are mainly derived from its capability to rapidly fabricate physical model exemption of shape complexity. Using FDM technology, the manufacturing cycle time for a typical rapid prototype part of virtually any complexity can be reduced. FDM finds its roots in various engineering applications, the highlighted fields such as Aerospace application, Automobile application and biomedical application [3].

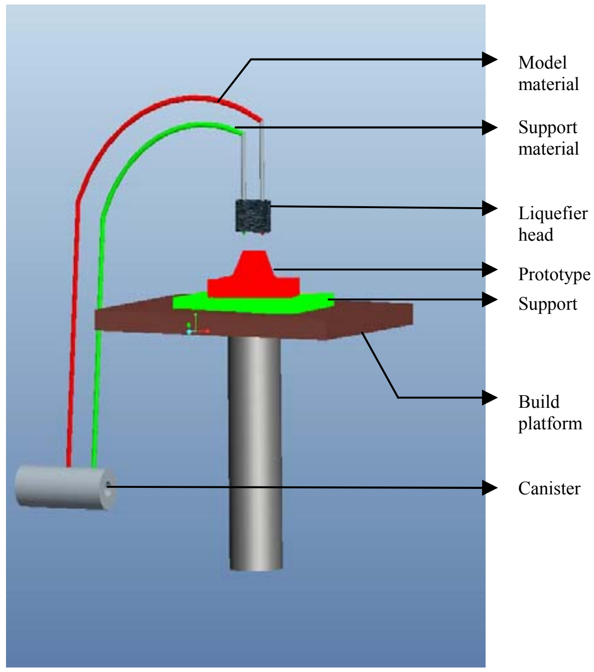

Fig 1 FDM Working Principle

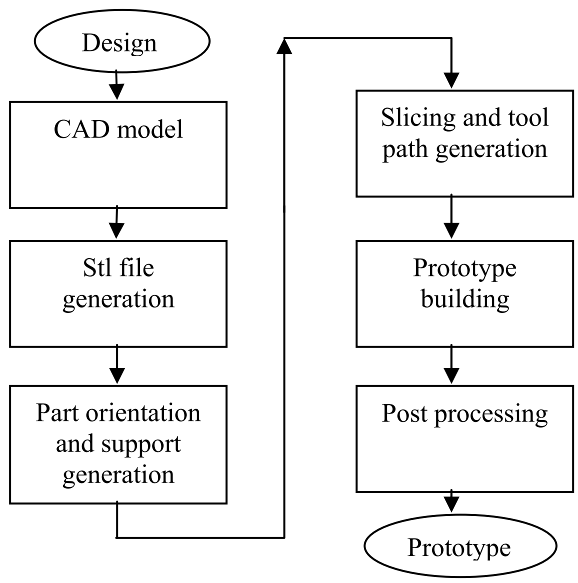

Fig. 2 FDM Process Chain

Table 1 FDM 400mc specifications

Material type	Solid Filament (1.27 mm diameter)
Materials	Thermoplastics such as ABS M30, PC, PPSF
Part size	355x254x254 mm
Minimum layer thickness	0.127 mm
Tolerance	0.127 mm
Surface finish	Rough
Build speed	Moderate
Software	Insight and control version

1.1 STL interface specification

STL interface is a file format specification for interfacing a CAD model with rapid prototyping equipment. STL interface was developed based on polyhedral representations widely used in solid modelers. Precise CAD surfaces are approximated with planar and linear primitive geometric elements into a tessellated (triangular) facet boundary surface model. The accuracy of conversion from a curved surface to a planar faceted surface is controlled by the number of facets where their organization is used to represent that surface. For a planar surface the conversion is exact since each of the converted facets lies on the original planar surface.

The description of STL specification is available in ASCII and in binary format. Both representations provide a list of triangular facets that from the STL model and for each of the triangles, the coordinates of the three vertices of the triangle in 3D space and the associated face normal pointing outside the model surface [4]. The slicing of the CAD model can be carried out either directly on a solid or a surface model of the product or on a tessellated model. In slicing, sets of horizontal planes are intersected with CAD model. This results in closed curves or polygons. The space between any two consecutive horizontal planes is referred to as a slice

When a CAD solid model is available, all CAD systems provide an option to export in the STL file format. The conversion from a precise solid model to an approximation facet model is controlled through a tolerance specification; CAD systems allow direct control of an absolute chordal tolerance. Model tessellation is a well-known problem associated with surface visualization. With a B-rep solid model, the tessellation process is quite straightforward since a mosaic of boundary surfaces is already defined explicitly within a CAD data structure.

1.2 Topological problems

It has been known for a long time that STL interface is associated with a number of potential problems during practical application. In a STL file, all vertices, edges and triangles must satisfy valid topological rules, all triangles around a vertex must satisfy a valid two-manifold condition with the vertex being located at the topological center [5]. All facet normals must point towards the same side; each of the edges must be shared exactly two triangles. The notion of surface normal's entirely unnecessary provided that facet vertices are ordered properly. In addition, the file repeats the coordinates of an individual vertex as many times it appears in the number of triangular facets. The problems are corrected through face flipping, local re-triangulation, and edge reconnection.

1.3 Tessellation and Slicing of FDM Parts

Accuracy became the major issue when the prototype is used for functional parts, where the efficiency of the whole process should be maximized to decrease product development time and reduce life cycle cost [6]. The part accuracy refers to the degree of deviation of the resultant part from the original CAD data. The major two parameters which affects the part accuracy are Tessellation and Stair case effect. CAD model can be created as a solid model (by using primitive instancing or constructive solid geometry) or a surface model (by using B-rep).

A tessellated (STL) version of the CAD model can then be exported. STL format is universally used in all RP technology, to convert the CAD model. The conversion of a 3-D model to STL format is done using the standard surface triangulation algorithms. It is an approximation triangulation model of a part with tolerance error specified by user. The greater the tolerance, the less accurate the STL file is able to represent the part. The triangulation algorithms are known to be simple, robust and more reliable when compared with other approximation techniques [7].

Tessellation is concerned with the unordered set of planar triangles as well as the outward pointing normal of these triangles as found in the STL file. It approximates the surface of the CAD model. It is a first-order approximation of the original CAD model and often loses the intent of original design as well as any geometric and topological robustness. The slice information is contained in a STL file, where it is described as a contour representing a closed planar surface. In the standard software processing, the slices are subsequently filled with a set of parallel lines, representing the roads. At the STL level, the slice represents the building unit and it belongs to a different "group" to which the following properties can be assigned as [8]:

a) Material
b) Build style
c) Contour
d) Road width
e) Air gap between roads
f) Raster orientation

The main constraint is the fixed nature of the raster, which is always made of straight parallel roads. This affects the physical structure of the part and all its characteristics, including mechanical properties, void contents, surface and bonding quality and accuracy. The exported STL is sometimes larger than the original CAD since it has high degree of redundancy. Each triangle is individually recorded and shared ordinates are duplicated. Tessellated CAD data generally carry defects like gaps, overlaps, degenerate facets etc [9]. The slicing error (real error) is quite high as compared to chordal error due to tessellation (given error) as shown in Figure 3.

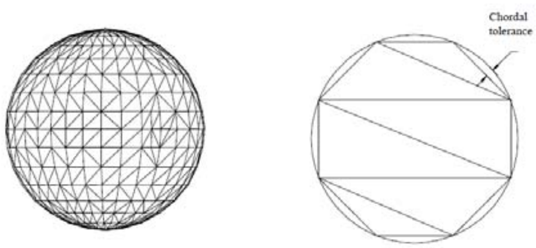

Fig. 3 Tessellation of sphere and its chordal distance

After tessellation, the model is usually sliced into a stack of layers with a plane parallel to the horizontal plane. The boundary of the RP part is then a stepped approximation of the boundary of the original CAD model. Each physical layer is generated as laser/forming head scans the planar profile on the interior of a 2-D slice. The main disadvantage of RP technique over other manufacturing techniques is the poor surface roughness of the part. The reason behind such low part quality is the discontinuous nature of the filaments in building up the part by FDM. Strength of parts made by FDM suffers from anisotropy and adhesive strength between layers is appreciably less than the strength of continuous filaments. As a result of this, all RP parts exhibit a staircase effect along the vertical direction. Figure 4 shows the stair case effect in FDM model.

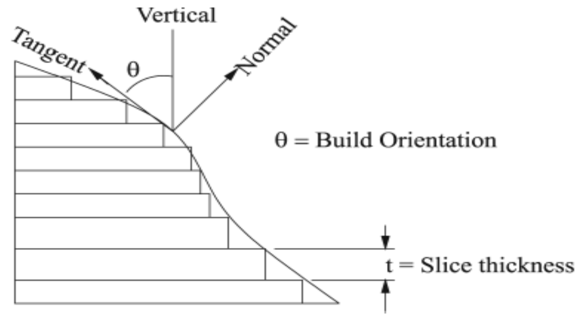

Fig. 4 Stair case effects in FDM parts

The stair case effect cannot be eliminated on a FDM part completely. Due to the presence of stepped edges, slices may be completely outside or inside the CAD model. In certain circumstances, the slice edges may be inside in certain portion of a CAD model and outside in the other portion as shown in Figure 4. This leads to the distortion of shape and is called containment problem [10].

1.4 Part orientation affecting part surface quality

Part orientation and support generation are two closely related issues in layer manufacturing. By selecting an optimal part orientation for model prototyping, it is possible to shorten build time and minimize the overall prototyping cost. There are two key parameters to be optimized in this respect. While ensuring that part is firmly supported during the entire prototyping process, the overall support contact area should be minimized. This helps in minimizing the influence of the support on the surface quality of the prototype [11]. It also reduces further efforts during post processing. We should also make good use of the allowable overhang angle that needs no further support. The total support volume should also be minimized to save time and material for building the support structures.

The extent surfaces produced should be as smooth as possible. As RP models are built in a layered fashion, a stair case effect is unavoidable, but it should be minimized. This can be achieved by reducing the number and areas of inclined surfaces. Part orientation will affect the volume of material required for model support and hence extend building time for RP process. In addition overhanging part areas having direct contact with support will have a poor surface finish and require more post processing. Several researches have proposed approaches to compute the volume of supports of determining part orientation.

As summarized, part should be orientated to meet the following criteria's [12]:

a) Maximize the number of perpendicular surfaces
b) Maximize the number of up facing horizontal surfaces

c) Maximize the number of holes with their axes in the slicing direction
d) Maximize the number of curved cross sections draw in the horizontal plane
e) Maximize the area of the base surfaces
f) Minimize the number of sloped surfaces
g) Minimize the number of trapped volumes
h) Minimize the total area of overhanging surfaces

1.5 Research objective

The objective of this research is to study about the surface roughness of the FDM built part and thereby increasing the surface quality of the model. Stair case effects are found on sloping planes and curved surface, which affects surface finish of the part. These effects are impossible to be removed but it can be reduced to improve the surface finish [13].

After the part is sliced the parameters such as build orientation, support generation and tool path generation has to be determined. The orientation of a part will affect the time needed to build the part, the surface quality and the need for support structures. Thus before the model is being sliced the part orientation should be determined, the optimized part orientation should contain less support generation and minimum build time.

Surface roughness can be defined as the amount of irregularities of the material deposited on part surface. The problem of stair case and tessellation are major concern as they affect the final quality of the prototype. Refinement of layers improves the surface finish of the part, but this will increase the build time [14]. The cost of the prototype is generally governed by the build time. This contradiction between build time and surface finish led to the development of new procedure that would increase the surface quality. Part orientation plays the major role in surface roughness of the part.

2 STUDY OF ANGULAR ORIENTATION OF FDM PART

A design geometry with various angle orientations was chosen for the purpose of this study. The model with various angle orientations is designed using CATIA. The part is fabricated using FDM 400mc machine and the roughness value of each surface is calculated. The experimental roughness values are compared with theoretical values. CATIA allows the users to specify the degree of resolution on curved surfaces by entering a quality value through its user interface. The value ranges from 1 to 10.

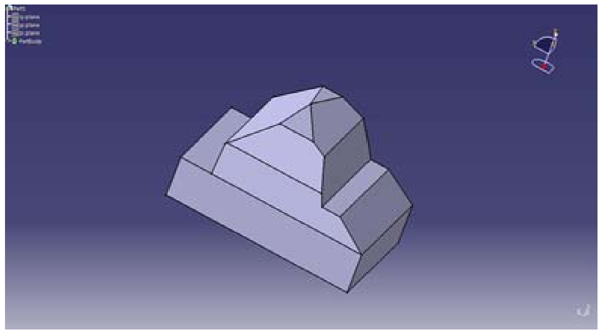

Fig. 5 CAD model showing various orientations

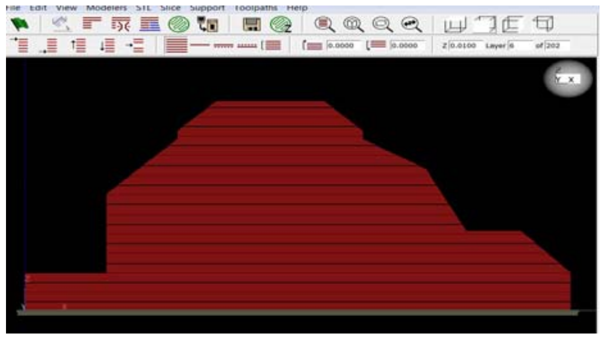

Fig. 6 Sliced model using INSIGHT software

2.1 Fabrication of Model Using FDM

The CAD model with various angle orientations is created using CATIA as shown in Figure 5 and the file is converted into STL file format. The STL file format of the model is then exported into computer and the model is sliced into equal thicknesses. The support material generations, tool path generations, and built time of the model are obtained using the FDM INSIGHT software. The optimized support and tool path movement are set and the file is exported to CONTROL CENTRE software. Then the model is built using FDM 400mc machine with Acrylonitrile Butadiene Styrene (ABS M-30) and has a shrinkage factor of 0.2% to 0.8% using T16 (0.256 mm) tip.

The sliced model using the INSIGHT software is shown in Figure 6. The red color lines in the model show the tool path movement of the tip. After fabrication of the part, the supports are removed but no post processing techniques has to be carried out. A surface tester is used to measure the surface roughness (Ra) of any surface in microns. Four trails on the surface roughness are measured and the mean value is obtained from the trails.

Rmax and Rmin values are obtained from the trails and the actual roughness values are measured using the related formula. Next, a comparison is made between the theoretical and practical surface roughness values and the results are discussed.

2.2 Theoretical calculations

Surface finish, by definition, is the allowable deviation from a perfectly flat surface that is made by the interested manufacturing process. Using numerical modeling techniques, it is possible to decompose the attributes affecting surface roughness and a mathematical representation of layer-by-layer manufacturing can be constructed. The final surface roughness obtained during a practical machining operation may be considered as sum of the following two independent effects.

i. Ideal Surface Roughness
ii. Natural Surface Roughness

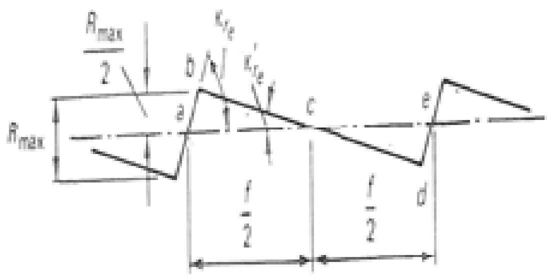

Fig. 7 Surface Variation calculation of machined profile using CLA method

To validate the experimental values, theoretical calculations have to be worked out. In order to define an expression to represent the surface profile of an ideal surface roughness, schematic conditions of the situation is shown as in Fig. 7. The surface profile depends on various factors, such as cross-sectional shape of the tool, surface angle, and layer thickness; thus, these factors can definitely be used to model the surface roughness.

The material in filament form (spool) is melted in a specially designed FDM head, which extrudes the material, and is referred to as "ROAD". Typically the defined road width is usually required to have a width value of 1.2 to 1.5 times the diameter of the nozzle. An expression that can compute the surface roughness value according to surface angle variation in FDM is derived by the following procedure. Using the centre line average method (CLA Method) of surface roughness evaluation, the Ra value is obtained as follows. In material removal operation, the following equations are widely applied for calculation of Rmax and Ra values.

$$R_{\max} = \frac{f}{\cot k_{re} + \cot k'_{re}}$$

$$h = 2 \times \frac{f}{2}\cos\theta = f\cos\theta = f = \frac{h}{\cos\theta}$$

$$\cot k_{re} = \cot\theta, \cot k'_{re} = \frac{f/2 \, \sin\theta}{f/2 \, \cos\theta} = \tan\theta$$

$$R_{\max} = \frac{\frac{h}{\cos\theta}}{\cot\theta + \tan\theta} = \frac{h}{\frac{\cos^2\theta}{\sin\theta} + \sin\theta} = \frac{h}{\frac{\cos^2\theta + \sin^2\theta}{\sin\theta}}$$

$$R_{\max} = h\sin\theta$$

$$R_a = \frac{R_{\max}}{4} = \frac{h\sin\theta}{4} = \frac{0.254\sin\theta}{4}(mm)$$

$$R_a = 63.5\sin\theta(\mu m)$$

FDM400mc uses polycarbonate, ABS M30, PC-ABS with SR 20 and SR 30 water soluble supports. SR-30 is ductile and dissolves up to three times faster than SR-20. The table 2 shown below, states the materials used for FDM400mc model tip diameter and its slice height. The slice height of material build up will be different for the tips used.

Table 2 FDM400 mc tips and their slice heights

Model tip	Slice height (h)
T10	0.127 mm
T12	0.178 mm
T16	0.254 mm
T20	0.330 mm

Using Fig. 7, the expression for machined surface can be derived using CLA method. The same expression can be utilized for analyzing the stair stepping effects that occur in FDM based material deposition technique. In this expression, maximum roughness depth is refered as Rmax, where Rmax is the maximum peak to valley profile height, and Ra, is the arithmetical mean deviation of the profile.

In the above procedure the term 'h' represent the slice height of the FDM tip used (in our case we use t16 whose tip slice height is equal to 0.254 mm), tip for building the model. The similar expression is used by Reeves and Cobbs for measurement of surface roughness of the RP process and is compared to the theoretical values obtained from trigonometrically derived equations [15]. The theoretical and experimental roughness values are tabulated; for better visualization the two roughness values, these are plotted against the part orientation, as shown in Fig. 8.

Table 3 Comparison between practical & theoretical Ra values

Degree	Ra (microns)		
	Practical	Theoretical	Difference
0	18.84	0.00	18.84
10	20.84	11.03	9.81
20	22.12	21.72	0.40
30	23	31.75	-8.75
40	26.56	40.82	-14.26
50	28.92	48.64	-19.72
60	31.1	54.99	-23.89
70	28.28	59.67	-31.39
80	21.16	62.54	-41.38
90	12.26	63.50	-51.24
100	20.78	62.54	-41.76
110	27.46	59.67	-32.21
120	33.04	54.99	-21.95
130	30.3	48.64	-18.34
140	25.42	40.82	-15.40
150	23.22	31.75	-8.53
160	23.56	21.72	1.84
170	21.18	11.03	10.15
180	19.78	0.00	19.78

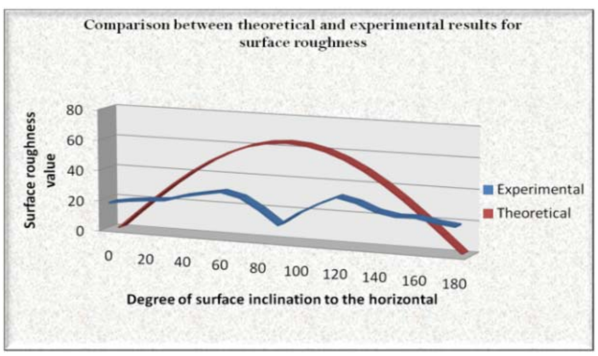

Fig. 8 Comparison between theoretical and experimental results for FDM surface roughness

3 DISCUSSION

This paper presents study about surface roughness values of a FDM model with different angular orientations. It is observed that there is little deviation in the surface roughness calculated by the theoretical and the practical approach at various points. The difference can be justified that theory assumes complete uniform distribution of the material over the surface of the part and thus the Ra value is zero, but practically there are steps formation all over the surface.

It can also be seen that the Ra value is maximum at 90 degree theoretically and it would be a constant but in practice, it is impossible to achieve the same and thus it cannot confirm with the practical results. Also there can be found that there is an inverse relation between the layer thickness and the roughness value due to which the quality in terms of surface finish decreases. In addition to surface angle orientations, layer thickness, liquefier head speed, fill pattern and other build parameters like material flow characteristics require optimization for a given material system for deposition defect-free FDM products. It is arrived from the experiment that the surface roughness of the FDM products is excellent when the part is inclined between the angles 20^0 to 30^0 to the build platform.

From the experiment, it is also found that edges of inclined part don't get enough tool movement (tessellated edges) because there is unfilled material in some layers of FDM model. Hence, it can be avoided by increasing the contour tool travel in those layers and minimizing the raster path to ensure reduced surface roughness value. Hence, it is concluded that angular orientation plays a significant role in achieving low surface roughness on FDM parts.

3.1 Conclusions

In this paper FDM principle, method of working has been studied. The work described in this paper has identified how far the surface roughness varies across a full range of surface angles. FDM test parts were fabricated to verify the proposed surface roughness expression. Empirical and computed roughness data were acquired by measuring the test part and implementing the proposed expression. By comparison Between the measured data and computed values, the validity of the proposed expression was proved.

Additionally, the effects of surface angle, layer thickness, cross-sectional shape of the filament, and overlap interval on surface roughness were analyzed and evaluated. The relationship between the part orientation and the surface roughness is analyzed and comparative statements between theoretical and experimental values of surface roughness are made. This methodology can lead to significant time and cost saving by minimizing the need of manual finishing of the FDM model.

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