Roughness Prediction for FDM Produced Surfaces

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***Abstract*—** Fused Deposition Modeling (FDM) technology has many potential advantages in industrial applications as it is an established additive manufacturing technique for creating functional prototypes from three-dimensional computer aided design models. Despite of these, surface roughness has become the main issue and many attempts have been made to predict the surface roughness Ra. Predicting the surface quality will allow compliance with design specifications and is useful to determine manufacturing strategies. Surface roughness prediction models for FDM process are reviewed and their advantages are highlighted.

***Keywords*—** Geometry tolerances, Rapid manufacturing, Stair-stepping, Surface roughness.

I. Introduction

WOHLER [1] reported that most companies use Rapid Manufacturing (RM) technology for direct part production and functional models. More widespread use of RM processes to fabricate industrial parts requires improvement on quality of parts being manufactured. The parts should conform to the required geometric tolerances specified in the design of the part. Therefore, part quality now becomes a major challenge for the future growth of RM industry.

Parts manufactured by RM processes when compared to other conventional manufacturing processes, can be inferior in terms of surface quality. Costly and time consuming operations may be required to improve surface quality of RM parts. These operations often executed by hand due to the shape complexity of the parts produced thus giving disadvantage of using RM processes for industrial production [2]. Many works have been carried out to improve the surface finishing as it could reduce the post processing operations and make the parts functional.

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II. Parts Surface Errors

Poor surface finish is mainly influenced by tessellation of the original Computer-aided Design (CAD) model and slicing during the manufacturing process. RM processes is characterized by build volume [3], which determines the largest single artifact that can be fabricated at one time. Any RM processes starts with a three-dimensional (3D) modeling of a part and then its STteroeoLithography (STL) file is exported by tessellating the geometric 3D model. In tessellation, various surfaces of a CAD model and corresponding triangle in the tessellated model is referred as "chordal error" [4]. Slicing of tessellated CAD model of any build volume is necessary for part manufacturing in RM process planning. However, it also created "containment problem" [4] which leads to distortion of the original CAD model of the designed shape. In certain circumstances, the slice edges may be in certain portion of a tessellated CAD model and outside the other portion as shown in Fig. 1 c and d.

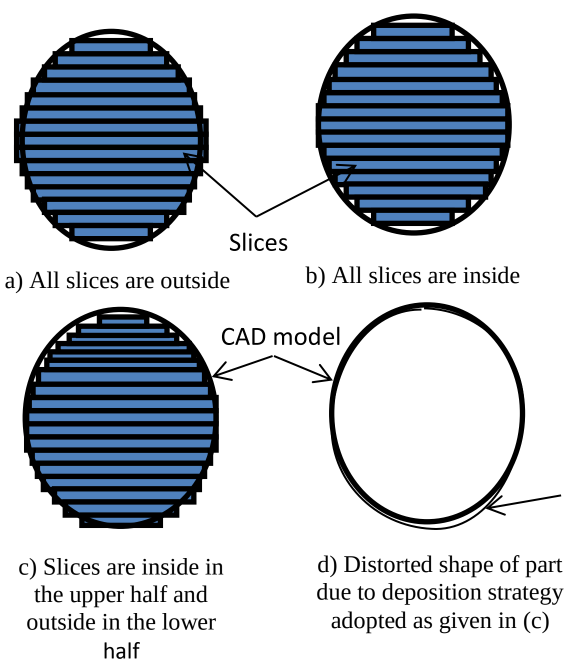

Fig. 1 Containment problems

In most of the commercial RM processes, the part is fabricated by deposition of layers contoured in a (x-y) plane in two dimensions. The third dimension (z) results from single layers being stacked up on top of each other, but not as continuous z-coordinate. Therefore, the part built on exact x-y plane but have stair-stepping effect in the z-direction [4]. Refinement of layers improves the surface finish of the part, but it increases the build time. Adaptive slicing procedures [5-11] which use slices of variable thickness instead of constant thickness were developed. Their thickness is governed by the part geometry and RM machine specification. Any RM system will have the capability of depositing the material between a minimum and maximum thickness with certain intermediate thickness. However, most available systems use fixed fabrication thickness to build part to minimised set up time. Hence, the thickness cannot be changed during the deposition operation in most of the commercial RM system.

Post processing surface treatments also add to the build time and leads to a degradation of the geometrical definition of the model [2, 12]. Geometrical gap occurs between the original CAD model and the fabricated RM parts due to the effect of stair-stepping as shown in Fig. 2. This error varies according to the surface angle [13]. The utilization of support structures to prevent deflection when stacking layers, and after detaching the supports, leave support removal burrs on the surface of the parts.

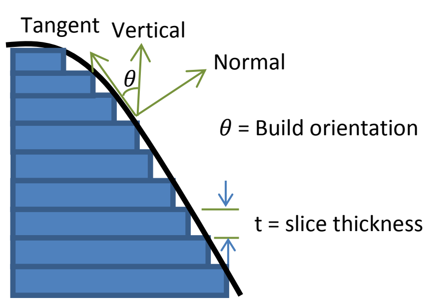

Fig. 2 Staircase effect in RM parts

Several experimental and theoretical investigations have been made to evaluate and predict surface roughness. Knowledge in advance of surface parameters is a critical point especially in the product design both for rapid prototyping and finished parts manufacturing. Most prediction models have been developed based on equations derived from the stair step profile and empirical roughness measured on several different RM platforms [7, 14-16]. The influences of other process parameters on surface roughness must also be taken into consideration to build a robust prediction model. Build orientation, layer thickness, road width and deposition feed are found among the most influencing process parameters affecting surface roughness of component produced using FDM process [14, 15, 17-19]. Some process parameters such as model filling and support generation method can also distort the shape profile of FDM components thus affecting its surface quality [20]. Therefore, more researches are required to improve the surface quality of FDM components before FDM process can be a reliable constructive method for finished products.

III. Surface Roughness Prediction Models For FDM

Poor surface roughness has been introduced as the main limitation of RM processes. Previous studies have attempted to improve the quality of RM products by predicting the surface roughness of parts processed on different RM platforms. Most accepted model for surface roughness estimation for FDM system was developed by Pandey et al. [15, 21]. Based on their observations [21] three major points were identified : (i) layer thickness and build orientation are the two most significant variables that affect surface finish (ii) the edge profiles of a layer manufactured part by FDM system is parabolic (iii) the radius of curvature effect on the surface roughness can be thought of independent as it varies within 5 percent over a wide range of curvature values. Based on these observation Pandey et al. [15] proposed a semi-empirical model by approximating the layer edge profile by a parabola with the base length of t/cosθ and height as 30-35% of the base length, using the center line method for surface roughness evaluation (Ra). The resulting expression for Ra is given by Equation (1).

$$\text{Ra}\ (\mu\text{m}) = (71\text{-}93)\frac{t(mm)}{cos\theta} \tag{1}$$

in which θ is the build angle in degree and t is the thickness of the deposited layer in mm as shown in Fig. 2.

For parts with build orientation in between 70º and 90º, a gap between deposited roads was observed [15] as in Fig. 3(b) thus surface roughness was calculated by assuming linear variation between $Ra_{70°}$ and $Ra_{90°}$ which is given by Equation (2).

$$\text{Ra}(\mu\text{m}) = \frac{1}{20}(90Ra_{70°} - 70Ra_{90°} + \theta(Ra_{90°} - Ra_{70°})) \tag{2}$$

for $70° \leq \theta < 90°$

Surface roughness for horizontal surface, $\theta = 90°$ was idealized [22] by semi-circle with base length t and height 0.5*t and represented by Equation (3).

$$Ra(\mu m) = 112.5 * t(mm) \quad for\ \theta = 90° \tag{3}$$

For the downward facing surfaces in range between 90° and 180°, the application of support structures are required. Therefore, the surface roughness is represented by Equation (4).

$$Ra(\mu m) = Ra_{(\theta-90)}(1+\omega) \qquad for\ 90° < \theta \leq 180° \tag{4}$$

Where ω is a dimensionless adjustment parameter for supported facet and chosen to be 0.2 for FDM systems.

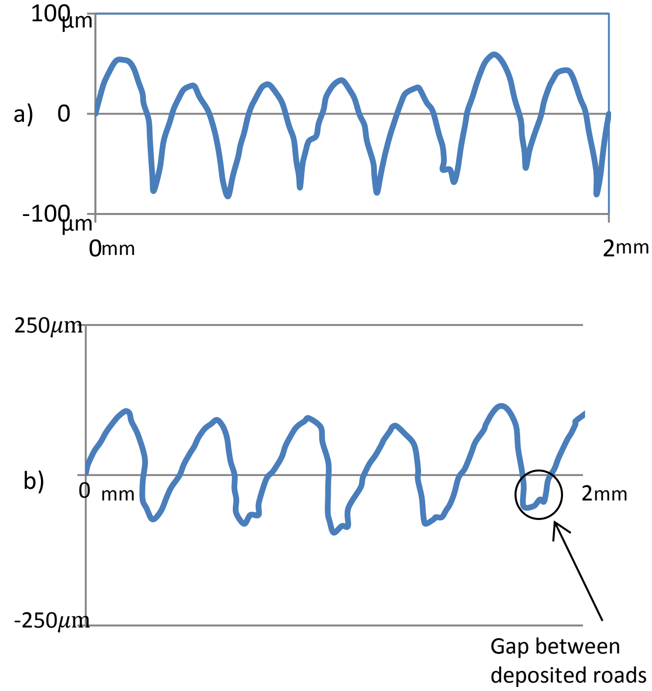

Fig. 3 Edge profile of FDM part surface; a) θ = 45°, t = 0.254mm; b) θ = 70°, t = 0.254mm

For several RM processes, the surface roughness varies across a full range of surface angle [14]. The surface roughness distribution in terms of surface angle using measured surface roughness data and interpolation [18] is expressed in Equation (5).

$$Ra = \frac{A}{W} = \frac{1000t}{2}\left|\frac{\cos((90-\theta)-\emptyset)}{\cos\emptyset}\right| \quad for\ 0° < \theta < 180° \qquad (5)$$

where ϕ is the surface profile angle in degree, A the step area and W the step width as shown in Fig. 4.

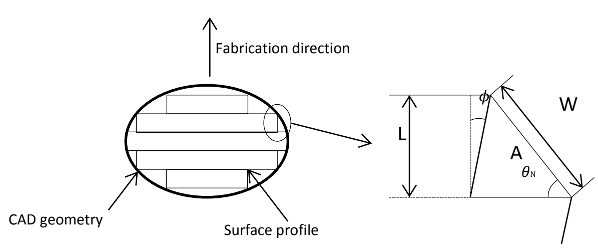

Fig.4 Surface angles in Ahn et al. [18] roughness model

However, the actual distribution of the surface roughness is different from that of the theoretical surface roughness. This is due to various factors such as stair stepping effect, support removal burrs, material properties and process attributes. Therefore the actual surface roughness can be calculated by Equation (6).

$$R_{actual} = R_{step} + R_{burr} + R_{material} + R_{process} \qquad (6)$$

Where R_{step} represents portion of the actual roughness due to stair stepping effect (calculated surface roughness value), R_{burr} due to support removal burrs in supported area, $R_{material}$ due to different build material properties and $R_{process}$ due to build process attributes.

Therefore, Ahn et al. [13] proposed the following distribution expression for average surface roughness.

$$R(\theta) = R(\theta_p) + \frac{R(\theta_n) - R(\theta_p)}{\theta_n - \theta_p}(\theta - \theta_p) \qquad (7)$$

where $R(\theta_p)$ and $R(\theta_n)$ are the measured roughness values at the previous and next surface angle θ_p and θ_n respectively.

Fillet radius , R_1, and corner radius, R_2, as shown in Fig. 5 are among parameters used to estimate the profile roughness of the surfaces made by FDM process [16].

The profile roughness Ra as a function of $f(t, \theta, R_1, R_2)$ was given by Equation 8.

$$\mathrm{Ra} = \frac{1000t}{4}\cos(90-\theta) - \frac{\left(R_1^2+R_2^2\right)\left(1-\frac{\pi}{4}\right)\sin(90-\theta)}{1000t} + \frac{\left(R_1^2+R_2^2\right)\left(1-\frac{\pi}{4}\right)^2}{(1000t)^3}\tan(90-\theta)\sin(90-\theta) \qquad (8)$$

Where R_1 is the fillet radius in mm and R_2 is the corner radius in mm.

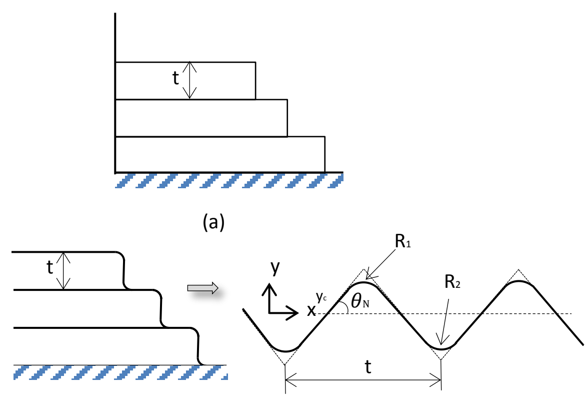

Fig. 5 (a) Ideal manufactured surface with sharp edges;
(b) Realistic manufacturing surface with round edges; R1 is the radius of fillet and R2 is the radius of the corner and
θN = 90 –θ

Test parts of a pyramid shape [15], [23] and a truncheon [14], [18] are used for measurement of surface roughness. For pyramid shaped parts as in Fig. 6, the angle between an upward vector tangential to surface with the vertical axis is called the surface build, with surface build angles of respectively 10º, 15º, 30º and 45º. Turncheon test part is used for a more comprehensive evaluation for surface roughness prediction models [14], [18]. The part has a geometry which enables measurement of surface roughness for a range of build angles between 0° to 180°. The reported surface roughness measurement results are presented in Table I.

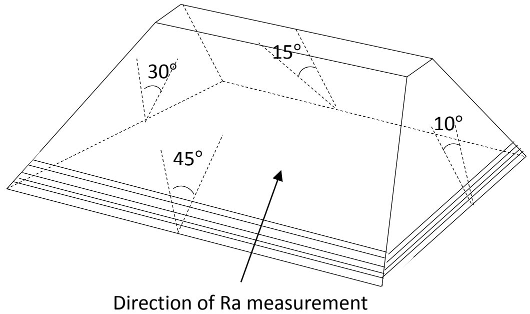

Fig. 6. Pyramid shaped test part for measurement of surface roughness for various build angles.

TABLE I
REPORTED SURFACE ROUGHNESS DATA FOR DIFFERENT TEST PARTS

θ^o	Layer Thickness (mm)		
	0.253	0.254	0.254
	Reported roughness data [14]. (μm)	Reported roughness data [18]. (μm)	Reported roughness data [15]. (μm)
0	28.57	33.47	NA
10	24.54	NA	18
15	NA	46.30	19.25
20	30	NA	NA
25	NA	NA	NA
30	32.31	49.31	22.1
35	NA	NA	NA
40	26.54	NA	NA
45	NA	29.56	25.2
50	23.59	NA	NA
55	NA	NA	NA
60	22.56	20.65	NA
65	NA	NA	NA
70	20	NA	NA
75	NA	18.58	NA
80	17.95	NA	NA
85	NA	NA	NA
90	17.43	16.73	NA
95	NA	NA	NA
100	17.56	NA	NA
105	NA	13.47	NA
110	17.69	NA	NA
115	NA	NA	NA
120	20.77	18.15	NA
125	NA	NA	NA
130	21.15	NA	NA
135	NA	28.36	NA
140	25.51	NA	NA
145	NA	NA	NA
150	34.36	49.34	NA
155	NA	NA	NA
160	33.33	NA	NA
165	NA	32.39	NA
170	27.56	NA	NA
175	NA	NA	NA
180	20	9.45	NA

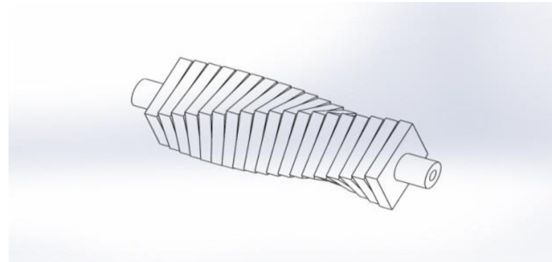

Fig. 7. Turncheon test part

IV. ADVANTAGES OF SURFACE ROUGHNESS PREDICTION MODELS

No complete and reliable knowledge about the surface quality achievable leads engineers and process managers to manufacture subsidiaries, or to replace the RM with subtractive machining with significant added costs. It also forces the technicians to use subtractive methodology to manufacture subsidiaries with improved costs. Surface roughness models that are able to replace the trial and error methods are necessary in the prediction of surface quality in order to save time and costs in product manufacturing.

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