A Visual Tool to Improve Layered Manufacturing Part Quality

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Abstract

A software tool is described that will aid the user in choosing the optimum build orientation to obtain the best composite set of surface finishes on a part built on a Fused Deposition Modeling (FDM) rapid prototyping machine. Experiments were conducted to obtain statistical surface roughness values as a function of orientation and layer thickness. Three types of surfaces (features) have been considered: planar (both upward facing and downward facing (overhang surfaces)), quadric and freeform surfaces. Data analysis of surface roughness of planar surfaces at various orientations and their mapping to quadric and freeform surfaces are presented. The decision support software tool allows dynamic color-coded visualization of the surface quality simultaneous with build parameters including orientation and layer thickness.

Introduction

The Rapid Prototyping (RP) or Layered Manufacturing (LM) industry has grown by leaps and bounds since it started off a little over a decade ago. Among its numerous applications, increased stress is now being laid on rapid fabrication and form and fit applications. This in turn lays increased importance on the confirmation of the part quality of a part built on a RP process with the CAD model or the scanned model, or MRI/CAT scan of the part. The term *part quality* encompasses surface quality, dimensional accuracy, part strength and build time among others. Surface quality is decided by certain factors including surface deviation (surface roughness), surface flatness and amount of support structures. Since the build process is layered manufacturing, there are certain factors specific to this process that decide the eventual part quality. Chief among these are part orientation, layer thickness, material characteristics and certain process parameters. In this paper, we deal with the influence of part orientation and layer thickness on surface roughness or surface deviation specific to Fused Deposition Modeling (FDM). Surface deviation on a part built on a RP machine influences the amount of time that needs to be spent on subsequent post-processing (finishing) and may, in the process, distort dimensional accuracy. Therefore, it is important to select a good orientation and a suitable layer thickness before starting a build. An interactive software tool has been developed and described in this paper which can used by a RP user as a confirmation tool in deciding a/set of *good* orientation before building the part. The main visual in the software is the display of a color-coded part (read from a file in Stereolithography Tessellation Language (STL) format) which indicates to the user by the way of colors, the expected surface roughness on different surfaces comprising the part.

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Previous Work

There has been some work carried out on the importance of factors like orientation and layer thickness for improved part quality, although none of them dealt with FDM. In fact, all of them have been carried out on RP processes such as Stereolithography (SLA) and Selective Laser Sintering (SLS). Thompson [1] conducted an experiment on a SLS machine using a factorial design of experiments method whose results validate the assumption that part orientation is *as* important as certain controllable process parameters such as laser power and layer thickness in deciding surface finish among other measures of quality. Since this surface finish effect due to the factor part orientation is a direct result of layered manufacturing technique, this particular result will hold true for other LM processes such as FDM. Frank and Fadel [2] have developed an expert system, which, with some user interaction, decides the best build direction with the best direction quantified by surface finish, build time and amount of support structures. In this case, the user can select two feature entities of a part that are important to him. Specifying more than two may lead to problems. Lan et al. [4] have developed a program that searches for fabrication orientations for a part with various build objectives like surface finish, build time and support structures on a SLA machine. Our system described in this paper, nicknamed the 'Orient Express', considers all surfaces simultaneously, gives a visual display for immediate feedback of both required and expected surface finish for FDM.

Approach

Surface quality becomes a key issue in Rapid Prototyping because of the manner in which 3-dimensional parts are built in the layered manufacturing processes. The layer by layer additive build process creates an imperfect texture on the surfaces of a part especially on sloped surfaces (stair-stepping phenomenon), intricate features (thin walls, etc.) and certain curved surfaces (small radius cylinders, etc,.). So, in view of the importance of surface quality in the rapid prototyped parts, these imperfect textures, which cannot be eliminated as such in many cases should be contained as much as possible. We have considered the effect of sloped surfaces on part surface finish. On the FDM, sloped surfaces affect the surface roughness through a combination of four effects - layer thickness, layer (edge) profile, layer composition [3] and sub-perimeter composition. The layer profile is the cross-sectional profile of the perimeter bead of material and is normally produced to smooth surface deviation at the edge of a step. "Layer composition is described as the method by which a layer is generated from its raw material, such as molten plastic, sintered powder or cured resin" [3]. Sub-perimeter composition is the composition of that region of a layer just inside the perimeter bead. The roughness value is largely dependent on the amount of this sub-perimeter region that is visible on the exposed part of a layer on an inclined surface. At surface inclinations (say 15° – 35°) where the sub-perimeter region and the corresponding perimeter bead are the only exposed part of the layers, the roughness is high.

Any 3-dimensional part is made up of planar and/or non-planar surfaces. Planar surfaces can be horizontal, vertical or at any inclination with a reference plane (throughout this paper we use a horizontal plane representing the build base as the reference plane). Non-planar surfaces usually consist of the set of quadrics (cylindrical, conical, spherical, etc.) or higher degree freeform surfaces. In a particular orientation, each of a part's surfaces can be either upward or downward-facing (overhang surfaces) with respect to the base plane and a surface, depending on this will have different surface roughness. One fact to be kept in mind is that not all downward-facing surfaces require support structures. In QuickSlice®[1] which is a software tool that works on STL files before building parts on the FDM machine, the user can control which overhang surfaces get supports under them based on their inclination with the base plane [5]. Among the support options available, at medium supports (where an inclined surface is supported if 50% or more of its perimeter roads are unsupported by the roads of the previous layer), surfaces at inclinations below the critical angle of 43° with the base plane are supported by support structures while at high supports (for inclined surfaces with 25% or more of its perimeter roads unsupported by roads of the previous layer), the critical angle is 26°. Normally downward-facing surfaces are smoother (lower surface roughness value) than upward-facing surface at the same absolute angle with the base plane and in general, horizontal and vertical surfaces of a part get the best surface finish though it has been found out through experiments that vertical surfaces on FDM parts are smoother compared to horizontal surfaces. This is because there are a lot of defects on the horizontal surface of a layer like sub-perimeter voids, inter-road defects, etc., which do not occur on vertical surfaces [6]. For all surface inclinations between the absolute values of 0° and 90°, the angle of inclination of the surface with the build plane decides the roughness on that surface. Typically, surfaces at shallow inclinations with the base plane are rougher than surfaces at higher inclinations. This behavior is not linear - roughness value does not increase linearly with inclination angle. At first we had perceived that a quadratic curve would fit this behavior as shown in Figure 1.

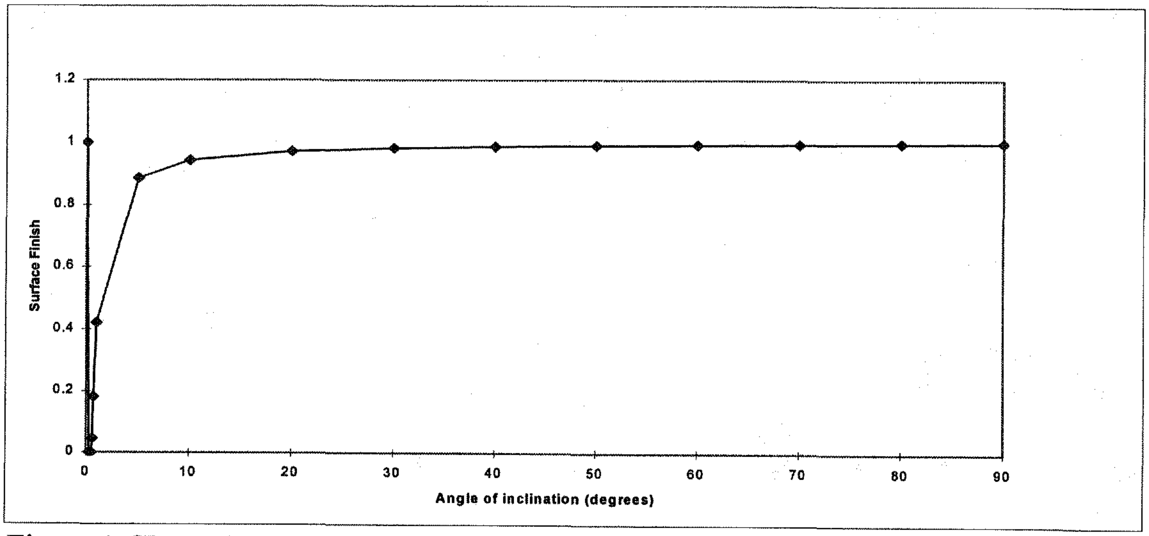

Figure 1 **Chart showing surface finish (smoothness) vs. surface plane orientation**

This curve characterizes surface roughness by the length of the exposed part of a step on a sloped surface at an inclination between 0° and 90° as shown in Figure 2. The length of the exposed part of a step (Y) is calculated by the equation:

$$Y = \text{layer thickness } (X) / \tan\theta$$

The concept behind using this equation is, the lower the inclination θ, the greater is the length Y and for a constant layer thickness along the height of a sloped surface of a part, the greater the difference in area between the actual surface and the desired surface which implies a greater surface deviation. This model is the initially forecasted mathematical model.

To validate this theoretical model, we built parts with planar surfaces at various inclinations and took roughness measurements on it using a surface profile scanner having a LVDT diamond stylus with a radius of 5 μm. At the end of this data acquisition phase, we realized that we would need a cubic B-Spline curve to fit the data points representing surface roughness (Roughness Average number Ra in micro inch) at inclinations between 0° and 90°.

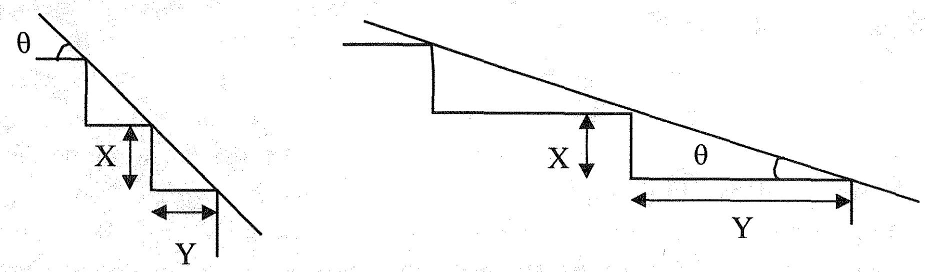

Figure 2 **Figures showing the horizontal part of a step on a steep and shallow angled inclined surface**

The part build process on a RP machine starts with the generation of a .stl file of the part. This .stl file is a surface (boundary) representation of a part in terms of a mesh of planar facets or triangles. In other words, all bounding surfaces or features of a part whether planar or non-planar and whether internal or external are represented by a mesh of planar triangles. Of course, surface representation by planar triangles is not what one would prefer during the data translation from a CAD file to a .stl file as it introduces some dimensional errors on curvilinear surfaces. Since the triangles literally 'stick' to the part surfaces and are planar, roughness values obtained on planar surfaces of parts during our data acquisition phase can be directly quoted as the roughness of a triangle at a particular inclination which decides the roughness on the area of the surface of the part it covers. Thus surface roughness values obtained on planar surfaces can be assigned to non-planar surfaces too.

In the software tool described later in this paper, part orientation (which decides the inclination of the part's constituent surfaces with the base plane) and layer thickness are the two parameters that can be manipulated to change surface finish on the surfaces of a part built on a FDM machine. The part 'read' from its .stl file is displayed with all its surfaces color-coded, which is the net effect of coloring individual triangles based on their inclination with the base plane.

Procedure

The process of obtaining roughness values on both upward and downward-facing planar surfaces at various inclinations started with the building of parts with such surfaces separately at 0.010" and 0.007" layer thickness on a FDM1650. Figure 3 shows one such part.

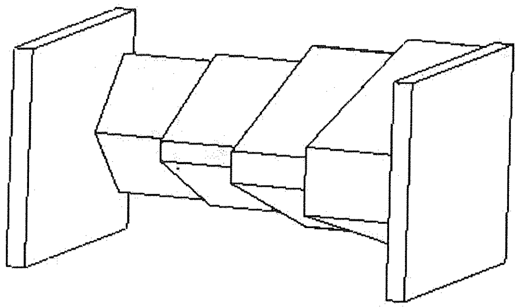

Figure 3 **A typical part used to obtain surface roughness values on its constituent planar surfaces**

Each of these parts has a set of upward-facing planar surfaces at certain inclinations between 0° and 90° and their corresponding downward-facing surfaces. The statistical roughness values on these surfaces were obtained by using a Sheffield Profile Measurement System which is a contact type surface roughness measurement system. Each measurement was taken over a traversal length which was ten times the sampling length or cutoff length of 0.030". So the roughness of a surface characterized by a Ra value (reported in micro inches) is a value averaged over ten cutoff lengths. All measurements were taken at 45° to the direction of the lay since positioning the stylus so as to take measurements perpendicular to the lay is a cumbersome task. A check was made by taking a measurement perpendicular to and at 45° to the lay and the roughness data obtained showed that the difference was quite small. More surfaces were built and measured in the shallow inclination (0° - 45°) region because of the greater variation of roughness in this region. The data obtained from the measurements and shown as a plot of surface roughness plotted against surface inclination in Figure 4 and Figure 5 proved this point.

The statistical data so obtained was compiled and used as a basis for assigning a roughness value to a triangle representing an area of a surface of a part from a stl file. Some interesting observations from the roughness data have been listed below:

1. The surface roughness (Ra) values reported in micro inch followed a more or less similar pattern for upward and downward facing surfaces on parts with slices 0.010" and 0.007" thick. A 'bell-shaped' pattern is seen in the 10° – 40° region with the peak appearing between 15° – 25°. The roughness decreases after the 40° inclination and decreases without much significant change to the lowest roughness value at 90° (a vertical surface).

2. At a particular angle, the roughness values on overhang surfaces are normally lower than on up-facing surfaces. This is logical since on an overhang surface filaments on the surface get deposited on an underlying layer of supports which introduces a smoothing effect on the modeling filaments. This effect is very much visible on parts made of 0.010" thick slices.

3. The effect stated above is reversed in the 10° – 40° region for parts made up of 0.007" thick slices

Software

A software tool has been developed as part of this project. It basically serves as a visual verification and informative tool that helps the user decide a /set of good orientation to build a part on a FDM machine and also provides him with an array of useful information and statistics.

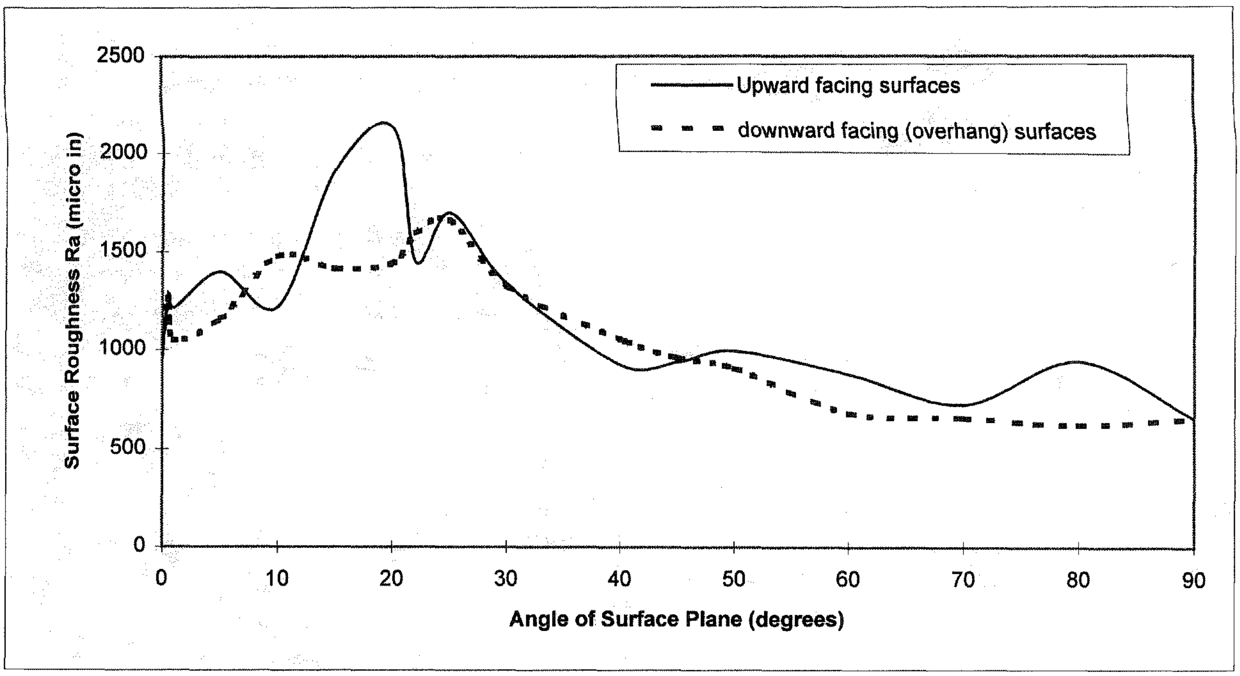

Figure 4 **Surface roughness Ra (micro inches) for upward and downward-facing surfaces at various inclinations at 0.010" layer thickness**

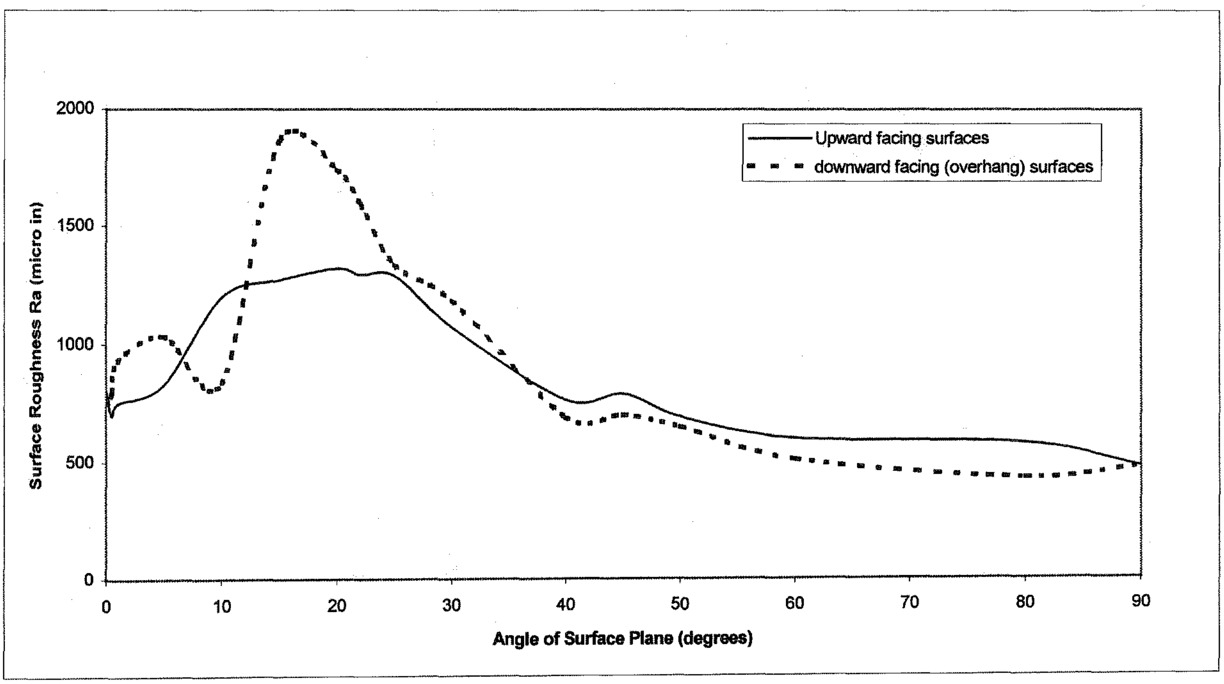

Figure 5 **Surface roughness Ra (micro inches) for upward and downward-facing surfaces at various inclinations at 0.007" layer thickness**

The main visual shown by the software when a user opens a .stl file is the part in the default orientation i.e., the orientation of the part when saving it in .stl file format. With the click of a button, the whole part is displayed as a color-coded entity with all its surfaces displayed with a hue of colors. The colors on the surfaces of the part is the net result of shading each component triangle with the color obtained by mapping its surface roughness value due to its inclination to a RGB color. Figure 6 depicts the steps that the software goes through before coming up with the color mapping on the part's surfaces.

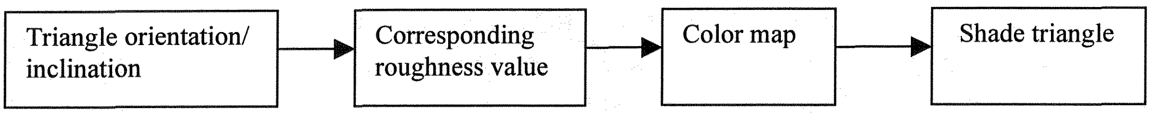

Figure 6 **Sequence of steps followed in obtaining the color-coded part**

The user can choose to reorient the part in either of two ways: specify values of rotation about the x, y or z-axis or use the mouse interactively. Irrespective of the mode the user may choose to operate in, any reorientation of the part will change the color-coding pattern on the surfaces of the part since all the surfaces and hence the triangles describing them are at new inclinations with respect to the base plane.

Another feature that will be incorporated is to give the user an option to view both the predicted and desired surface finishes simultaneously on a surface. The ***predicted*** finish is the estimated finish when produced that is calculated according to the orientation of the face. The ***desired*** finish is that specified in the CAD model as a tolerance. Such a surface will be displayed with two colors matching both the predicted roughness values in the present orientation superimposed by the stripes of the color corresponding to the predicted roughness. As the user reorients the part, the predicted color changes and the goal will be to orient the object such that the predicted and desired finishes are the same, that is, the stripes disappear and the surface is one color.

The volume of support structures required in a particular orientation is reported. Provision has been made for the user to view the part from various angles while the part remains fixed in a particular orientation. Several intermediate orientations can be saved for future review and any of these can be saved as a stl file of the part in the new orientation. The user also gets information regarding the percentage of triangles that are horizontal, vertical and in the critical range (between 10° - 40°).

Results And Conclusions

From the data collected, it is obvious that the surface roughness deteriorates between 10°-40° with the worst occurring in the 15° - 25° for both upfacing and downfacing surfaces at 0.010" and 0.007" layer thickness. So whenever possible, it is better to avoid having surfaces oriented at angles in this range. The layer composition on the FDM is uneven especially near the edges.

The software can be used as a useful educational tool to improve the user's knowledge of the dependency of surface finish on layer thickness and orientation. It will be handy to RP users in reducing the time and costs during the part building phase since the possibility of making a wrong decision about the orientation and layer thickness is reduced. Portability is an important end-result of this research. The software in its current state can be used to evaluate the effect of two build parameters- orientation and layer thickness on surface finish *before* starting the build on a FDM1650 at the default process parameters at 0.010" and 0.007" layer thickness. But the same software can be used on an RP machine based on any layered manufacturing process. For this, the software can be made to read the set of surface roughness data from surfaces on parts built on that machine. Adding more parameters that affect surface quality including material properties and process parameters such as air gaps, widths of roads, etc., can increase the usefulness of the software. Also, it can be made more general by making it a tool to *predict* part quality.

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