Surface Characterization of Polycarbonate Parts from Selective Laser Sintering [1]

Irem Y. Tumer David C. Thompson
Graduate Research Asst. Graduate Research Asst.
Richard H. Crawford Kristin L. Wood
Assistant Professor Associate Professor

Mechanical Engineering Department
The University of Texas at Austin

Abstract

Surfaces of polycarbonate Selective Laser Sintering parts are investigated to determine the characteristics affecting part quality. Surfaces are obtained from experiments by varying four factors, namely, layer thickness, laser power, part orientation, and build angle. First, spatial modes on SLS surfaces are decomposed using a qualitative spectral analysis in an attempt to find their origins. Thermal modes on the top surfaces of polycarbonate SLS parts result in the other modes being obscured; melting and part curl are concluded to be the dominant modes on these surfaces. Furthermore, surface modes resulting from building the part at an angle to the powder bed are identified and modeled. Then, mathematical measures are computed for the surfaces to determine surface precision quantitatively. An analysis-of-variance study is performed to reveal the trends in surface precision with respect to control factors. Surface precision is shown to change significantly with laser power and part orientation, and trade-offs with part strength are presented.

Introduction

The quality of parts fabricated with Selective Laser Sintering (SLS) [7] is a crucial consideration. Functional prototyping, which is a major advantage of the SLS process, depends heavily upon the ability to build accurate parts on a repeatable basis. In an attempt to model part quality, this paper aims at investigating the different spatial modes on surfaces from SLS and the different factors that influence part quality.

Background and Motivation

The quality of parts from SLS has been investigated in the literature in terms of measures such as part overall dimensions [2], part strength [6], and sintering depth and density [1]. These studies give a broad picture of what parameters affect part quality in order to present the operators with a set of preferred parameters when building SLS parts. However, none of these studies attempt to provide an insight on why surface deviations occur on SLS parts.

As in every manufacturing process, the finished part is the end product that the SLS researchers are interested in improving. The nature of the signal from surfaces of manufactured parts contains very useful information that can provide great insight into the types of modes present in the system [13]. As a result, an investigation of signals from polycarbonate SLS part surfaces will provide more insight on the nature of error generating mechanisms in SLS. Here, we take errors to be surface deviations that produce spatial modes, such as the modes presented in Figure 1.

Experiments

Two types of surfaces are investigated to determine the quality of surfaces from SLS; namely, those surfaces that are parallel to the horizontal build plane (called "top surfaces"), and those

---

[1] Published in the Proceedings of the 1995 Solid Freeform Fabrication Symposium, pp.181-188, Austin, Tx, August 1995

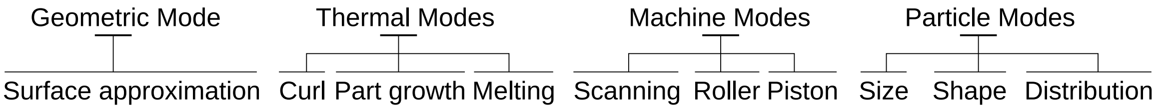
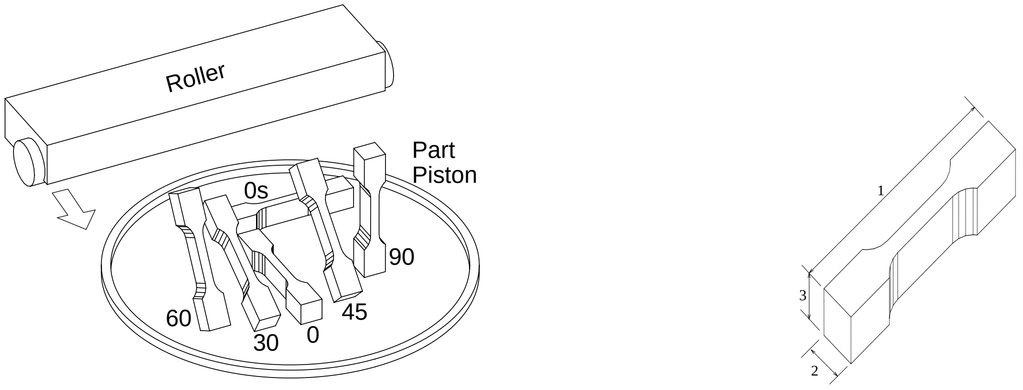


Figure 1: A taxonomy of surface spatial modes for SLS.



(a) Part layout for each run in the powder bed.

(b) Tensile test specimen with dimensions.

Figure 2: Specimens used in the design of experiments.

surfaces that are built at an angle to the horizontal build plane (called "angled surfaces"). To determine the effect of system parameters on surface quality, test specimens are built on a DTM SLS 125 at different orientations, build angles, power levels, and layer thicknesses. The part layout on the powder bed for each laser power and layer thickness is shown in Figure 2(a). Build angle (labeled as 0, 45, 90 parts) refers to the angle between the part's longitudinal axis and the horizontal build plane, while part orientation (labeled as 0 and 0s) is the angle between the part and the direction of roller travel. In addition to these test levels, in-between tests at 30 and 60 degrees are run as shown in Figure 2(a). The experimental control factors and their values are shown in Table 1. The responses of interest are surface characteristics and other measures of part quality, such as tensile strength. Quantities not varied in this set of experiments are held constant at values found to make the highest quality parts possible.

Run	Power, X_1 [W]	Thickness, X_2 [in.]	Orientation, X_{3a}	Build Angle, X_{3b} [deg]
A1,A2	10	.005	0,0s	0,45,90
B1,B2	10	.007	0,0s	0,45,90
C1,C2	15	.005	0,0s	0,45,90
D1,D2	15	.007	0,0s	0,45,90

Table 1: Factor levels for design of experiments

The top and angled surfaces of the final parts are then measured using a contact profilometer to obtain profiles of the surfaces. The deviations of a profile from its ideally smooth shape are used to indicate the existence of error modes resulting from the physics of the SLS process. On the top surfaces, we expect to see error modes from the consecutive scanning of the laser beam, from the scanning errors, from the melting of the powder particles due to high laser power, from the powder particle size and distribution, and from part curl due to the in-bed thermal response. Note that the surfaces for this study need to be long enough to pick up the low-frequency modes (e.g, curl). As a result, only horizontal parts with a long (40 mm) top surface are selected for investigation (i.e., 0 and 0s parts). In addition, angled surfaces not contained in a single build plane are measured.

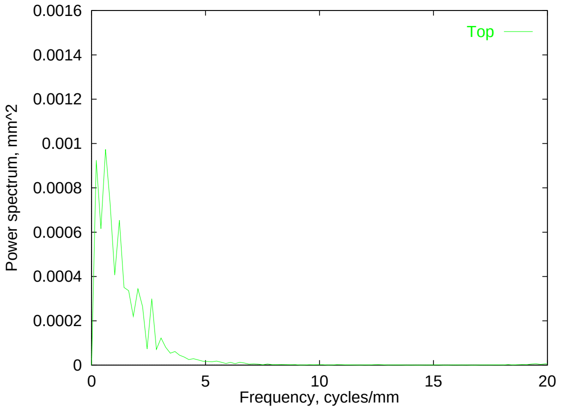


Figure 3: Power Spectrum for top surface measurements.

In order to detect the effect of the layers approximating a surface, the surfaces of parts built at an angle are investigated in more detail. Specifically, parts built at 30, 45, and 60 degree angles are compared for this part of the investigation. Finally, the 0, 45, and 90 degree parts are used to determine trade-offs between surface precision and part strength.

Spectral Analysis of SLS Surfaces

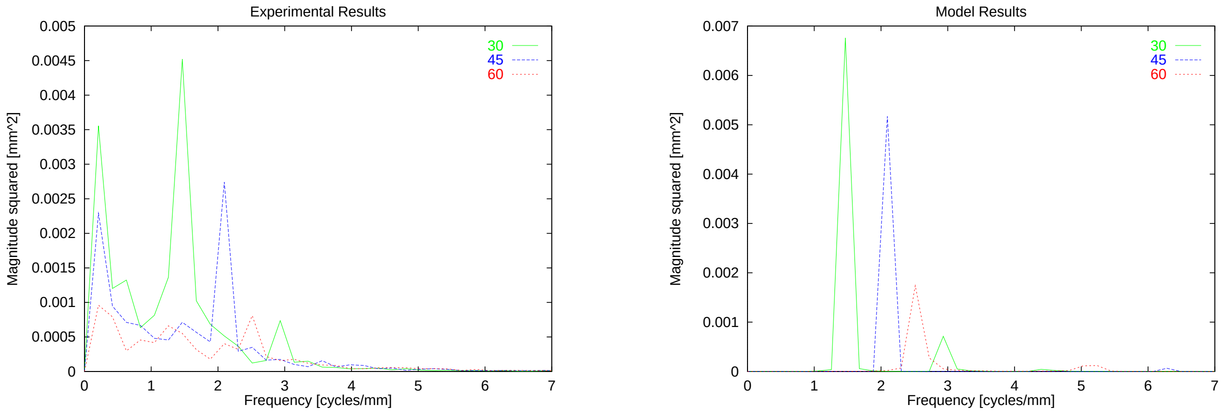
As an initial inspection of the signal content, a spectral analysis is performed on the surface profile measurements on both types of surfaces (top and angled surfaces). The spectral analysis is a way of detecting the dominant deterministic modes in a signal. The power spectrum is a plot of the magnitude squared of the Fourier transform of a signal [8, 13].

In Search of Surface Modes

A sample power spectrum of the top surface measurements (Run A2, 0 degree part) for the 0 degree build angle parts is presented in Figure 3. A common method of computing the power spectrum is to separate the discrete data into smaller segments, compute the power spectrum for each segment, and ensemble-average the power spectra [8]. The resulting power spectrum is more accurate in that the random “freak” events in the signal are averaged out, leaving the dominant modes only.

When segment-averaging is performed on the top surfaces, we observe a single wide-band frequency component, accompanied by random peaks, as shown in Figure 3. When smaller segments are used, the randomness disappears, leaving one low frequency component only. Unfortunately, these observed frequency components are too low to correspond to any of the measurable frequency components, such as beam width and particle size. The low frequency component on the top surface may be explained by melting and curl. From the top surface power spectra, we also expected to observe modes corresponding to the beam width due to the successive scanning of the top surface, and to the particle size and distribution. For example, for a particle size of 0.075 mm, the periodic component would have a frequency of about 13.3 $cycles/mm$, which is not observed on the power spectrum. These modes are obscured by the thermal modes, and cannot be detected on polycarbonate using the power spectrum.

In conclusion, the power spectrum proves to be a weak tool in detecting modes in signals from the top surfaces of polycarbonate SLS parts, except for dominant low-frequency modes. Specifically, modes caused by the machine dynamic errors are obscured by the thermal modes (such as melting of the powder and curl) on surfaces from polycarbonate parts. In general, polycarbonate powder is known to exhibit a large amount of viscous flow, which contributes to the melting mode. Other



(a) Measured power spectra.

(b) Expected power spectra.

Figure 4: Comparison of power spectra for different build angles.

powder materials might show the machine modes better [4]. To detect scanner error modes that cause surface errors, it would be more useful to measure the error at the output of the scanners. Ongoing work focuses on trying to model the scanner errors so that they can be compared to actual error modes measured at the output of the scanners [11].

Finally, to detect the modes obscured by melting on the top surfaces, it might be more beneficiary to use another signal processing technique, which can be used to extract the dominant modes in signals. This method, called the Karhunen-Loève technique, has been successfully applied to surfaces from a surface grinding process [12], and will be investigated further using surfaces from Selective Laser Sintering.

Surface Modes Due to Aliasing Effect

In addition to the 0-degree parts (built horizontally on the powder bed), we also examine the modes introduced on the surfaces of parts built at different angles (see Figure 2(a)). Surfaces of more complex SLS parts are often built at an angle from the horizontal and vertical axes. The accuracy and surface finish resulting from such surfaces are typically less acceptable than that of the vertically or horizontally oriented surfaces [4]. Therefore, it becomes important to determine the effect of build angle on the surface characteristics of SLS parts.

Despite the unsuccessful attempt to detect modes on the previously mentioned surfaces, the power spectrum can be effectively used to detect predominantly periodic modes on the SLS surfaces. In this portion of the work, we examine the periodic mode introduced by the successive stacking of layers on parts built at an angle from the powder bed. The power spectra of parts from run B2 at three different angles are shown in Figure 4a. Two dominant peaks are seen on these signals. The low frequency component is mainly due to the shifting of the layers from the motion of the roller, as well as linear trends caused by curl. When the roller shifts the part, the next layer will be offset slightly from the rest of the part, as shown in Figure 5. This appears as a low frequency term in the power spectrum of a segment containing a shift. The high frequency component observed on these surfaces corresponds to the aliasing effect caused by the layer-by-layer forming of the parts. A simple model of this expected effect is presented next.

Because SLS is a layered manufacturing process, faces at angles to the build direction other than 0 or 90 degrees are approximated by a series of "stair-steps," as shown in cross-section in Figure 6a. Using a coordinate system with one axis placed on the plane being approximated, an error function can be constructed as the distance between the original plane and the discretized facsimile. This function is depicted in Figure 6b. Clearly, the period and magnitude of the function depend on the layer thickness and the angle of the plane to the build direction. To assure that this phenomenon

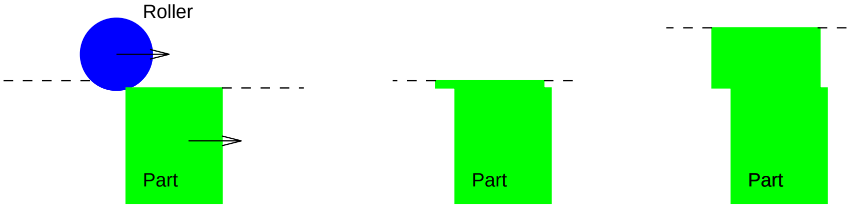
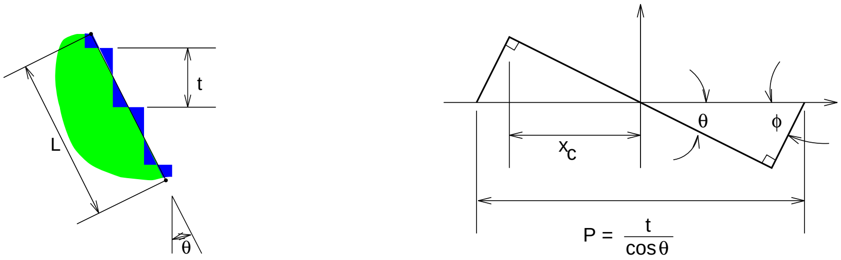


Figure 5: Mechanism for shifting of layers

is not masked by other errors, the power spectra from the experiments are compared to the power spectrum of an expected profile. The machine used to build these parts repeats each slice; this doubles the effective layer thickness used in the expected profile. A sample of these plots for one experiment is shown in Figure 4. Note that the frequency component shifts to a higher frequency with smaller magnitude as the build angle increases, as predicted by the model. In addition to verifying that aliasing occurs as predicted, the transformed data make it clear that the magnitude of this effect can dominate other surface errors at build angles near horizontal. This suggests that the angle of large facets to the build direction can significantly affect the surface quality of a part. The aliasing model can be used to minimize surface error by varying part build angle [10].



(a) Approximation of planar surface (edge on view)

(b) Error function for the surface

Figure 6: Error in layered parts.

Mathematical Measures to Characterize SLS Surfaces

The previous sections present possible interpretations for the dominant error modes on SLS top surface profiles. However, as shown previously, it is not always possible to observe modes on the top surfaces due to the abundance of thermal modes in polycarbonate SLS parts. Therefore, it is more reasonable to investigate the composite error on the top surfaces by means of mathematical measures. As a result, in this section, the effect of the experimentally controlled parameters on the overall error on the top surface measurements will be determined.

One set of mathematical measures to characterize surface precision involves the use of average parameters such as the arithmetic average of the profile height variations and the geometric average of the profile height variations. These average measures are the best known and the most common measures used in manufacturing and are readily available from the profile measurements [13]. These two measures are computed on the filtered roughness signals from top surface measurements. The arithmetic average R_a is computed as follows: $R_a = \frac{|y_1|+|y_2|+...+|y_n|}{n}$. The geometric average, or rms value, R_q, is computed as follows: $R_q = \sqrt{\frac{y_1^2+y_2^2+....+y_n^2}{n}}$.

The parameters varied for the analysis are laser power, layer thickness, and part orientation facing the roller (see orientations 0 and 0s in Figure 2(a)). The response is the precision of the top surfaces. A 2^3 factorial ANOVA analysis, shown in Table 1 is performed on the rms roughness data. Effect X_1 refers to the laser power, X_2 refers to the layer thickness, and X_{3a} refers to the part orientation with respect to the roller.

Based on these results, laser power and part orientation are the only significant control factors affecting surface precision characterized by the roughness rms measure. In addition, the interaction between laser power and part orientation can be potentially significant. The regression model from the ANOVA [5] results is

$$y = 35.79 + 1.74X_1 - 2.04X_{3a} - 1.32X_1X_{3a} \tag{1}$$

As the laser power is increased from 10 W to 15 W, the rms measure of the surface deviation increases (positive effect), hence surface precision decreases. This trend can be explained by increased flow, due to high power; the effect of the successive scans on the top surface is more accentuated. As the part orientation changes from 0 degrees to 0 degrees sideways, the rms roughness measure decreases (negative effect), and hence, surface precision increases. This can be explained by the way the parts were measured; since the long axis of the part was always used for profile measurements, the 0s part was measured along the line of contact of the roller. Measurements made transverse to this will not be as smooth because the entire profile did not have a normal force applied by the roller at once. The results of the same type of analysis on the R_a roughness value gives the same conclusions. However, the rms measure gives a more accurate picture of the significance, since it is the more reliable of the two average measures, and it is also more statistical in nature [13].

As average measures, R_q and R_a are highly reliable. However, the averaging effect removes some of the features that might be significant in characterizing a given surface profile, pushing researchers to constantly investigate other possibilities. To overcome this problem, one approach is the use of fractals to characterize manufactured surfaces. Fractal measures describe an intrinsic structure of naturally formed surfaces. This structure is characterized by an intermediate (fractional) dimension which lies in between two Euclidian dimensions [3, 13]. Fractal measures have been used to differentiate between different machining surfaces [9]. These measures work very well when the manufacturing surfaces are created by some type of fracture mechanism. However, their validity on surfaces where plastic flow occurs is questioned [13].

To answer this question, fractal parameters are computed using two methods. The Box-Counting algorithm assumes that the irregular profile is traversed by a dial gage, where the profile, embedded in two-dimensional space, is covered by boxes of different size corresponding to standard probe sizes. The log-log plot of the number of boxes versus the size of the boxes gives a straight line whose slope defines the fractal dimension [9]. The log-log plots for the SLS surfaces result in a straight line. This indicates that the surfaces are fractal at the scale studied. However, the resulting ANOVA analysis on the fractal dimension shows no trends or significant effects, which seems to imply that surfaces are not fractal. This contradiction is further investigated by computing fractal measures using another method, proposed by Srinivasan [9]. The original profile is decomposed into different scales using Wavelet transforms, giving an approximation of the profile at each scale. The difference between each approximation is called a detail. From a power-law relationship, the log-log plot of the variance of the details versus the scale should form a straight line, whose slope is related to the fractal dimension [9]. The log-log plots for the SLS surfaces using this method show several different line fragments with different slopes each. This indicates that the surfaces are not fractal at the scales studied; however, the existence of several different slopes is an indication of a “multifractal” structure [9], which explains the earlier contradiction. Further investigation is required to determine the fractal measures of surfaces at the different scales. If the surfaces are fractal, fractal measures should perform better than the average measures commonly used to characterize manufactured surfaces.

An Additional Measure of Part Quality

A surface characterization of a material may point towards possible improvements that can be made to a process; however, implementing these improvements may come at the cost of other quality measures decreasing. The specimens used in the surface characterization were built as tensile specimens so that the trade-offs between strength and surface quality could be examined. In this section, tensile tests results are investigated to determine the effect of laser power, layer thickness, and part build angle on part strength.

During testing, we observed several phenomena. In general, fracture occurred along the direction of the layers. The part strength decreases with increasing build angle since the layer area is smaller. However, some of the specimens built at high power do not show the reduction in strength with increasing angle. This observation is caused by good bonding between layers – the fractures do not occur along a layer boundary in runs such as D2.

To analyze the strength data, a factorial approach is used once again. Laser power (X_1) and layer thickness (X_2) have two levels; however, part build angle (X_{3b}) has three levels (0, 45, 90 degrees). As a result, a mixed 2^2 and 3^1 factorial experimental design is used to determine the significance of the experimental parameters on part strength. A three-level factor is used to model build angle effects because a non-linear response is expected since the area changes non-linearly with build angle.

From the ANOVA results, all of the main and interaction effects except for two are significant. X_1 and X_3 interaction (power-build angle) and X_2 and X_3 interaction (layer thickness-build angle) are insignificant. Based on this analysis, the model is:

$$\begin{aligned} y &= 1.1 + 0.545X_1 - 0.545X_2 - 0.794X_{3b} - 0.24X_1X_2 + 0.529X_{3b}^2 - 0.054X_1X_{3b}^2 \\ &\quad + 0.196X_2X_{3b}^2 - 0.064X_1X_2X_{3b} + 0.133X_1X_2X_{3b}^2 \end{aligned} \tag{2}$$

where y is the part strength in kN. Notice that as the laser power increases, part strength increases as well (positive effect); as the laser power is higher, there is better bonding or sintering between the layers, and the parts become stronger and tougher to break. Also, as the layer thickness increases, part strength decreases (negative effect); when the layers are thicker, there is not enough bonding between the layers, thus making the parts easier to break. Finally, as the part build orientation changes from 0 degrees to 90 degrees, part strength decreases (negative effect); since a 0-degree part has larger cross sectional areas for bonding between the layers than a 90-degree part, the 90-degree parts will be easier to break.

Conclusions and Future Work

This paper presents experiments designed to characterize the spatial modes that manifest on SLS parts. Experiments are run by varying four parameters: laser power, layer thickness, part orientation with respect to the roller, and build angle with respect to the horizontal powder bed. The only dominant periodic mode observed is due to the surface aliasing effect; in addition, some low frequency modes are observed, possibly due to melting, curl, and shifting of layers. Scanner modes that might have been present on the top surfaces of parts are obscured by melting due to flow in polycarbonate parts. In order to determine modes from scanner dynamics, laser positional deviations are investigated separately in another study.

The results of the study on the composite error represented by mathematical measures show that laser power and part orientation affect surface precision. An additional ANOVA study is performed to determine part strength with respect to the experimental parameters. Laser power, layer thickness, and build angle are shown to have a significant effect on part strength.

The contribution of this study is that the models developed allow trade-offs between surface precision and other measures of part quality, (e.g., part strength) to be considered. Note that an increase in laser power implies an increase in surface roughness, hence a decrease in surface precision. On the other hand, an increase in power also implies an increase in part strength. Unlike laser power, higher layer thickness leads to both decreased part strength and lower surface precision. Finally, while an increase in build angle decreases the rms roughness, hence increasing the surface precision, it also decreases part strength. As a result, when trying to improve surface quality, other measures of quality, such as part strength, must be considered as well.

Surfaces from Selective Laser Sintering, as well as other signals such as the laser beam position, will be investigated further to determine the various modes during the manufacture of a part. The real contribution of this overall work will lie in gaining an understanding of how the various modes affect SLS part accuracy and precision, as well as where these modes originate.

Acknowledgements

This material is based on work supported, in part, by a grant from the Office of Naval Research, project number N00014-92-J-1514; by The National Science Foundation, Grant No. DDM-9111372; an NSF Presidential Young Investigator Award; by a research grant from TARP; plus research grants from Ford Motor Company, Texas Instruments, and Desktop Manufacturing Inc., and the June and Gene Gillis Endowed Faculty Fellowship in Manufacturing. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the sponsors.

References

[1] Xiaoming Deng and Joseph J. Beaman. Application of factorial design in Selective Laser Sintering. In *Solid Freeform Fabrication Symposium*, volume 3, pages 154–160, Austin, TX, August 1992. The University of Texas at Austin.

[2] Paul Forderhase. Sinterstation 2000 scanner optimization. Internal document on DOE studies on dimensional accuracy, October 1994.

[3] B.B. Mandelbrot. *The Fractal Geometry of Nature.* W.H. Freeman and Company, New York, 1983.

[4] Kevin McAlea. Personal conversation, July 6, 1995.

[5] Douglas C. Montgomery. *Design and Analysis of Experiments.* John Wiley and Sons, New York, 1991.

[6] James Christian Nelson. Scanning method comparison. Internal Document (Confidential), September 1993.

[7] James Christian Nelson. *Selective Laser Sintering: A Definition of the Process and an Empirical Sintering Model.* PhD thesis, The University of Texas at Austin, May 1993.

[8] Edward J. Powers. Polyspectral analysis and its applications. Class notes (EE 381L), 1990. Department of Electrical and Computer Engineering, The University of Texas at Austin.

[9] R.S. Srinivasan. *A Theoretical Framework for Functional Form Tolerances in Design for Manufacturing.* PhD thesis, The University of Texas, Austin, Tx, 1994.

[10] David Thompson. Optimizing part orientation for SLS. In *SFF Symposium Proceedings.* The University of Texas at Austin, 1995.

[11] Irem Y. Tumer, Ilene J. Busch-Vishniac, and Kristin L. Wood. Modeling of dynamic errors caused by the beam delivery system in selective laser sintering. In *SFF Symposium Proceedings.* The University of Texas at Austin, 1995.

[12] Irem Y. Tumer, R.S. Srinivasan, and K.L. Wood. Investigation of characteristic measures for the analysis and synthesis of precision-machined surfaces. *Accepted for publication, Journal of Manufacturing Systems*, May 1995.

[13] D.J. Whitehouse. *Handbook of Surface Metrology.* Institute of Physics Publishing, Bristol, UK, 1994.