# QUANTIFICATION OF PART SURFACE QUALITY: APPLICATION TO SELECTIVE LASER SINTERING [1]

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## ABSTRACT

Quantifying faults in manufacturing processes is a crucial concern, particularly in new manufacturing processes where continual product improvement is desired. We present an approach to incrementally diagnose fault patterns on surfaces of product components. Contemporary experimental and surface-analysis techniques are adapted at each step of the approach. Specifically, a maturing layered-manufacturing process, Selective Laser Sintering (SLS), is investigated. The paper concludes with a summary of fault mechanisms on SLS parts, implementation issues for improving part quality, and insights for applying our approach to other processes.

**KEYWORDS:** surface quality, surface analysis, fault patterns, manufactured surfaces, fault diagnosis, Selective Laser Sintering, Solid Freeform Fabrication.

## INTRODUCTION

Traditionally, the quality of manufactured products is assured by a good knowledge of the machine: parameters affecting part quality are monitored regularly and calibrated off-line or adjusted on-line. For example, in-process inspection of workpiece diameter in a turning operation can indicate a deviation in the system parameters; adaptive control tools installed in the system can automatically detect this deviation and adjust the cutting tool position to produce the correct diameter [4].

In most manufacturing processes, the variables and mechanisms to monitor and control are known in advance: methods to diagnose faults that result in poor part quality rely on previous knowledge of fault patterns, using either known patterns, models, or predetermined specifications and control limits [2]. However, when a newly-developed manufacturing process is being investigated, the nature of the fault patterns is not known [2].

In this work, we aim to eliminate the need for pre-existing knowledge, and present methods that can be applied systematically to detect and diagnose faults that affect part quality. We present a formal means to quantify and characterize the significant parameters and fault patterns. Once these are identified, monitoring and control tools, along with optimization schemes, can be implemented to assure the production of high quality parts.

The following approach is proposed to investigate faults in a newly-developed manufacturing process in an efficient and systematic manner: select appropriate system response; identify relevant mechanisms and parameters; apply experimental design and analysis; analyze experimental results for surface characteristics; determine fault patterns with random process analysis; and, choose remedial actions for monitoring and control. The steps of this approach are selected carefully to gain incremental insights into fault detection.

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[1] The 1996 World Automation Conference Proceedings, pp. 731-736, Montpellier, France, May 1996

## Current Focus: Selective Laser Sintering

This paper presents an investigation of part surface profiles from a maturing manufacturing process, namely Selective Laser Sintering (SLS), to provide an understanding of the nature of fault generating mechanisms that affect part quality. The SLS process is based on the system depicted in Figure 1 [3]. The powder delivery system deposits a thin layer of powder onto the work surface from the powder cylinder. A roller mechanism spreads the powder evenly, and a computer-controlled laser beam scans the surface of the powder layer to the desired shape by means of scanners and mirrors. The beam is turned on and off to heat up and sinter the powder in the selected areas to be occupied by a part at a given cross-section. Successive layers of powder are deposited and sintered until the entire part is produced.

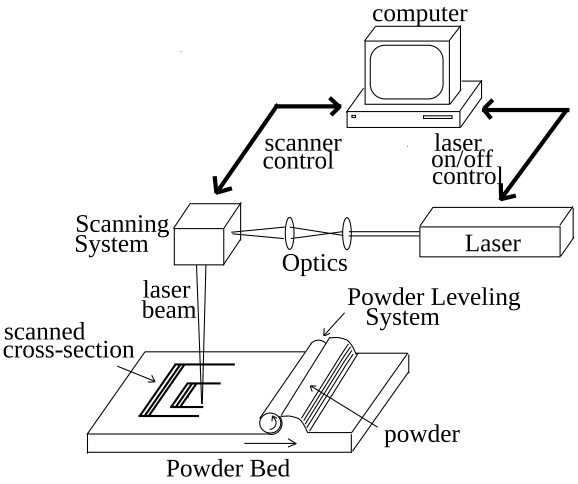


**Figure 1:** The Selective Laser Sintering Machine Process.

The physical mechanisms that may generate faults on final SLS parts can be divided into four main categories: namely, faults caused by the machine's dynamic response, faults from the system's thermal response, faults due to the part's geometry and orientation in the powder bed, and faults caused by the surface texture as a result of the size, shape, distribution, and sintering properties of the powder material. Figure 2 shows a subset of these mechanisms.

## SURFACE QUALITY ANALYSIS

In this section, the effect of the experimentally controlled parameters on the overall surface deviations is determined. Surface analysis is often used to study the irregularities in surface geometry, providing a “fingerprint” of the manufacturing process [9].

### Experimental Design and Analysis Methods

One subset of parameters, identified to potentially affect part quality, consists of layer thickness, laser power, and part orientation. These parameters are operator controllable; their values are typically set by trial-and-error and calibrated regularly to produce the best part possible. A factorial experimental design and an analysis of variance (ANOVA) study are performed to analyze the results. Profile measurements are made using a contact profilometer, along the long axis of the tensile specimen on the face pointing “upwards,” over a length of 40 $mm$. The details of these experiments are presented in [8].

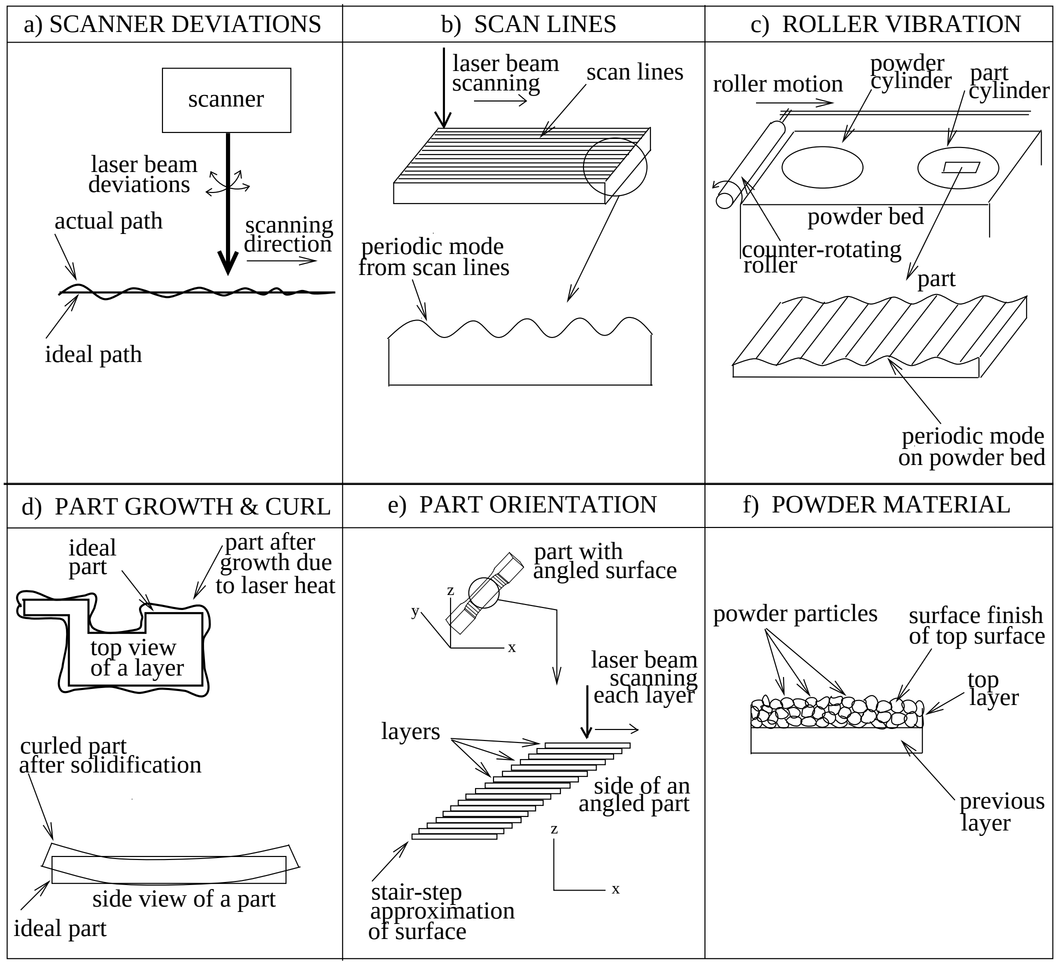


**Figure 2:** Possible Error Mechanisms in SLS.

## Average Surface Height Measure

The geometric average $R_q$ (RMS roughness) height measure is an appropriate measure for communicating the desired surface precision [8, 9]. The effect of laser power ($X_1$), layer thickness ($X_2$), and build angle ($X_3$) on surface quality (defined in terms of surface roughness) is investigated by means of ANOVA. The resulting regression model is given by:

$$y = 38.72 + 5.544X_2 - 5.222X_3 - 6.097X_3^2 + 2.741X_1X_3^2 - 4.347X_2X_3^2. \qquad (1)$$

The model shows that surface roughness increases with layer thickness (positive effect) and decreases with build angle (negative effect). An increase in surface roughness implies a decrease in surface precision, and hence part quality.

## Discussion of Experiments and Characteristic Measures

The results of this portion of our diagnostic approach provide information about the average surface characteristics of the SLS parts with respect to the selected process parameters. Specifically, we have shown experimentally that build angle and layer thickness significantly affect surface precision. The empirical models developed can be used to predict the general trends in surface precision and determine tradeoffs among process parameters [5].

However, monitoring an average single value such as the surface RMS roughness can often lead to false or incomplete conclusions about the surface precision [9]. An average profile measure will indicate the steady-state values of the faults on the part surface, and not the onset of the problem. This measure provides crucial information necessary to detect potential problems and failures in the system. Additional knowledge of the character, or shape of the fault pattern, is often necessary to determine the source of the fault causing a change in surface precision.

An alternative and complement to average measures is to use random process analysis techniques to determine the true characteristics of the fault patterns. More advanced random process analysis methods are used to study signals from manufacturing to gain insight on the nature of the fault patterns that result in poor surface precision, identified in Figure 2.

## RANDOM PROCESS ANALYSIS

The second part of the diagnostic approach investigates the specific fault patterns on the manufactured parts, using random process analysis tools.

### In Search of Fault Patterns on SLS Surfaces

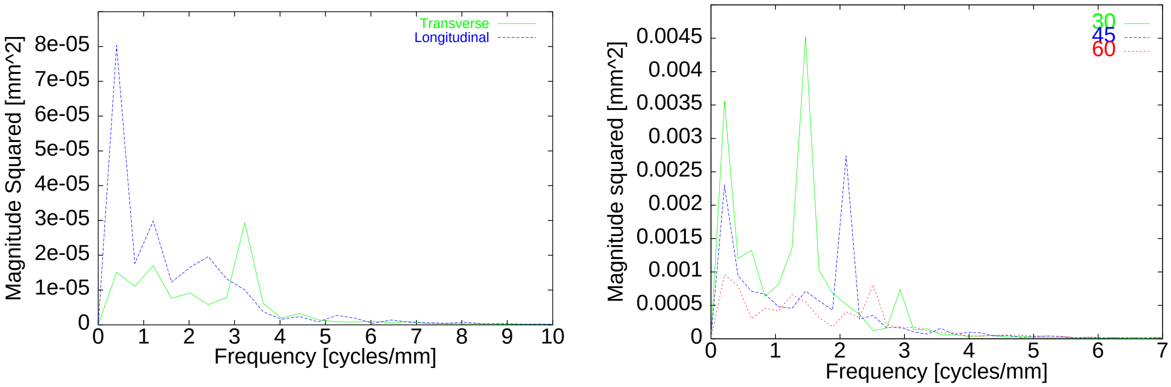
To determine and quantify the nature of fault patterns, SLS surface measurements are analyzed using spectral analysis [1, 9]. From the top surface measurements of the horizontally-built parts, we expect to detect faults due to the machine, the high temperatures, and the powder (see Figure 2). From the measurements of angled surfaces, we expect to see fault patterns caused by the geometry and orientation of the part (see Figure 2).

Spectral analysis is first performed on the top surface measurements of the horizontally-built SLS parts. The results of this analysis show that thermal patterns dominate and mask the remaining patterns on the top surfaces of horizontally-built polycarbonate parts. Specifically, the fault patterns caused by the machine dynamic errors are obscured by thermal patterns, such as excessive flow from melting of the powder. In general, polycarbonate powder is known to exhibit excessive viscous flow, which contributes to melting. One way to circumvent this problem is by using another powder material exhibiting less viscous flow, which might show the expected fault patterns more accurately.

To search for the fault patterns that are masked by melting due to excessive flow in polycarbonate parts, a similar part made using a different commercial powder product is used to analyze the top surfaces of $0°$ parts. The commercial powder product is similar to the standard polycarbonate powder, but with smaller particles of more spherical shape; these are two properties that eliminate the problem we encountered using the standard polycarbonate powder.

The power spectra of measurements in the longitudinal and transverse directions are shown in Figure 3(a). The spectrum for the longitudinal measurement reveals three frequency components. The dominant frequency component at $0.403\ cycles/mm$ (period of $2.48\ mm$) corresponds to the frequency of the fault pattern left on the powder surface due to the roller vibration as a new layer is deposited (Figure 2(c)). Furthermore, the analysis reveals two additional frequency components at frequencies of $1.209\ cycles/mm$ and $2.419\ cycles/mm$. These frequency components will be verified by measuring the vibrations of the roller motion, and studying the relation to the frequency components that we computed from the surface profile measurement. The spectrum of the transverse measurement also shows three frequency components. The dominant frequency component at $3.22\ cycles/mm$ (period of $0.31\ mm$) corresponds to the periodic pattern left on the part surface due to the scan lines of the laser beam (Figure 2(b)). The predicted value of the period of this fault pattern can be derived from the knowledge of the beam width and overlap between scans used when the part was built.

To search for fault patterns on angled surfaces, spectra of profiles of the $30°$, $45°$, and $60°$ parts are compared to spectra of surfaces predicted from a model. Specifically, the periodic fault pattern introduced by the successive stacking of layers on parts built at an angle from the powder bed (Figure 2(e)) is examined.



**(a)** Horizontal surfaces, commercial powder.

**(b)** Angled surfaces.

**Figure 3:** Power spectra showing different fault patterns.

The power spectra of parts at three different angles are shown in Figure 3(b). The high frequency component observed on these surfaces corresponds to the aliasing effect caused by the layer-by-layer forming of the parts. Note that the frequency component shifts to a higher frequency with smaller magnitude as the build angle increases, as predicted by the model. The magnitude of this fault pattern dominates other surface faults 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 low frequency component is due to the observed shifting of the layers from the motion of the roller. When the roller shifts the part, the next layer will be offset slightly from the rest of the part.

## Discussion of Fault Patterns

We have detected several important fault patterns from this analysis. First, the orientation used to build a part introduces a periodic fault component that is easily detected on the surfaces of angled parts using the spectral analysis technique. The results show that increasing the build angle and the layer thickness increases the severity of this fault component. The fault pattern can be minimized using the resulting regression model. In addition, an acceptable threshold for this fault pattern can be preset and then compared to measurements from the surface to monitor the surface quality.

Second, we have shown that thermal patterns dominate the top surfaces of horizontally built parts, attributed to the melting from excessive flow in polycarbonate powder. A commercial part made with a powder material is measured to show that periodic fault patterns from the roller vibrations and from the beam scan lines can be detected using the spectral analysis method. Based on acceptable thresholds for the surface fault pattern, the vibrations of the roller can be monitored and remedial action can be recommended when this threshold is exceeded. The marks left on the part due the scan lines can also be monitored to recommend proper beam width and beam overlap parameters based on acceptable fault magnitude levels established by the customer.

We were unable to detect fault patterns due to the particle size and due to errors caused by deviations in the scanning system. The patterns from the powder material are obscured due to their random nature. Since the spectral method averages over time and frequency, the stochastic and nonstationary features are completely smoothed out [9]. To detect these obscured fault patterns on the top surfaces, other signal processing techniques can be used to extract the dominant fault patterns in signals. One such method is proposed in [7]; the method, called the Karhunen-Loève technique, has been applied to surfaces from a surface grinding process. The suitability of other methods is also being studied, such as higher-order statistics and wavelet transforms.

The fault patterns due to the deviations of the scanner system were also not identified from this analysis. An alternative approach to analyzing such faults is to isolate the source of the fault and analyze this system's output to detect any deviations from the ideal path of the laser beam. For example, the source of the deviations in the ideal laser beam path has been associated with the dynamics of the beam delivery system [6]. By measuring the vibration from this system, a threshold can be established to prevent the laser beam deviations from exceeding acceptable limits.

In addition to the fault patterns we were searching for, we also detected a spatial fault pattern due to layer shifting. A shift in the layers was observed as the roller traveled over each newly-formed layer. Using results from this analysis, the implementation of remedial actions can be automated. For instance, a threshold can be established to indicate acceptable and unacceptable levels of this fault pattern and compared to the actual patterns from the part; remedial action, such as, inclusion of larger cross-section layers to keep the layers from shifting, or calibration of relevant parameters, can be initiated once the severity of the fault pattern is declared unacceptable.

## CONCLUSIONS AND FUTURE WORK

This paper presents experiments designed to characterize the spatial modes that manifest on polycarbonate parts from faults in Selective Laser Sintering. Part quality can be affected by fault patterns that are generated on surfaces because of various fault-generating mechanisms. This work aims at identifying these mechanisms by using surface analysis tools, along with factorial experimental design and ANOVA tools.

The systematic approach described in this work can be applied incrementally to any newly developed manufacturing process to determine the parameters that effect part quality, so that an optimization scheme can be proposed to improve part quality, and to determine the types of faults and their origin, so that remedial action can be taken. Such formal means of detecting, quantifying, and characterizing faults in a manufacturing system are necessary to allow for the monitoring and control of the system to assure the production of improved quality parts.

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