STATISTICAL PROCESS CONTROL FOR SOLID FREEFORM FABRICATION PROCESSES

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ABSTRACT

Statistical process control (SPC) has not been widely used for solid freeform fabrication (SFF) processes, primarily due to the wide diversity of geometries in builds. In addition, typical parts created on SFF platforms are not of simple, nor easy-to- measure geometries, which further complicates the application of SPC. A study is currently in progress to establish a method to apply SPC to SFF. Three SPC test parts were studied to determine the added build cost and accuracy improvement when SPC is applied to stereolithography. In this study, SPC was applied to X & Y shrinkage, and line-width-compensation factors over a period of time. If SPC can be effectively applied, it will alert the operator to otherwise unnoticed system changes before valuable build-time is lost.

INTRODUCTION

With the advent of Solid Freeform Fabrication (SFF) technologies, new manufacturing techniques are emerging. Users of SFF will continue to demand improved accuracy and repeatability for these new manufacturing techniques. Statistical process control (SPC) has not been widely used for SFF, but there is a rising competitive need to improve the quality of SFF processes.

Control-charts are one answer to quality improvement for SFF. Dr. Walter Shewhart of the Western Electric Company developed a control-chart to monitor the manufacture of fuses, heat coils, and station apparatus as early as 1924 [1]. Since this early control-chart, SPC has evolved, and is now widely used to monitor many modern manufacturing processes.

SFF is now being used in roles other than a conceptual three-dimensional printer; for example, it is being used for custom-manufacturing [2], rapid-tooling [3], and medical applications [4]. SFF materials and processes used vary considerably, but each technology has several distinct controllable variables that are key to optimizing quality. The ability to monitor and control these variables must be improved, if SFF is to move to a higher level of manufacturing quality.

In current SFF practice, quality control is accomplished by a periodic evaluation of build parameters by building specific diagnostic parts. For the Fused-Deposition-Modeling (FDM) process, a calibration box [5] is used to calibrate Z-offset. For the Stereolithographic (SLA) process, WINDOWPANES™ and CHRISTMAS-TREES™ [6,7] are used to adjust penetration depth (D_p), critical exposure (E_c), X/Y shrinkage compensation, and line-width-compensation (LWC). For the Laminated-Object-Manufacturing (LOM) Process, a Helisys test part is used to evaluate the build process. In addition to these technology-specific diagnostic parts, several RP-user parts have been developed to compare and evaluate different SFF technologies. Because these diagnostic parts could be used for SPC, but were not designed for SPC, new SPC designs are needed. Other reasons why SPC charts have not been adopted for SFF include:

- Variation in part geometry from one build to the next.
- Cost of producing a measurable part on each build.
- Variations among SFF technologies.
- Variations in materials used in individual SFF machines.
- Variations in build styles in individual SFF machines.
- Operators and customers who are satisfied with the current quality level.

Since SFF technologies vary widely, SPC must focus on those variables that are critically related to build quality. For FDM, the density of a part may suggest something about the extrusion fusion quality. On the Selective Laser Sintering (SLS), perhaps the flexural modulus of a small nested sample would indicate part quality. For the SLA, the X/Y shrink-factors and LWC that can be monitored to improve accuracy, are the variables focused on in this paper. In the following sections the SPC approach, results, conclusions, and future SPC research are discussed.

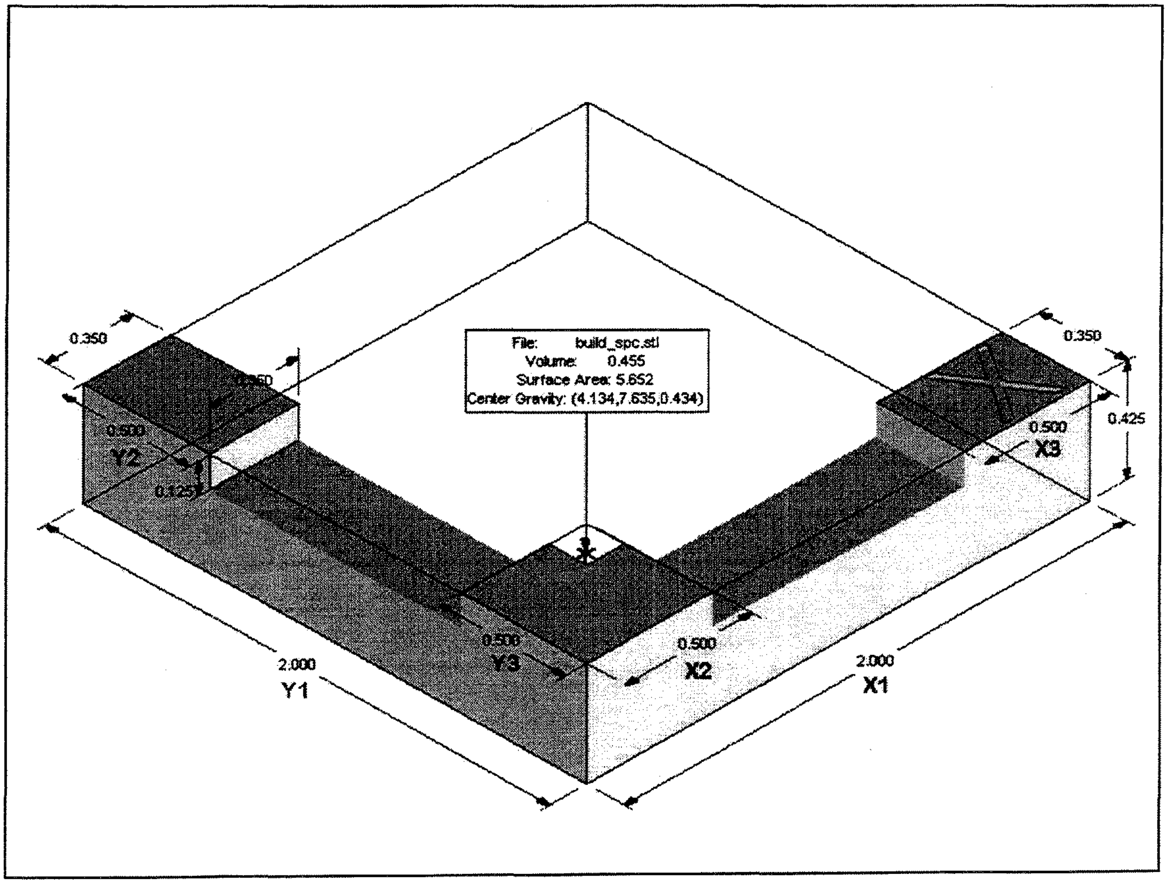

Figure 1. SPC L-block* (units in inches)

SPC APPROACH

The approach to applying SPC to stereolithography reported here, used an Exponential Weighted Moving Average (EWMA[8]) chart, to monitor both X/Y shrinkage-factors and line-width compensation factors. This chart was chosen over conventional X-bar & R charts, due to the EWMA chart's ability to use one test-block per build. The EWMA chart is able to smooth an inherently variant data set, to make trends more apparent. The L-block* shown in Figure 1, was designed to have minimal build volume, while being a fair representation of the entire build. In other words: if all parts on the build were created with the same LWC, layer thickness, and build style, one small L-block will accurately represent the quality of the entire build (neglecting part size and position).

The L-block was randomly positioned with the "X" leg parallel to the X-axis, placed anywhere. For this SPC experiment, the L-blocks were built with 0.006 inch layer-thickness builds, and typically only one copy was created per build. After the build was complete, the L-block was handled as if it were one of the actual parts to be post-processed. TPM and denatured alcohol were used for resin removal, followed by support removal, and ultraviolet light curing. Next, the L-block was measured for the EWMA charts. The following calculations were used to find X_t (the L-block X-axis result) from the average of three measured values of three dimensions (L-block, measurements, and CAD dimensions are illustrated in Figure 1). The target value for X_t was 3.000 inches.

$$X_t = 2\overline{X}_1 - (\overline{X}_2 + \overline{X}_3) \approx 3.000 \text{ inches (target)}$$

Next, the EWMA for X_E was calculated using the following formula:

$$X_E = \omega X_t + (1-\omega) X_{t-1}$$

Where X_E = Exponentially weighted moving average,
X_t = Measured value at time t,
and
ω = Constant for weighting (0 to 1)

After X_E was calculated for 30 L-blocks, the standard deviation and control limits were calculated for the X-axis as follows:

Standard deviation of raw measurements for X-axis calculation:

$$\sigma_E = \sigma_t \sqrt{\frac{\omega}{2-\omega}}$$

Where σ_E = Standard deviation of calculated data
and
σ_t = Standard deviation of raw measurements

Upper and lower control limits for X-axis calculation:

$$UCL = \mu + 3\sigma_E$$
and
$$LCL = \mu - 3\sigma_E$$

Where μ = the average of all X_t values,
UCL = upper control limit,
and
LCL = lower control limit

Next, X_t, X_m, UCL, LCL, and μ values were plotted on the EWMA chart (figures 2). As shown, the UCL, μ, LCL were drawn as straight lines.

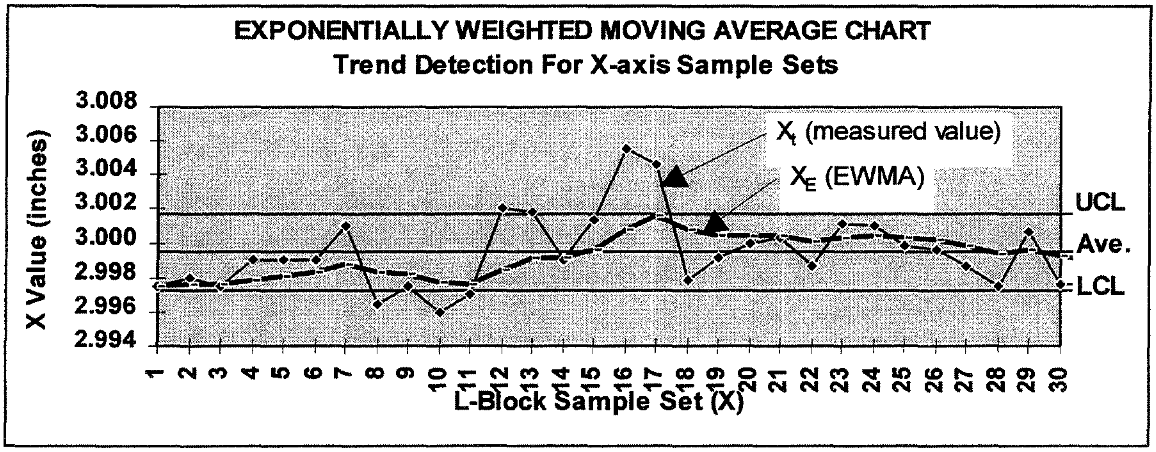

Figure 2

The calculations used to produce the chart for the X-axis measurements were repeated for Y-axis measurements, to generate Figure 3.

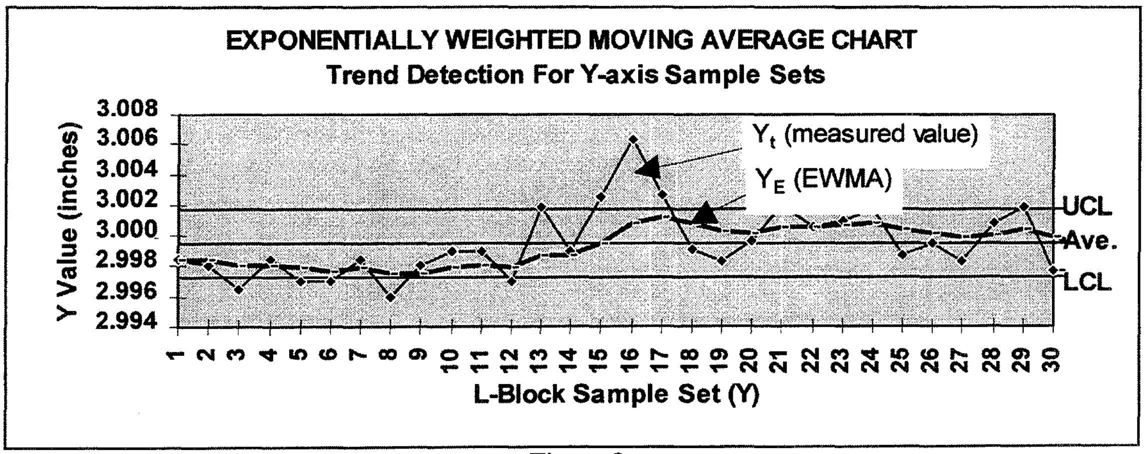

Figure 3

With the control-charts generated, with 30 points for X-axis & Y-axis the standard method for monitoring a control-chart was used. When a point or a series of points showed a trend, the X/Y shrink-factors or LWC were adjusted.

By using a spreadsheet to calculate EWMA, future LWC and shrink-factors were automatically predicted. When the EWMA indicated a trend, the next predicted shrink-factors and LWC (from trend-line) were used for the new settings. To calculate the LWC and shrink-factors the following equations were used:

Line-width-compensation (LWC) calculation:

$$\mathrm{LWC} = \frac{1}{6}(\overline{X}_2 + \overline{X}_3 + \overline{Y}_2 + \overline{Y}_3) - \frac{1}{12}(\overline{X}_1 + \overline{Y}_1) + \mathrm{LWC}_{\mathrm{now}}$$

Where $\mathrm{LWC}_{\mathrm{now}}$ = Current line-width compensation

X-axis shrink-compensation (X_{SC}) Calculation:

$$X_{sc} = 100\left[\left\{\frac{3\{(0.01X_{sc-now}) + 1\}}{\mathrm{X_E}}\right\} - 1\right]$$

X_{sc-now} = Current X shrink factor

Y-axis shrink-compensation (Y_{SC}) Calculation:

$$Y_{sc} = 100\left[\left\{\frac{3\{(0.01Y_{sc-now}) + 1\}}{\mathrm{Y_E}}\right\} - 1\right]$$

Y_{sc-now} = Current Y shrink factor

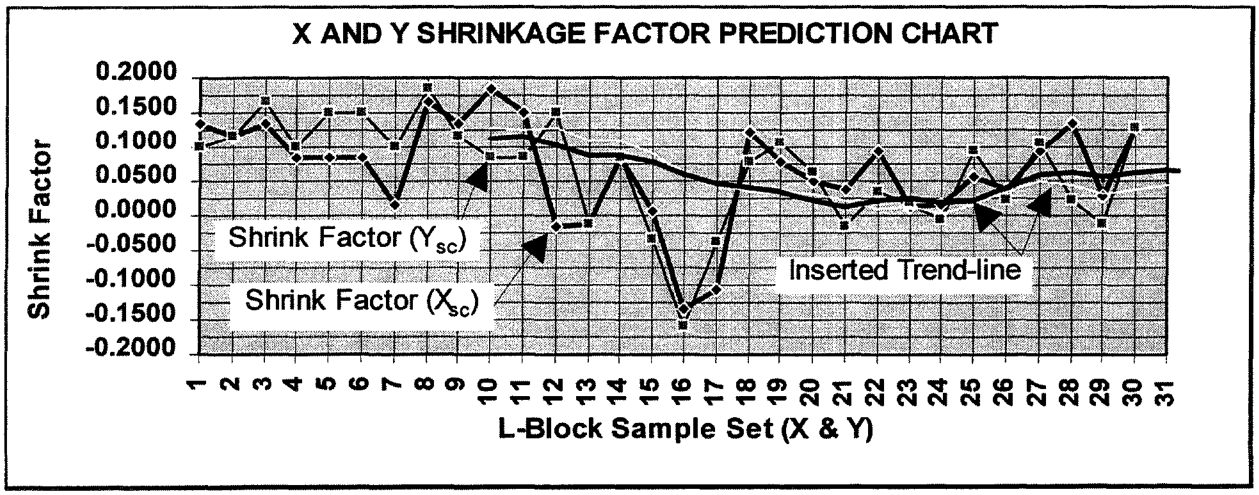

Figure 4

Thirty shrink factors (X & Y) and LWC's were plotted on separate charts as shown in figures 4 and 5. Moving average trend-lines were added to Xsc, Ysc, and LWC plots to predict the best X/Y shrink-factors and LWC for the next build. These numbers were only needed when a trend was detected, although, these values could be used more often to form a feed back loop.

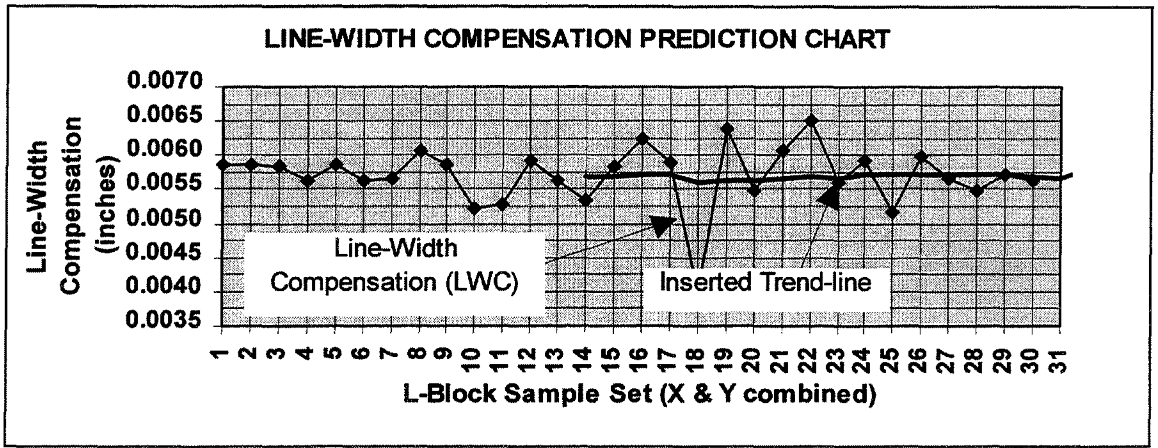

Figure 5

RESULTS/DISCUSSION

The first phase of this study focused on designing a reliable test block, generating 30+ data sets from that test block, applying EWMA chart techniques using the data, and finally predicting future SLA build parameters. A total of three block designs were studied and the final L-block shown in Figure 1 was used to generate the 30 data-sets. The data-sets were used to create the charts shown in figures 2,3,4&5. The results of the first phase of this multi-phase study are discussed below.

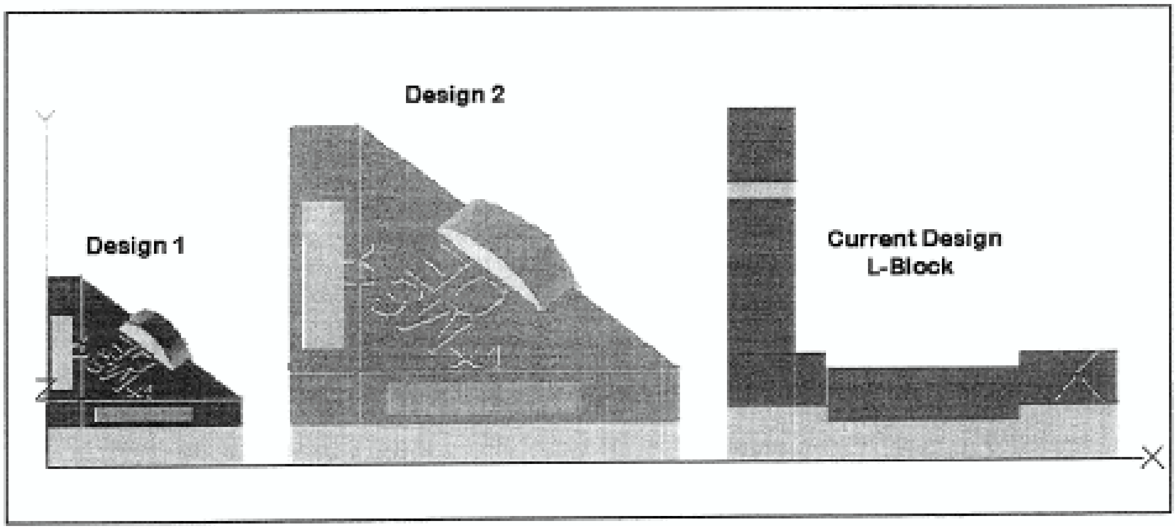

Figure 6. Three SPC Test-block Designs

The three test-block designs were tested for this experiment are illustrated in figure 6. The goal was to find a design that could be easily measured, have minimal volume, and have a minimal foot-print. Yet another important characteristic of the chosen test-block was to have similar results when measured by several people. The first design proved unreliable when different technicians took measurements. The small size caused shrinkage to become too small for accurate results. The second design satisfactory, but the volume and footprint were larger than desired. The L-block did have the best repeatability of measurements by different technicians. The total volume was approximately 0.5 in^3 with a footprint of 2 inches by 2 inches. The L-shaped foot-print worked well, and was easily fit into most builds.

The first two charts (figures 2 & 3) were generated to display the X_t & Y_t (measured) values, X_E & Y_E (EWMA) values, averages, and upper/lower control limits. A weighting constant (ω) of 0.20 was used for X_E and Y_E to produce the smoothed EWMA curves. The value of ω can be adjusted from 0 to 1 to obtain desired smoothing. Interestingly, both curves follow very similar paths. This similarity suggests that the L-block measurements are repeatable and that changes in build accuracy usually occurred in the X and Y simultaneously. The fluctuations of the two EWMA curves were also worth noting. The peak around data point 17, on both charts, apparently was caused by a variable that can be controlled. This may be due to fluctuations in laser power, humidity, resin properties, blade residue, and/or other factors. The main point in this example was that trends like this can be addressed.

The X and Y shrinkage factor prediction chart (Figure 4) was used when an EWMA curve shows a trend. A trend was detected around data set 17, but the trend-line value was very close to the current shrink factor, so no change was made. Again, it is worth noting that both trend lines are surprisingly similar.

The Line-width compensation prediction chart (Figure 5) is also used when an EWMA curve shows a trend. When the trend was detected at data set 17 on both charts a new LWC value was implemented. The previous LWC value was 0.005 inches replaced with 0.006. As shown in the succeeding EWMA chart values (sample sets 18 to 30) this adjustment was successful in increasing accuracy.

CONCLUSIONS/ FUTURE DIRECTION

Statistical Process Control can be used for SFF processes if the critical variables are identified and a means of monitoring these variables is used. In this particular SLA application of SPC it was shown, in one instance, that a trend can be detected and corrected. The EWMA control-chart does seem to fit this application, and perhaps other SFF processes will adopt SPC methods.

The next phase of this study will be to further verify that this SPC chart does signal significant changes in the build process and that they can be corrected. Changes in blade-gap, laser-power, build-style, Z-wait, build size, post-processing, humidity, resin viscosity, resin age, X/Y beam ratio, laser remelts, number of sweeps, and other variables will be studied. In addition, window panes and christmas trees will be performed to learn whether calibrated Dp and Ec will improve accuracy over time, and to compare the current X/Y shrink-factors and LWC to those derived from the L-block results.

The third phase of this study will be to develop SPC models for several other SFF processes. SPC will be applied to LOM, FDM, and SLS as well as other important characteristics of the SLA. The development of user-friendly software programs and measurement systems will also be developed.

The objective of this SPC effort is to identify methods to improve product quality, and to improve the SFF industry in general.

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* The L-block and related equations were developed at the Milwaukee School of Engineering Rapid Prototyping Center in March, 1997