On dimensional stabilities : Modeling of the Bonus-Z during the SLS Process

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Abstract

This work is a first step towards the prediction of the dimensions and thermo-mechanical properties of parts made with the Selective Laser Sintering (SLS) technology. An important variation of the dimensions is found in the Z-direction of the build. This phenomenon is known as the "Bonus-Z" where material properties differ from those in the rest of the part due to a non-homogeneous sintering. The focus of this work is the characterization and the modeling of the bonus-Z phenomenon, by relating it to the energy input. The polymer powder used in this study is polycarbonate.

1. Introduction

In a recent tensile experiment we have dealt with problems of dimensional stabilities of the tensile samples using polycarbonate powder. The results we got are biased by the failure to obtain the same dimensions on parts built with different process parameters. The most important variation was found in the Z-direction of the build, a phenomenon known as "Bonus-Z". Bonus-Z counts for the extra sintering of powder that occurs under the first layer built. This extra sintering is due to laser energy that is in excess from the ideal laser energy that would be enough to sinter the particular layer.

Due to the phenomena of growth, shrinkage and curling, we also get different dimensions in the X-Y directions when building a specific part with different process parameters, but the highest difference is found in the Z-direction. As a result, the tolerances in the Z-direction are far away from the wanted ones.

Rapid prototyping part accuracy has been documented in a number of studies [1-4]. In most of these studies accuracy is reported as the deviation of measured dimensions from the desired ones. The basic remedy to the bonus-Z phenomenon is the sintering of the first layers with less laser power, implying less energy delivered to the powder bed. Due to the complexity of the part's geometry, a dynamic variation of the laser power during the build is a very complex task. In this study, the accuracy of SLS parts in the Z-direction of the build will be discussed. We will focus on the energy delivery into the powder bed.

To fabricate a part, powder is first spread in a thin, uniform layer over the part bed surface, and a typical layer thickness is 0.12 mm. The laser beam is raster scanned over the part bed surface with the scanning mirrors and the laser energy modulated so that only the area which corresponds to the cross section of the object is fused. The two dimensional cross sections are defined by software that "slices" the three dimensional CAD model into layers. Once the first layer is built, a new layer of power is spread. This new layer is then scanned with the laser and this process is repeated until the part is completely built. Sufficient laser energy is used so that each new layer is bounded to the previous layer and as the part is fabricated, the unsintered powder beneath the scanned layers provides support for features as overhangs.

The part bed temperature is typically held just below the glass-transition temperature of the polymer, so that little laser energy is enough to sinter the desired areas. This method also prevents high thermogradients within the powder bed. However, controlling the amount of energy that penetrates into the powder bed within and beneath the scanned layer is a very complex task mainly due to the following reasons :

i) when about to build a layer that is scanned on unsintered powder (in contrast with a layer built on previous layers), we need to know the exact amount of energy to deliver in order to sinter only the powder that corresponds to the thickness of one layer. Otherwise, powder beneath this layer will also be sintered resulting in bonus Z.

ii) the properties that dictate the behavior of the sintering (such as powder density, thermal conductivity, temperature) change with the degree of sintering, and are function of the time and the geometry of the build (such as scan direction, scan pattern, scan spacing, scan speed etc.).

iii) a certain amount of energy penetrating beneath the scanned layer is needed in order to bound the currently scanned layer with the previous one.

2. Experiments

At Clemson University, we are working on the SLS with the objective of developing process understanding that will lead to system performance improvements. Previous studies from our team [5-6] have dealt with the control of thermal gradients within (and beneath) the layer being sintered (or melted) that has been identified as a key process issue. Large thermal gradients are a significant feature of the SLS process using polycarbonate, the material we used in our studies.

We are interested in finding the contribution of each layer of a build to the final bonus Z of the part. The experimental approach uses square parts of one inch side, fabricated on a research SLS workstation. In the same run, eight squares are being built, all with the same process parameters. The process parameters are kept constant for all the layers and the most important parameters are :

Bed Temperature : 120°C
Laser Power : 7.5 Watts

Beam Speed : 5.70 in/s
Glass Transition Temperature : 150°C

The first square is one layer thick, the second square two layers thick and so on. Then we measured their thickness, compared it to the expected thickness and we derived the bonus-Z. Table 1 shows that, out of 19 mils (482 μm) of bonus-Z after 8 layers, 12 mils (305 μm) of the bonus-Z are obtained during the building of the very first layer. 3 more mils of bonus-Z are related to the third layer. One more mil of bonus-Z comes with the building of the fifth, and with the seventh layer. Finally two more mils of bonus-Z result from the eighth (the last) layer. These results were obtained by using the above process parameters. When the laser power was increased to 12.5 Watts, a bonus-Z of 18 mils (457 μm) was obtained for the first layer. Our objective was to build these squares with the less bonus-Z possible. For laser power values less than 7.5 Watts, sintering in our SLS station was not enough to sinter a first layer.

Table 1 : Evolution of Bonus-Z during the built of 1 in. side squares

Layer Number	***Measured Thickness (mils)***	***Expected Thickness (mils)***	***Bonus Z***
# 1	0.017	0.005	0.012
# 2	0.022	0.010	0.012
# 3	0.030	0.015	0.015
# 4	0.035	0.020	0.015
# 5	0.041	0.025	0.016
# 6	0.046	0.030	0.016
# 7	0.052	0.035	0.017
# 8	0.059	0.040	0.019

3. Simulations

In order to reduce bonus-Z, DTM Corporation advises to reduce the laser power while building the first layers. However, bonus-Z is not only a function of laser power : It also depends on the geometry of the part to build, and manual control of the energy delivery becomes impossible due to the high speed of the build. In order to control automatically the delivery of the laser energy, both a hardware and a software have been developed at Clemson University. The hardware part is described in full details in [7]. It is now possible to include in the scan file (file that describes the part to build in scanning commands) a new command that controls the laser power. Based on the remarkable work of Sun and Beaman [8-9] a building simulator has been developed. We have implemented the model of Sun and Beaman to simulate the building of a part using the same scan file that is sent to the General Scanning Inc. (GSI) scanners. As an output we get predictions of the time of the build, temperature, density and energy in the powder bed. In their physical modeling of the SLS process, Sun and Beaman have used three sub-models : a optical sub-model that predicts the energy input from the laser, a thermal sub-model solving the heat transfer model, using finite differences method and a sintering model that predicts the change of the material properties.

We have implemented these three sub-models as in the work of Sun [8]. We added to this implementation the simulation of the operations the GSI scanners. According to the GSI scanner user manual, we have implemented all the operations performed by the CPU controlling the scanners. Each of these operations last usually 270 microseconds, which is a common value for the Step Period parameter. By simulating all the operations done by GSI processor, we are able to predict the time needed for the building of a layer. These predictions are shown in Table 2 and compared to the real time to build one layer of different objects. The "Real Time" was obtained by measuring the difference of the starting time and the ending time of the build, given by the SLS building software.

Table 2 : predicted built time versus real build time

File Number	Real Time	Predicted Time
File #1	0:38.69 s	0:39.04 s
File #2	0:20.44 s	0:20.50 s
File #3	0:03.84 s	0:03.78 s
File #4	0:13.82 s	0:13.24 s
File #5	1:16.62 s	1:16.03 s
File #6	0:38.84 s	0:38.65 s
File #7	0:34.18 s	0:33.93 s
File #8	1:05.50 s	1:05.58 s

In order to validate the time prediction, we have used different scanning files, Table 2, representing different patterns to be scanned. File #1 represents a tiger paw in which, each of the vectors to be scanned is of a different length. File #2 represents three tensile dogbones built simultaneously. Files #3, 4 and 5 represents squares of different sizes. Finally, files #5, 7 and 8 were randomly chosen from the wide collection of scan files we have.

The Optical Model :

The models dealing with the energy delivery and the heat transfer that we are using in the simulator can be found in the literature [8-9-10]. The intensity of the laser beam within the powder bed as a function of depth is :

$$I(z)=(1-R)*I0*\exp(-b*z)$$

where

R = surface reflectivity (assumed constant over time)
I0 = laser light intensity at the surface (value derived from the process parameters given by the user)
b = extinction coefficient (assumed constant over time)

z = the depth into the powder bed.

The Thermal model :

The absorption of the beam by the powder creates a three dimensional heating of the powder. The energy input at a point is time varying due to the motion of the beam. From [8-9], the heat source function is :

$$g(x,y,z)=(1-R)*b*I0*\exp(-((\Delta X)^2+(\Delta Y)^2)/w^2-b*z)$$

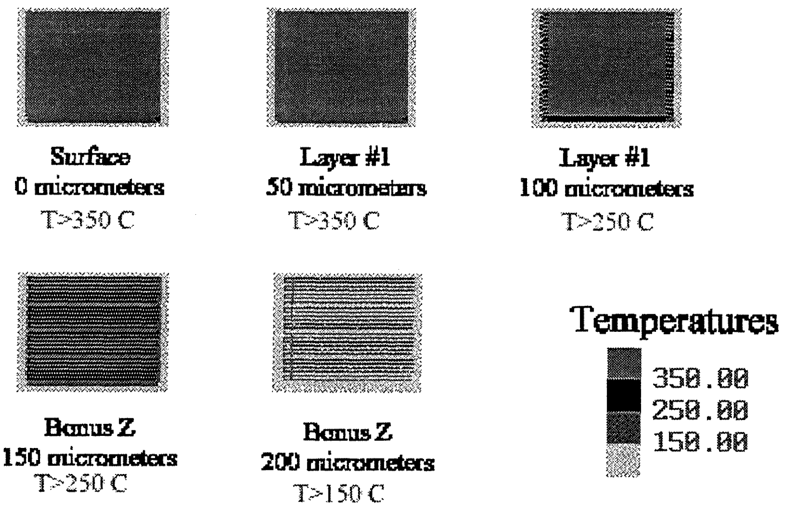
where

x,y,z = coordinates of the point we want to consider of the powder bed

ΔX,
ΔY = difference between the current position of the laser beam and the point of the powder bed we consider in the X-Y plane.
w = radius of the Gaussian laser beam.

When the energy input is calculated using the optical model, the resulting temperature distribution becomes the initial condition for a three dimensional transient heat transfer problem with variable coefficients [9]. Based on the work of Sun [8], this problem is solved using a finite difference method. The computer implementation of this method constitutes the basis for the development of the simulator. For the simulations, we have used a powerful PC compatible computer.

Results of Temperature Distribution : We simulated the temperature distribution in the first layer of a one inch (25.4 mm) square build. As it can be seen in the following figure, underneath the imposed thickness of 5 mils (127 µm), the temperature is still higher than the glass transition temperature of polycarbonate. At this range of temperatures, sintering is likely to occur. This is an indication of growth in the Z-direction (bonus-Z). This observation correlates qualitatively well with the experimentally observed bonus-Z.



Status and further work : The simulations we have conducted so far give us very encouraging results. Based on these results, the next steps are :

(i) Validate the temperature and density simulation results using the adequate equipment.

(ii) Use the hardware and software we already have to create an advanced laser power management that will allow us to vary dynamically the laser power.

(iii) Use the results given by our simulator to design a building script that would minimize the bonus-Z.

4. Conclusion

Key issues which define the requirements for an improvement in the vertical accuracy of parts in the SLS process and preliminary experimental and simulation results are presented. These are the issues that are driving the SLS process research at Clemson University. This work is a first step that should lead to an improvement of the accuracy in the SLS process.

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