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Experimental Determination Of Uniform Heating In The Selective Laser Sintering Part Bed

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Abstract

Selective Laser Sintering (SLS) is an Additive Manufacturing (AM) process in which powdered material is spread out on a part bed and sintered with a laser layer upon layer in succession. The design for this part is usually prescribed by a CAD file uploaded to the SLS computer system. Part bed temperature is typically raised to just below the melting temperature of the material being processed. It is critical that the part bed temperature remain uniform in the selective laser sintering machine, so that warping and shrinking of the part leading to defects does not occur. A user-friendly testing method was developed to ascertain whether or not the part bed is at uniform temperature so heating adjustments can be made accordingly. The optimum heater setting for various zones was established using a structure of a thermocouple-embedded, 0.25-in think, 12-in by 12-in polytetrafluoroethylene (PTFE) sheet. Testing was conducted on a multi-zone SLS machine for various heater settings to establish the optimum parameters needed to maintain a uniform temperature throughout the structure. It was determined that recommended settings were keeping a relative uniform temperature while uniform heater settings were not. Optimum settings were decided upon and tested to reveal a more uniform temperature distribution than before. Testing was then conducted on a regular SLS machine with only two heater zones; it was concluded that this machine was not as consistent nor as capable in keeping a uniform temperature as the multi-zone SLS machine.

Keywords: Laser Sintering, part bed, uniform temperature, multi-zone heater

1. Introduction

Additive Manufacturing (AM) is a name associated with the expansive field of 3D printing. During the processes described as AM, parts and prototypes are made layer by layer using additive techniques as compared to the typical industrial subtractive techniques. Within this field, there are various methods and machines which layer by layer create a model prescribed by a Computer-Aided Drafting (CAD) or other design system file. Selective Laser Sintering is one such AM process[1, 2]. During the part build, a powder material is spread out across a part bed and heated to just below its melting temperature. After being heated to this point, a laser of known criteria is used to sinter together a design for a part. This is done layer upon layer in succession until the part is built successfully and without any deformities. It is critical that the part bed keep a uniform temperature during part building. Should the part bed temperature not be uniform, the material will melt before its due time and in areas unnecessary to the build[2]. This phenomena results in warping and shrinkage of the overall part[3]. These defects are unsatisfactory in a 3D printed material.

1.1 Past Work

The main issue at present with SLS processing is indeed that of a lack of uniform temperature in the part bed. Thermal gradients have been found numerous times during this part build process[2, 3]. Said thermal gradients could be explained by heat transfer mechanisms such as radiation, convection and conduction occurring during part build stages[2]. Many different methods have been investigated for the use of predicting the thermal gradients, identifying them, measuring them, and correcting them[2]. Analytical and numerical models have been used thoroughly to predict when and where a thermal gradient will appear in the part bed, most often using a method such as a solved Fourier or Laplace equation or a Gaussian model[1, 4]. These models, precise though they are in the prediction thereof, are lacking in the fact that they are strictly theoretical[2]. For a more intensive study of the part bed temperatures, these models must be coupled with experimental methods of measuring the temperatures before and during part build[1, 5]. Parameter control, including control of the laser scan, scan intensity and beam width, has also been employed as a method of correcting these thermal gradients.

Figure 1: Warped part from SLS[8]

Among the preferred measurement instruments in past works were IR cameras, thermocouples, and Resistance Temperature Detectors (RTD's) [2, 3,6]. IR cameras, along with photodiodes, were useful in giving a thermal image of the part bed at a decent accuracy. That accuracy however has been found to be fickle; it is dependent on the distance from the part bed to the IR camera itself, along with the angle which the IR camera is faced towards the part bed[2]. SLS systems have been upgraded to incorporate IR cameras into their internal structure, however, these only give a general overview of the part bed instead of a full investigative authority on the individual part bed zone temperatures. RTD's were used in a previous work to account for the temperature of powder in the part bed being heated as close to a surface as possible, though in that work, the position varied[3]. Thermocouples on the other hand, while not as accurate as RTD's, are also not nearly as expensive and have been found to be accurate enough for the purpose of measuring temperature in the SLS as well as giving a view of the thermal gradients as they occur in each part of the build area[7]. Type K thermocouples specifically have been incorporated in past patents of temperature measurement in the SLS part bed and been found to function appropriately[6, 7].

1.2 Current Work

In the Rapid Prototyping Center (RPC), there are two SLS machines, one of which has been upgraded with a "multi-zone" heating system consisting of a 3 by 3 grid denoting 9 separate heating zones. As compared to the other machine which has only two heating zones, this upgrade is supposed to provide a more uniform temperature across the part bed. There still remains to be seen whether or not thermal gradients are present in this system. In order to prevent such defects as shrinking during the build, what is needed is a testing method to determine the part bed temperature uniformity before each build. This current work is concerned with developing that testing mechanism.

2. Methodology

To ensure the testing method was applicable for a user with a most basic knowledge of the SLS machine, it was required that the method be simple and straightforward. The idea was to test the machine's heating system without building a part over the apparatus, as this would be unfeasible during testing. As such, the space above the part build bed was replaced with a material which can be measured for temperature differences over time.

2.1 Material Consideration

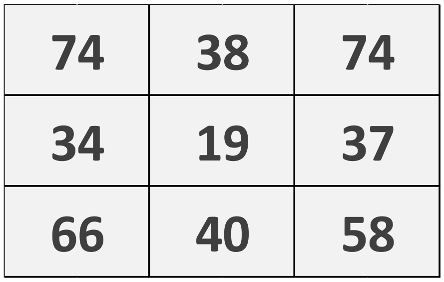
For this testing method, it would be foolhardy to use a material with a high thermal conductivity such as copper due to the fact that under a single heater, the heat will conduct across the surface of the entire sheet and be registered as a single temperature. This is, however, incorrect to use due to the fact that what is desired are thermal measurements of individual zones across the entirety of the material being used. It is therefore required that the material being used have a low thermal conductivity as well as a resistance to deformation under heating up to 200ºC. For this purpose, polytetrafluoroethylene (PTFE) was selected as the material of choice for the sheet to be imbedded with thermocouples. PTFE has a melting point of around 342ºC as well as a low thermal conductivity of .26 W/mºC[9]. These properties will aid in testing to the effect of allowing for each zone to have unique temperatures in different areas of the material as it sits under a multi-zoned heating system. To this end, two polytetrafluoroethylene (PTFE) sheets embedded with thermocouples were assembled in order to measure the temperature of the part bed during the heating up process.

2.1 Structure Assembly

This structure was made from 5x6 inch sheets first as a prototype for the official 12’’ by 12’’ testing structure. Once it was ensured that the method would work on a small scale, the structure was rebuilt using 12’’ by 12’’ inch sheets to fit the dimensions of the SLS machine part bed. In both structures, the top sheet was the main priority. It was embedded with thermocouples designated as the temperature reading instruments glued down using 100% Silicone Sealant. These thermocouples were placed as close to the surface of the sheet as possible in order to read the temperature of the sheet in different zones as it was heating. The bottom sheet was attached strictly to keep the thermocouples in a tight space and less free to move about to spring free from their positions. The two sheets were screwed together at the corners, completing the overall mechanism.

2.2 Testing

The SLS machine used was a DTM Sinterstation 2500 plus. Preliminary testing was conducted using 5’’ by 6’’ PTFE sheets to ensure that the apparatus would operate inside the SLS environment as well as to fool proof the 12’’ by 12’’ apparatus. In both the preliminary test and the official first test, the heater settings were that prescribed by the company that built the multi-zone heating system. The structure was set inside the SLS machine on the part bed, preventing any actual parts from being made. The heaters were turned on, and while the machine was heating up to a designated temperature of 172ºC, the thermocouples in the structure were to read the surface temperature of the PTFE sheet as it was heating up. It must be noted that this is the standard operating temperature of the SLS for building parts. Thus, it was chosen as roughly the steady state temperature for these experiments. All thermocouples (9 in the preliminary test, 20 in the secondary tests) were installed into a data acquisition system which was attached to the operator’s computer system. This test was performed on the upgraded SLS machine at recommended settings, at a uniform temperature setting of 80%, and finally with optimized settings. Recommended settings can be seen in Figure 2, with each number as a power percentage, and the grid is representative of the nine heater zones in the multi-zone SLS. After this was done on the SLS, a last test on the SLS machine with only two heater zones was performed for comparison. The data acquisition system used for acquiring all thermocouple temperature measurements was Agilent Benchlink Data Logger Pro 3. All data was analyzed using Microsoft Excel 2013 and Matlab.



74	38	74
34	19	37
66	40	58

Figure 2: Recommended heater percentage settings for each heating zone

2.3 Determination of Thermocouple Time Constants

Tests were conducted in an attempt to find each thermocouple's time constant following the preliminary testing of the 5x6 structure. Here, the time constant is defined as the time it took the thermocouple to read 63ºC during the process of being immersed in ice water and then immediately in boiling water. Each of the twenty thermocouples was held at ambient for 20 seconds, placed in ice water for 20 seconds, and then placed in boiling water for 20 seconds. Scanning speed was once every quarter of a second. Time constants were determined successfully for each of the 20 thermocouples. Equation [1] was used to calculate the time constant of each thermocouple.

$$(T - T_0) / (T_\infty - T_0) = 1 - e^{-1} \qquad [1]$$

Here T_0 is the initial temperature and T_∞ is the final temperature. Due to the test entailing being immersed in ice water then boiling water, the variables T_∞ and T_0 were roughly 100ºC and 0ºC respectively. With those values factored in accordingly, the time constant definition is true at T(t) = 63.2ºC. It was shown from testing and resulting calculations that each of the thermocouples' response times were less than or equal to one second. It is imperative that response times be as quick as possible for temperature measurement. If the temperature changes suddenly, the thermocouples must be relied upon to respond accordingly and accurately. With time constants calculated to be less than one second for every thermocouple used, the thermocouples were considered as efficient thermal measurement instruments and accurate enough for the job of measuring each temperature zone in the upgraded SLS machine.

3. Results

Preliminary results verified that this apparatus would operate appropriately in the SLS part bed under heat. After this verification was attained, the primary testing was conducted and results examined.

3.1 Uniform Heater Settings at 80%

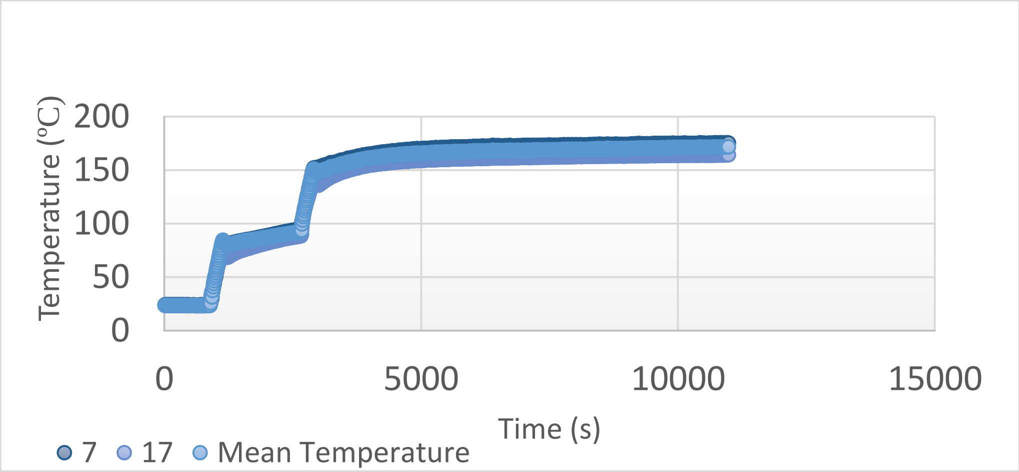


Figure 3: Temperature versus time graph of SLS heating process using uniform heater setting.

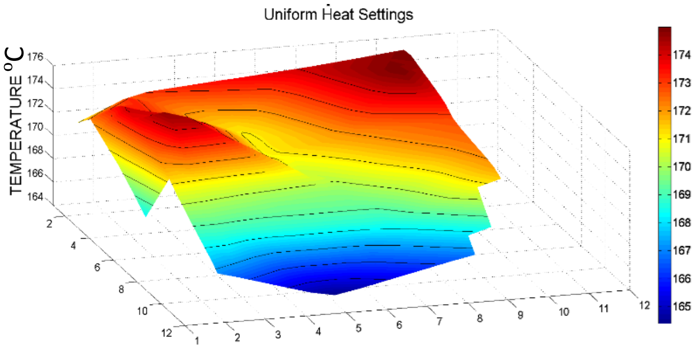


Figure 4: Interpolated surface plot of temperature readings for uniform heat settings at t=10,000s

Testing was conducted using a uniform heater setting of 80% across all nine heat zones. The 12'' by 12'' inch structure was placed over the SLS part bed at ambient temperature, and the machine was heated to 172ºC, held there for 30 minutes, and then cooled down to 100ºC. This same procedure was used for all testing done. The thermocouples had been calibrated just before this test, such that they all read roughly within 1ºC of each other at ambient. This uniform setting however did not provide a uniform temperature in the part bed, as was expected from the experience of the RPC staff themselves. While in Figure 3, all three plotted temperature readings overlap, the difference between the three can be seen more clearly during testing and data analysis. There could be seen at one point a 20ºC difference between the highest and lowest temperature readings, and there existed a 12ºC disparity between highest and lowest temperature readings at steady state. This led to the conclusion that a uniform heater setting across the heater zones will not cause a uniform temperature in the SLS part bed. The reason for this disparity amongst the temperature zones can be explained by the fact that each zone is being heated by two or three heaters at any given time. As such, being influenced by many heaters all with the same settings will lead to an increase in temperature in certain areas while not in others. This disparity leads to a lack of uniform temperature across the part bed, making the use of uniform temperature settings ineffective.

3.2 Recommended Settings

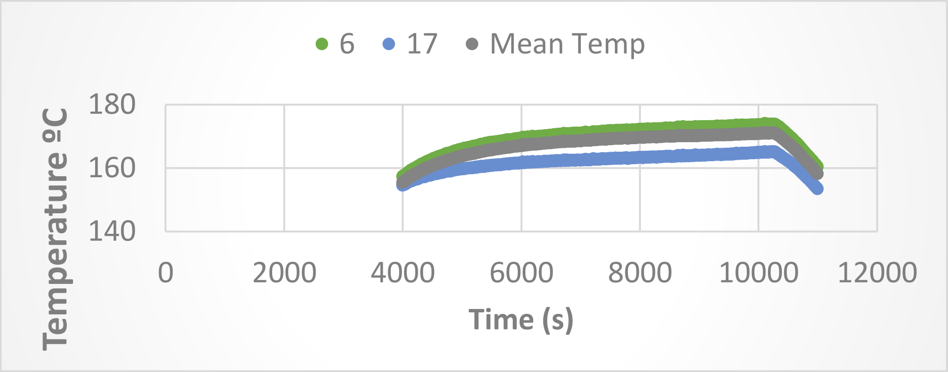


Figure 5: Highest, lowest and mean temperature readings from running the SLS under the recommended heater settings at steady state.

The test of the recommended settings has shown that these settings are good for close to optimum performance of the SLS machine as the readings from the thermocouples were within their standard degrees of deviation, with the exception of those placed closed to the part bin wall. A rough sketch of the temperatures can be seen in Figure 5, where only the steady state temperatures are plotted. In Figure 5, it is easier to discern the disparity in temperature. Figure 6 is a surface plot of all the thermocouple readings in the middle of steady state.

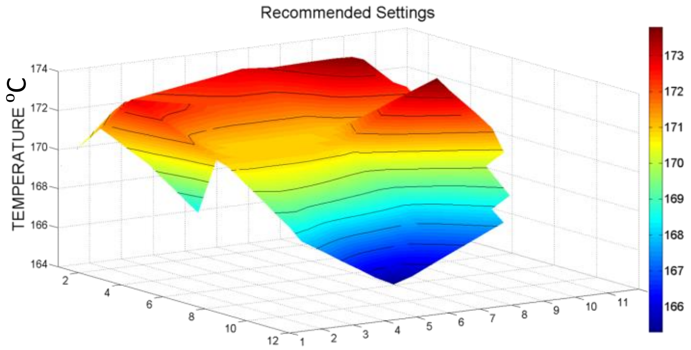


Figure 6: Interpolated surface plot of temperature readings for recommended settings at t=10,000s

It can be said that there is a relative uniformity of temperature in the part bed under these settings as there is only a 9ºC difference between the highest and lowest temperature readings at steady state. While this is a smaller disparity than the results from using uniform heater settings, it can be improved upon. This was sought later by refining the recommended settings so as to close the gap between highest and lowest temperature values seen in Figure 5.

3.4 Final Testing on Multi-Zone Heater System

The focus of final testing was to finalize more efficient heater settings for the upgraded SLS machine, such that its part bed would have a more uniform temperature in future part building endeavors. This testing required much trial and error in that some chosen settings would cause a larger difference in temperature across the bed while others changed nothing at all. Optimized settings were attempted twice, the second time with only a slight change in heater settings than the first. The first attempt provided temperature readings which possessed an outlier towards the back wall. With the outlier, the temperature difference between highest and lowest readings was 14ºC; without the outlier, the difference was 6ºC. On the second attempt, there was a confirmed 5-6ºC difference, which is a marked improvement from all previous testing. Figure 7 is a comparison of surface plots of temperatures shown in the first and second attempts at optimized setting testing. Final optimized settings for this experiment are seen in Figure 8.

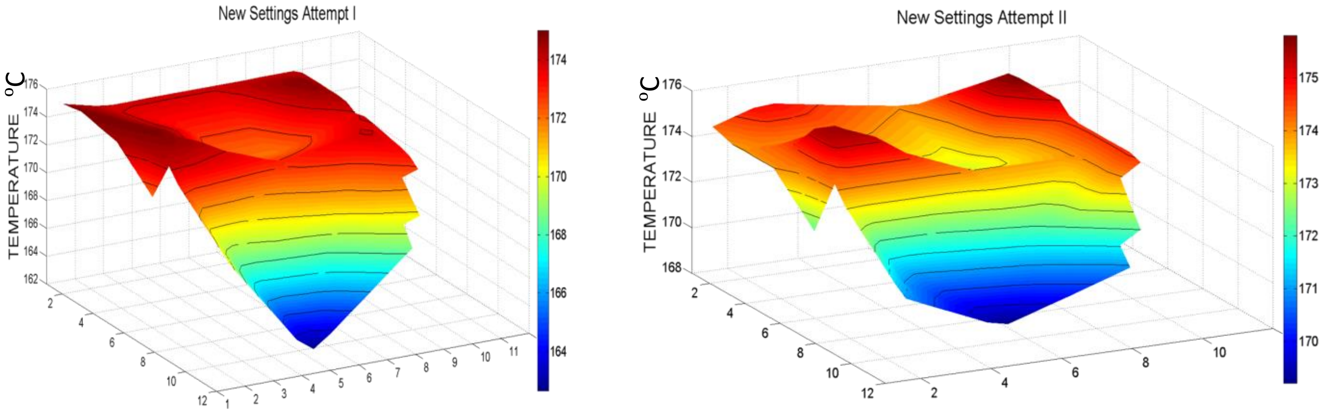


Figure 7: Left: The first attempt at optimized settings at t = 10,000s; Right: The second attempt at optimized settings at t = 10,000s.

76	50	76
34	23	37
62	45	64

Figure 8: Final optimized settings for the multi-zone heater system

In the future, it may be proposed that the RPC test these settings officially by making a part using them. If the part is made with no defaults, it can be said that the settings are efficient parameters for uniform temperature control. Conversely, if moderate defects are detected via observation, then it would be expedient to experiment again for better settings.

3.5 Testing Results of the Second SLS Machine

The testing of the system which had not been upgraded was strictly for comparison to the multi-zone system. This testing would, in effect, provide an insight into SLS machine part bed temperatures which do not have nine different heaters placed above them. This second system instead had only one heater which was merely turned on to begin heating. The complications had with balancing out nine heater settings in the multi-zone system were not had in testing the 2-zoned system. It would seem that the SLS machine without the multi-zone system keeps a relative uniform temperature in the part bed as compared to the upgraded heater system due to a temperature difference of roughly 8ºC at steady state. It would seem comparable with the exception of an outlier "low" region denoted as a blue area towards where the window of the SLS machine would be. This lower area in temperature was unanticipated after testing on the multi-zone SLS, and there can currently be no precise explanation for it. A second test identical in procedure to the first provided insight into the consistency of the two-zone heater system. In this second test, the outlier low temperature region was absent, and the temperature disparity was as much as doubled at a certain point during testing. Comparisons between the two tests of this system shown in Figure 9 can lead to the conclusion that the two-zone heater is inconsistent with relation to temperature uniformity and less capable of keeping a uniform temperature in the part bed compared to the multi-zone system.

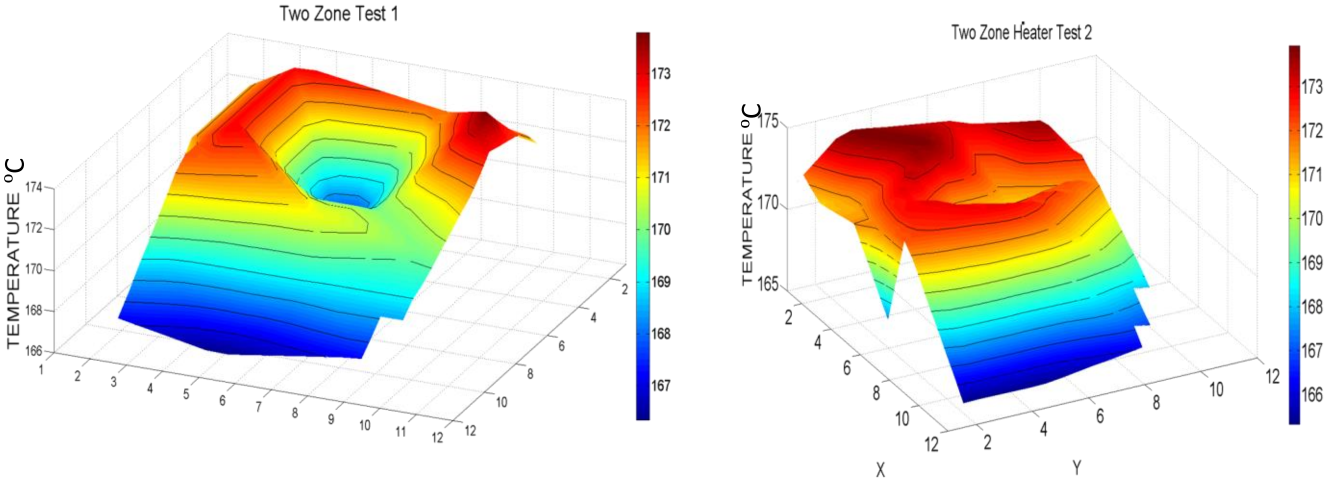


Figure 9: Surface plots of the two tests on the two-zone heater SLS at t = 10,000 s.

Future consistency testing for the two-zoned heating system is strongly advocated. More test results added to those done previously will provide a wider range of data and further determine the machine's heating consistency. Until that is done, only these two test results exist to say that the two-zone heater is less consistent and less capable in keeping a uniform temperature than the multi-zone SLS.

4. Discussion/Conclusion

It can reliably be concluded that uniform heater settings do not promote uniform temperatures in the part bed of the multi-zone SLS when compared to the temperatures read at the recommended settings, which decently promote part bed temperature uniformity. The final, optimized settings which have been found in this study should promote further part bed temperature uniformity as there was only a six degree difference between highest and lowest at the optimized settings. This, in turn, will aid in producing overall better products from the RPC when conducting builds with the SLS multi-zone heater system. This work has been useful for the study of optimizing said heater system settings such that a more appropriate build chamber environment can be achieved through the use of the final optimized settings. The two-zone heater system, in comparison to the multi-zone, does not possess the consistency part bed temperatures nor the capability to keep a uniform temperature in the part bed area.

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