A Thermal Study of the Selective Laser Sintering™ Process

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Abstract

Through temperature measurement and thermal analysis of the DuraForm™ polyamide nylon powder used in the sintering process, it is possible to find a systematic approach to the operation of the selective laser sintering (SLS) machine. A process can be established to find the glaze point of the powder, control the surrounding chamber temperature, and set the carbon dioxide sintering laser wattage to appropriate levels. This research involves obtaining appropriate instrumentation for temperature measurement in the harsh operating conditions of the Sinterstation® 2500*Plus* system, and finding exact temperatures for which the carbon dioxide laser melts the nylon powder over a range of laser powers. This temperature data will be useful for making higher quality parts, and will allow the SLS machine operators to follow a predictable and proven pattern when adjusting settings on the machine. By measuring the temperature gradient of the powder in correlation with the laser power, this set of experiments may be extended to different materials used in solid freeform fabrication, as well as other technologies involving micro applications.

Keywords: Selective Laser Sintering (SLS), polyamide (PA) nylon powder, temperature measurement, infrared thermocouple

1. Introduction

Selective Laser Sintering™ (SLS) is one of many solid freeform fabrication (SFF) processes used by numerous companies for preliminary samples, and sometimes for custom manufactured parts. Therefore, it is very important to these firms that they obtain accurate prototypes as quickly as possible. Some complications that the SLS process has encountered, which can hinder a manufacturer, include weak or low quality parts. These characteristics are most commonly placed in association with the reuse of powder. Each time a 3-D object is built there is left over material, which is sifted through and reused to make other parts. As the powder is reused, the appearance of SLS parts becomes progressively poorer. Some qualities imperfect objects display include visible flaws, such as rippling surfaces, and weaker material properties as a result of poor sintering, or densification processes. This research examines the imperfections of reused powder and finds a thermal solution for making parts with recycled powder through variation of environment temperature and laser power.

1.1. Selective Laser Sintering™

Selective laser sintering is an additive process in which 3-D objects are made layer by layer. For each layer, a small amount of nylon powder is deposited over the part build chamber, and then a carbon dioxide laser fuses the powder particles together to make another layer of the object [1]. Each layer is of the same thickness and only the cross-section of each layer is sketched into the powder, or densified with each pass. When the entire part has been sintered together it is contained in the bottom of the part build chamber, and needs to be broken free from the loose powder around it. Since there is constant support from the surrounding powder, the parts made in the SLS machine can be very intricate, yet need no support structures.

There are also several different materials used to make SLS parts. Some include DuraForm™ polyamide (PA) nylon powder, and the DuraForm™ glass filled (GF) polyamide nylon powder. Others are SOMOS, a flexible rubber, and metals such as aluminum with plastic coatings around each powder particle for sintering. The powder used in this research is the PA since it is the most commonly used and has the most problems with poor surface finishes.

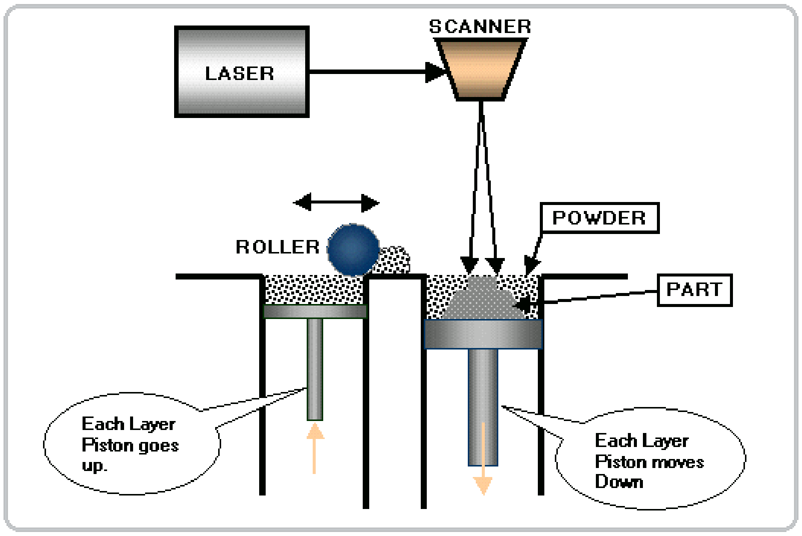

Figure 1 SLS process chamber [2].

1.2. problems addressed in SLS process

The current process used to build SLS parts at the Milwaukee School of Engineering (MSOE) Rapid Prototyping Center (RPC) was arrived at, for the most part, by trial and error. The powder cartridges are filled with new powder, then a small amount of powder is placed on top of the part build chamber and the temperature in that area is raised until the powder just starts to melt or look ‘wet’. This temperature is recorded and set as the glaze point, which is the minimum temperature that the powder needs to be raised to in order to sinter the part together. Then the part build chamber is lowered to a temperature that is 13°C below the glaze temperature, because it is thought that the laser will raise the temperature of the powder just above the glaze point, creating a perfect part.

There are many problems with assuming that this may be the correct procedure. One factor that makes the SLS environment not very optimal is that the infrared sensors in the machine are not accurately measuring the temperature, and the heaters are not evenly heating the part build chamber. This causes the laser to sinter the part at different temperatures at various layers, and even from one end to another of the same layer. These temperature differences cause rough surface finishes and warping of parts. One solution to this problem has been to vary the laser power for different layers of a part. This creates more uniform parts through keeping more constant temperatures at various layers.

Another setback that the SLS process encounters is the reuse of heated powder. After a part has been extracted from the loose powder that surrounds it, that loose powder is sifted and put back into the powder chambers to make more parts. After so many heating cycles the powder particles start to fuse together permanently and the sifter cannot break them apart [3]. This creates a problem when sintering these new particles because the larger particles require a higher laser power to fuse together properly. Since these particles are not sintered correctly, they create rough surface finishes from not being raised to their new, higher glaze temperature. One solution to this problem has been to mix new, or virgin, powder in with the older powder [4]. This creates a more uniform mixture for which the glaze temperature is not significantly higher than that of the original virgin powder. Although this has significantly increased the amount of parts that can be made from reused powder, it is still more costly than just being able to reuse the powder without adding any virgin powder into the mix.

1.3. infrared thermocouple

Infrared thermocouples (IRt/c) operate like a thermocouple where the temperature output is determined by a voltage potential created at a junction. However, they read temperature like infrared thermometry, by measuring radiation emitted from a surface. This creates a very accurate, user-friendly non-contact temperature sensor [5]. This device is perfect for measuring temperature changes in the SLS machine because it is non-contact, maintains accuracy, has a high degree of repeatability, and data can be output to a conventional thermocouple data acquisition system.

The model chosen, microIRt/c.4 from Exergen Corporation, is a small cylindrical unit (3 inches long and 3/8 inch diameter) which allows simple integration into the SLS machine. It also has a 4:1 field of view; allowing mounting on an angle and at a greater distance without losing the small spot size from which it measures thermal radiation. Other characteristics of this sensor include a high degree of repeatability within 1%, instantaneous update time, and temperature measurement up to 500^{o}C. Lastly, even though the sensor must be connected to a fairly long cable, it will not lose accuracy [6].

One disadvantage of this particular sensor for this application was that it required cooling to properly read temperatures. The best way to cool it was to feed an air line to the sensor, and constantly pump air at 17L/min and 5psi around it; this will allow the sensor to operate in temperatures of up to 175^{o}C [6]. The problem for this specific application was that the atmosphere of the SLS machine needed to stay inert at 94.5% nitrogen or higher. The solution found was that the nitrogen fed into the machine had several different lines; one of these lines was not being used so it could be used and regulated to pump nitrogen to the sensor at the rate needed to cool it.

To calibrate the IRt/c, the voltage readings and corresponding temperatures from the data acquisition system were compared to those values of the factory calibration tables. From that analysis a graph and related equation was obtained (below) to convert the recorded temperatures into actual temperatures, accurate within ±1^{o}C. A linear graph was chosen to simplify the conversion process when analyzing data. Also, please note that this equation is only valid for this specific device, and for temperatures between 110^o-170^{o}C.

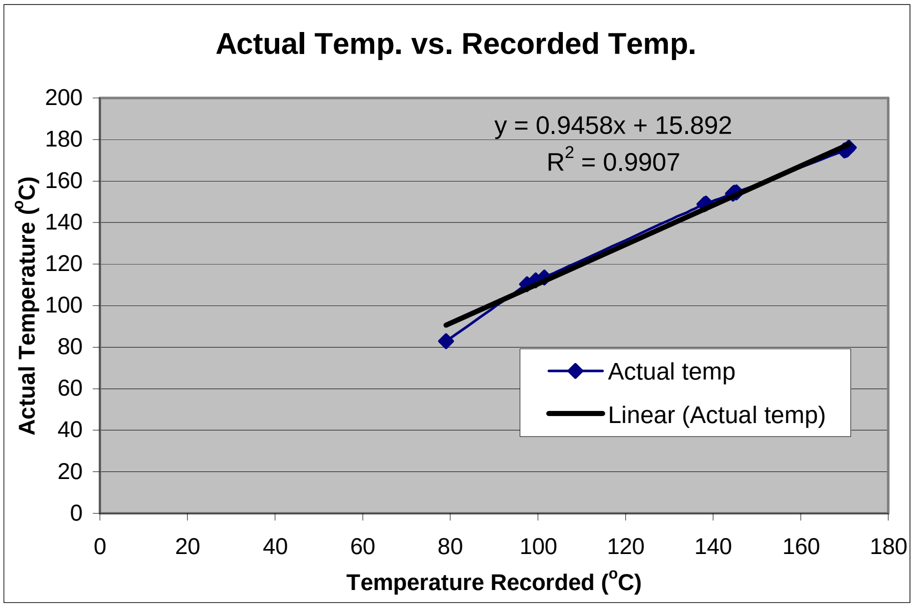

Figure 2 Calibration graph and equation.

2. Objective

The goal of this study was to find a systematic approach for the operation of the SLS process. This includes mapping a procedure to find the glaze temperature of the particular material used (PA), setting the laser at a certain power, and then controlling the part bed temperature accordingly so that the laser sinters the powder to temperatures just above the glaze point. This approach also involves determining the exact temperature gradient created by various laser powers, and setting the part bed temperatures accordingly to make optimal parts with the best surface finishes.

3. Approach

To find a set procedure by which to operate the SLS machine, thermal analysis was done on the CO_2 laser and the part bed chamber. This was done by mounting an IRt/c into the SLS machine while operating. After finding a temperature gradient for several different laser powers while controlling part bed temperatures, those temperatures could be varied according to the gradient for a certain laser power.

3.1. air temperature

To determine if the IRt/c needed to be cooled while in the SLS machine, an initial air temperature test was conducted to find the exact range of temperatures in the machine. Up until now, the only thermal readings taken from inside the machine were through existing infrared sensors, and a test run with conventional thermocouples while no part was being made in the machine. That test run was preformed to check if there were variations in temperature from uneven heating of the SLS chamber, which led to the variation of laser power over a large part due to temperature differences.

To test the air temperature, thermocouples were placed into the machine. They were held in place by inserting them through the slots for the swinging doors that separate the part bed from the powder beds. This allowed the thermocouples to measure the air temperature in the same area that the IRt/c would be located. The thermocouples were then connected to a data acquisition system which recorded the temperature once every minute during a six hour build. This was sufficient because only the general air temperature was needed to tell how much the IRt/c would have to be cooled when inside the SLS machine.

3.2. mounting device

A mounting device was fabricated to hold the temperature sensor above the part bed, but not directly below the laser. This meant that the IRt/c had to be mounted in such a way that it was angled toward the part being produced. Another consideration was the ambient temperature of the machine, and what material could withstand temperatures of up to 200°C. These considerations, along with detailed measurements of the SLS machine made it possible to create a mount and parts of the SLS machine in a 3-D modeling program. The drawing simulated the actual machine (below), which was very helpful in the design stages of the mount and also helped to illustrate the experimental setup.

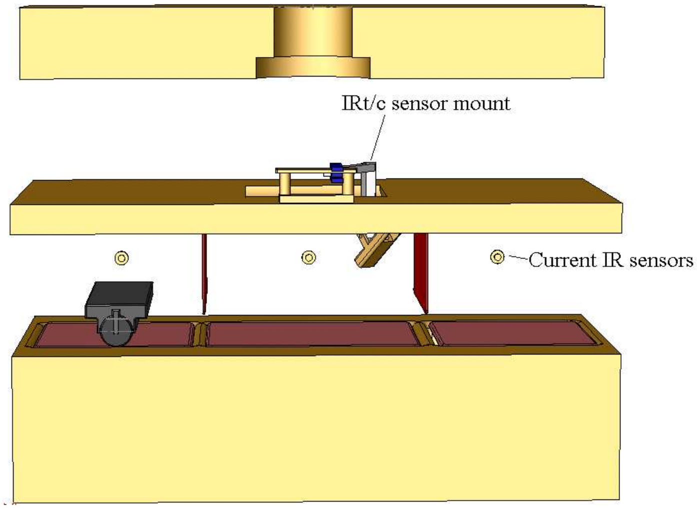

Figure 2 SLS machine with IRt/c sensor mount.

Since MSOE has such an extensive rapid prototyping center, the conclusion was easily made to construct the mount from a very durable plastic that is used in the Fused Deposition Modeling SFF machine. The mount was then designed according to the dimensions of the SLS machine, and made to fit into the opening that allows the laser to sinter parts (where mount is inserted in drawing above). Although the mount was designed for this particular set of experiments, possible changes were considered. The piece that holds the mount to the heater handle (1) was made separately to be able to adjust the mount arm (2) in various places in the machine. The sensor sleeve (3) was also produced unattached to accommodate any moves that needed to be made, but also to feed the IRt/c wires and air hose out of the holder. The two places in which the sleeve attaches to the mount arm allow for more room to make a larger part or to position the sensor closer to a smaller part. Lastly, an air cavity was added to the sleeve to allow air to flow through the plastic mount to partially cool the sensor.

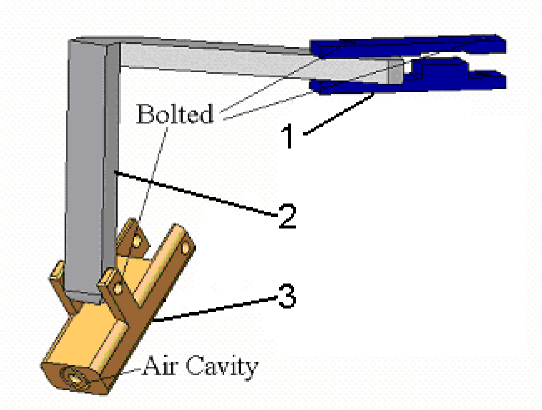

Figure 3 Sensor mount.

3.3. controls

To control these experiments, the test part made in the SLS machine was a small solid disc. This ensures that the sensor was measuring the same cross-sectional area every time the laser was sintering the part. Choosing a thin disc (3 inch diameter) as the cross-section also eliminated the need for varying laser power, required less build time, and did not allow the unused powder to be heated for an extended period of time. The height was .1 inches, allowing for enough layers to be measured, but keeping the build time to a minimum to permit many parts to be made in the same build with identical powder.

The powder properties also remained constant. The powder age was kept at around 320-330 part build hours and only PA was used so that the powder in question of creating poor parts was tested. Although the results will most likely vary for different powder ages, this study, for lack of time restricts the tests to just the powder in this age range.

3.4. variables

The laser power remained constant during each part in an experimental build to ensure that the temperature change created from the laser could be measured accurately. The experiment was repeated several times at different laser wattages, to find a correlation between the temperature differences of the powder as it was being sintered and the laser setting. With each experimental trial the part bed temperature was held constant so that the difference in temperature could only be attributed to the sintering laser.

4. Results and Discussion

Each of the areas measured, air and powder temperatures, were recorded via a data acquisition system and computer. The results are analyzed graphically and analytically through data manipulation. A graph was made for each test to show the general trend of the temperature changes, and the data was used to find averages of different temperature gradients for various laser powers.

4.1. air temperature

The results from the air temperature test indicated that the chamber was quickly heated to about 140^{o}C and reached maximum temperatures of 150^{o}C during the build. The results were very consistent, and the temperature did not change much during the build. Since the IRt/c can only accurately measure temperatures in ambient surroundings of 100^{o}C or less, the sensor will have to be cooled approximately about 50^{o}C with nitrogen air flow.

4.2. powder temperature

Analysis of the powder test results had to be considered carefully, since there were 25,000-30,000 data points in each set. First, the data was evaluated in an equation established for calibration. Then a graph was made of the entire run, and from this it was clear where the parts were being sintered. A new graph could be made like the one below, focusing on just the data in question. From these newly developed graphs, general sintering temperatures and gradients could be found, and the general time ranges for each part were obtained. With these time ranges, each layer could be analyzed. To do this, the temperatures before sintering, during sintering, and after were averaged for each layer and compared for each individual laser power. Since the temperatures in each of these categories were similar for a given laser power, the condensed data was averaged before, during, and after the sintering of a part to find the general gradient for each laser power.

The results from the powder temperature tests were quite amazing, when they worked correctly. A clear temperature change was seen from the graphs, and the changes increased with increasing laser powers. From test one it is clear when the roller went over the part bed (1), when the laser sintered the part (2), and where each of the three parts that were built with different laser sintering powers.

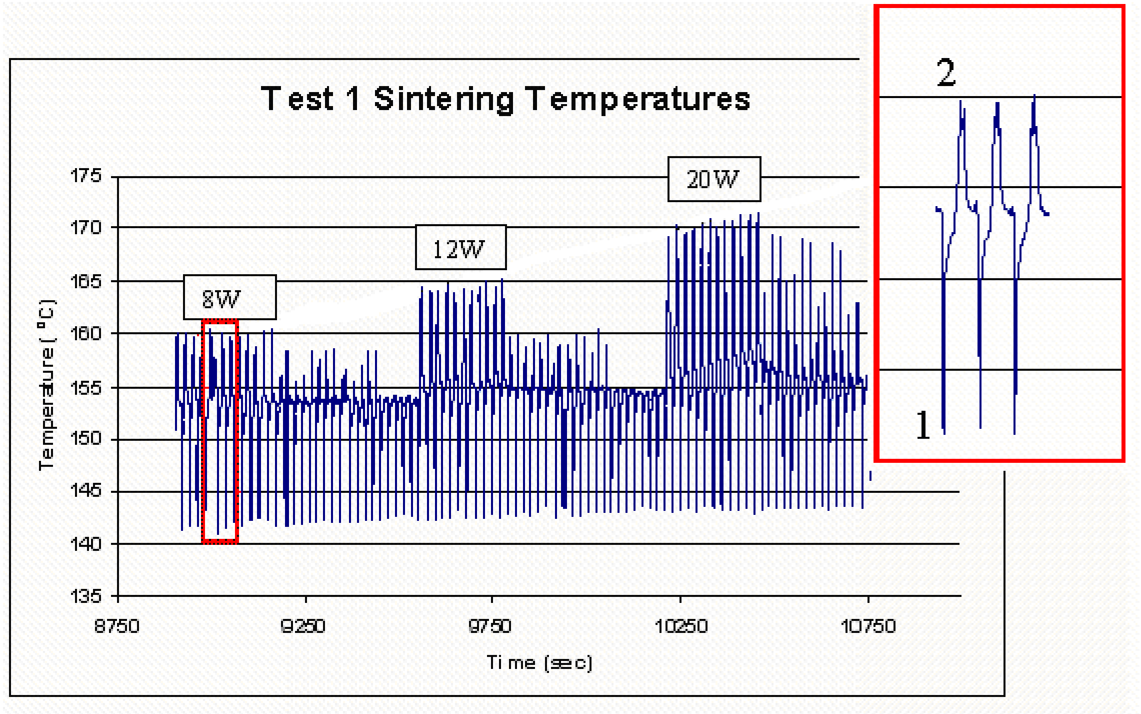

Figure 4 Sintering temperatures for 8W, 12W, and 20W laser parts.

Unfortunately, not all the tests worked this smoothly. During tests 2, 3, and 4 the disc being built rose above the powder level as it was being made. This caused problems because the powder being distributed over the part bed chamber was not covering the part or creating even layers. Eventually the part rose too far above the powder level causing the roller to push the part across the part bed, and the process had to be terminated. Some possible reasons for this problem include incorrect part bed temperatures, a bad IR sensor not regulating the heaters correctly, or the air that was cooling the sensor may also have been cooling the part. After changing the part bed temperature and replacing the IR sensor controlling the heaters, it was very easy to see that the problem was caused by the air cooling from the sensor; it was also cooling the part, curing it fully before needed. To solve this problem more testing was done to determine if the air flow could be turned down so that it was still cooling the sensor enough to measure properly, but not cool the part being built. In fact the air flow could be turned down because the first test worked very well, and there was a lot of air leakage from improper setup of the airflow. Also, the nitrogen air was also cool, so the air flow was turned down to 5L/min, and the sensor still operated correctly.

After the air flow was turned down, one more valid test was preformed, but the results from this test did not fully match the valid data from tests 1 and 2. Where the temperature rise from tests 1 and 2 increased for increasing laser power, the temperature differences for test 5 stayed relatively the same for increasing laser power. This discrepancy may be contributed to the parts being built on an angle. After tests 2, 3, and 4 the part was built on a slight angle to help with the problem of the part rising above the powder. Therefore the data from test 5 may have been affected by this change because the cross-sectional area being measured varied with each layer. This means that the sensor was taking an average of the area it was measuring, which may have included surface area where the part was not being sintered. Test 5 was therefore not included in the analysis of a general temperature change trend. Please note that even though the problem occurred during test 2, some valuable data was obtained, although overall temperatures were low from the air cooling. No valid data was collected from tests 3 and 4.

Table 1 general Δtemperature for various laser wattages, separated by experiment.

	Laser (W)	**Temp. Before (^{o}C)**	**Temp. During (^{o}C)**	**ΔT (avg)**	**Gradient (^{o}C/W)**
Test 1	8	151.7	158.2	6.5	0.81
	12	152.8	162.3	9.5	0.79
	20	153.9	167.7	13.8	0.69
Test 2	7	140.5	146.0	5.5	0.79
	9	140.8	147.5	6.7	0.75
	10	141.3	148.4	7.1	0.71
	11	141.3	148.7	7.4	0.68
Test 5	9	154.3	161.2	6.9	0.77
	10	154.9	162.0	7.1	0.71
	11	154.7	161.8	7.1	0.64
	12	154.1	161.0	6.9	0.58

When the temperature differences from tests 1 and 2 were put together to form a general trend for laser power, the correlation was quite high. Test 5 was not included in this trend because the results were inconclusive being that they were all about the same and did not match the results from tests 1 and 2. Although the general gradient, .64 ^{o}C/W, was a little lower than the individual gradients found for each run, with more testing these values should become closer, creating one number or a chart showing the temperature rise for each watt the laser is increased.

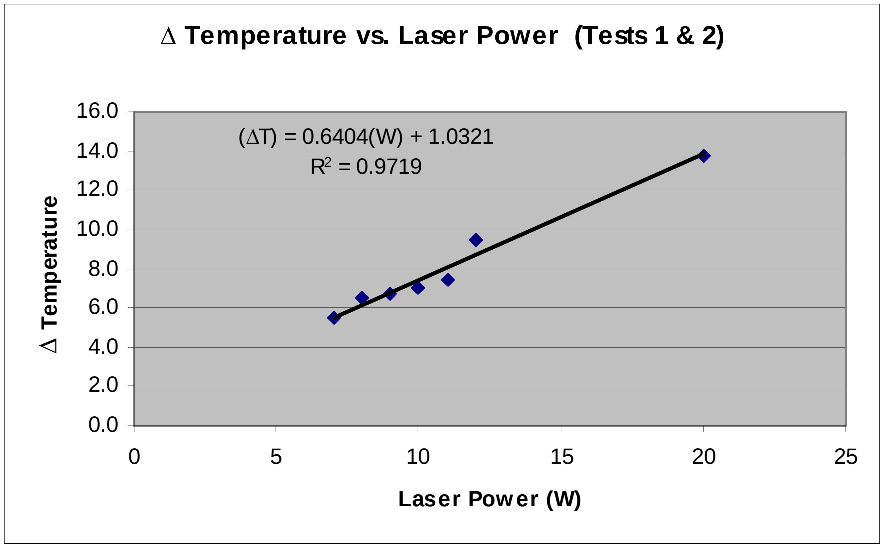

Figure 5 Graph of ΔT from tests 1 & 2 with trend line.

With this data, it may be possible to set up a SLS machine through a systematic procedure rather than through trial and error methods. First the user would have to consider the part to be made and chose an appropriate laser setting. Then by determining the proper ΔT for the laser power, the user could find a target part bed temperature by finding the difference between the glaze point of the powder being used and the gradient. This target part bed temperature should raise parts to the appropriate temperatures for optimal sintering, which produces the best parts.

5. Conclusion

Although more thermal analysis needs to be done on the Sinterstation® 2500*Plus*, this research has started the process for finding a systematic approach for setting up the SLS process. Since temperature analysis during the sintering of a part in the SLS process has never been accomplished before, this research has explored ways to do that, and has investigated many possible problems with this type of testing. Now, with a few valid tests from this study, a general trend for temperature differences according to laser power is known so that part bed temperatures may be set accordingly for older powder. Through further testing, this process will hopefully save SLS operators time and money when making polyamide (PA) parts.

6. Further Work

More work will be required to make the SLS setup systematic. Further tests are required to prove that the temperature differences which were found in this study are in fact accurate. Also, alternate ways to mount the sensor in the machine may need to be examined, as well as how to control the air cooling of the sensor to keep it working properly but not allow the air to cool the parts being made. One solution may be to find new sensing techniques, although this study exhausted many of the options which are currently available.

Other work may include extending this set of experiments to other powders found in the SLS machine, as well as to test a larger variety of PA powder ages. One major step would be to test this theory on a large scale to determine if it in fact works to enhance the properties of SLS parts and increases the number of good parts obtained from one cycle of polyamide powder.

7. Acknowledgements

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