An Experimental Study of Heat Transfer in Selective Laser Sintering™ process

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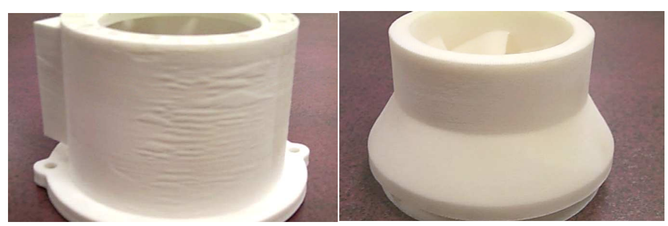
***Abstract* - Selective Laser Sintering (SLS) is a type of solid freeform fabrication whereby parts are produced layer by layer. Understanding of the sintering process is essential to a systematic operation of the SLS machine, improved part quality, and enhanced powder life. Previous studies have empirically tested part quality and the effects of powder age, but none offer a greater understanding of the temperature dynamics. Other studies provide sound mathematical models of sintering on a particle level, but fall short of embodying the process on a macro level inside the machine. This research explores the thermal conditions inside the Sinterstation® 2500Plus SLS machine while the part is built. Through a rigorous, custom made access for experimentation, the changes in Duraform® Polyamide (nylon) powder temperature are measured throughout the sintering process using an infrared thermocouple (IRt/c). Careful analysis of these data yields interesting insights into what happens before, during, and after sintering. The temperature profile is obtained, and a linear relationship between laser power and temperature increase during sintering is established. This first-of-its-kind data will be useful for making higher quality parts, and is intended to 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.**

Index Terms – Selective Laser Sintering, Infrared Thermocouple, Measurement, Polyamide Nylon Powder.

Background And Rationale

Selective Laser Sintering (SLS) is one of the rapid prototyping/ solid freeform fabrication techniques whereby parts are produced layer by layer: one cross-section built on top of the last and fused together until a solid part is made. SLS uses a fine powder as its raw material. The powder is raised to a temperature just below its melting point. Next, a CO_2 laser is used to heat up the powder and sinter, or melt, it to the surrounding particles. As it quickly cools, this produces a solid layer. Finally a roller deposits another thin layer of powder and the process repeats. 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. Several materials used in making SLS parts 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 I portrays the challenges industry faces to produce parts that are acceptable.



“Orange Peel” Good Surface Finish

FIGURE I
IMPACT OF SLS PROCESS ON PART QUALITY

Several studies have been done in the area of SLS powder life and process stability [1]-[2] but fall short of understanding the process. Others offer complex models of sintering [3], but also do not predict how different laser powers affect sintering. To better understand this dynamic process, this research focused on measuring the temperature of the powder throughout the part-build. Variables such as part bed temperature and laser power are taken into account to determine their influence on the process. While the PA powder was used for all experiments, different batches of powder were used each time.

Instrumentation

I. Temperature Sensor Selection and Calibration

An IRt/c was selected to measure the temperature during the process. An IRt/c measures, not its own temperature, but the temperature of the surface at which it is aimed. It measures the radiant energy given off by the object and converts this to a small voltage difference. This allows it to operate at a lower temperature than the measured object and also be non-contact [4]. It does, however, measure an average temperature of an area. The size of this area depends on the sensor's field of view and its distance from the surface. 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 could be output to a conventional thermocouple data acquisition system. The model chosen, microIRt/c.4 from Exergen Corporation, is a small cylindrical unit (7.6cm long and 0.95cm 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. The IRt/c requires 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 [5]. 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 those lines 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 to convert the recorded temperatures into actual temperatures, accurate within ±1^{o}C. The following is the equation, valid for this specific device, and for temperatures between 110^{o}-170^{o}C.

$$T = 0.946\,x + 15.9 \qquad (1)$$

where x is the IRt/c reading C and T is the corrected/adjusted temperature C [6]. A different experiment was conducted the following summer by heating a small sand bath in a crucible using a ceramic heater, placing thermocouples on the sand surface, positioning IRt/c about 1 cm away and running compressed air through the IRt/c air jacket for its cooling. The data was analyzed and found to yield (2), a very close fit similar to (1) that confirmed accuracy of measurements [7].

$$T = 0.954\,x + 15.3 \qquad (2)$$

II. Sensor Mounting

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^{o}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, which was very helpful in the design stages of the mount and also helped to illustrate the experimental setup (Figure II). Notice the current IR sensors in the machine. These machine have only measured average temperatures of a large area within the SLS and have not given any significant direction to streamlining the sintering process parameters.

Since MSOE has such an extensive rapid prototyping center, it was decided to construct the mount from a very durable plastic that is used in the Fused Deposition Modeling 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 (See Figures II and III). 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.

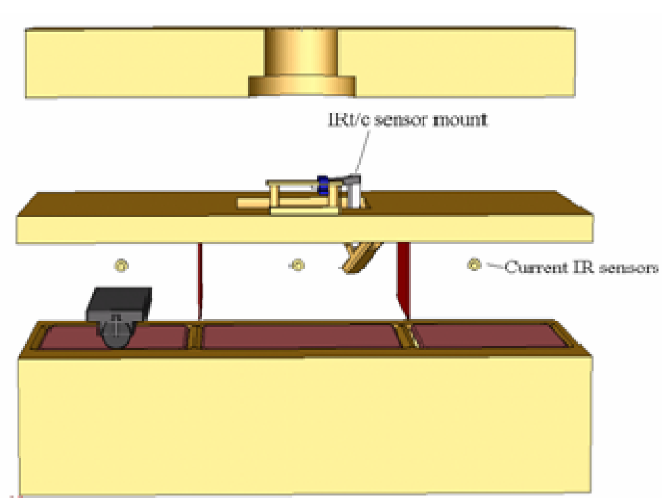


FIGURE II
SLS MACHINE WITH IRT/C SENSOR MOUNT

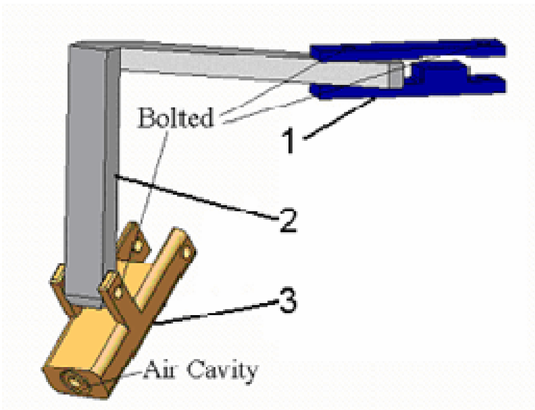


FIGURE III
SENSOR MOUNT

The above articulating arm made it possible to maneuver the IRt/c within the SLS machine. The arm clamped onto the handle of the heater tray and allowed the sensor to be lowered through the laser window. It was moved to the corner so as not to obstruct the laser and then adjusted to view the center of the part bed (Figure IV). It remained roughly 10cm above the surface of the powder such that the roller could move freely from one side to the other. Also attached to the sensor is the tube which provides cooling. A jacket was made specifically to cool the sensor while ensuring that the gas flow was not directed at the powder bed. Once set up, the sensor monitored the powder temperature from inside the machine safely and without interfering with the sintering process.

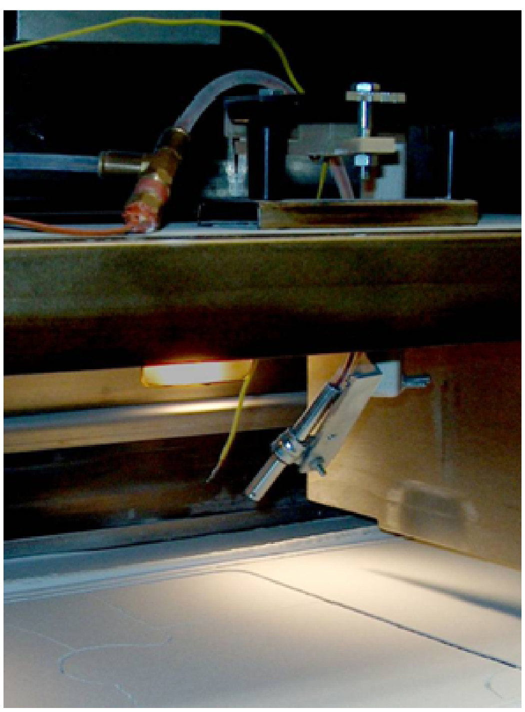


FIGURE IV
SENSOR MOUNTING ON THE SLS MACHINE

EXPERIMENTAL

The goal was to better understand and measure the temperature changes that occur during sintering. This places no special constraint upon the part being built. A flat disc was chosen so that the sensor's field of view would fall on an area that was sintered all at once. The part was 7.6cm in diameter and 0.25cm thick. Because part-builds used layers 0.01cm thick, each disc was comprised of 25 layers. This allowed sufficient data to be recorded for each trial. Every experiment was conducted using the PA powder. In summer of 2004, the powder age was kept at around 320-330 part-build hours. Only PA was used so that the powder in question of creating poor parts was tested while keeping its age constant. In summer of 2005, the powder age was unknown. Because the Rapid Prototyping Center also uses powder donated from outside companies, the age and properties of each individual batch were unknown. Hence, each experiment was run using a different batch of PA with an unknown age. The powder age is not a parameter in this study for obvious reasons but more importantly, the heat transfer process is the critical focus of this work.

The experiment was performed 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.

RESULTS AND DISCUSSION

Trial tests were conducted on single discs at laser power setting of 8W which tested the sensor setup and verified the correct operation of the IRt/c. Test A included the building of discs at different laser powers. With the part bed at 149°C, tests were conducted for 8 discs at intervals of 1 W from 6 W to 13 W and sampled data every 0.5 seconds. Test A revealed unexpected results as shown in Figure V.

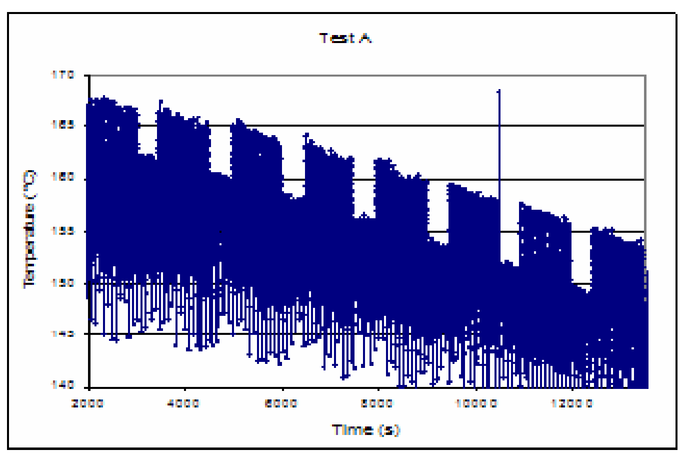


FIGURE V
FALLING TEMPERATURES OBSERVED IN TEST A

It was unclear as to why the recorded temperatures were dropping throughout the build, and so in Test B discs were built at laser power settings of 6 to 13 W as before and then also from 13 W back down to 6 W. Again, the negative slope in the data was observed. However, at the end of this longer experiment it was more clearly seen that powder had accumulated on the sensor. Powder inside the machine was slowly building up on the lens of the IRt/c effectively lowering the readings by obscuring the field of view.

Significant changes made during Test C showed anticipated trend in the results. The sampling rate was increased to once every 0.04s to better capture the sintering process. Also, after each disc was built, the SLS machine was stopped and the sensor was cleaned using alcohol and a cotton swab. Finally, Test D was conducted. The parameters were very similar to those used in Test C. The sensor was moved slightly closer to the powder bed in order to decrease the spot size, and the sensor was cleaned after every two discs.

The results of these experiments shed light on the sintering process. Figure VI depicts the sintering of 3 discs during Test C. Unlike the previous experiments, during this test, 7.6cm square discs were built rather than circles. The test results are the same, because the spot size is smaller than the disc in either case. The change was made only to more easily measure the scan rate of the laser. Each plateau depicts the building of a single disc. Each peak within that range is the sintering of a single layer of the part. 10 layers are inserted between each disc to provide separation.

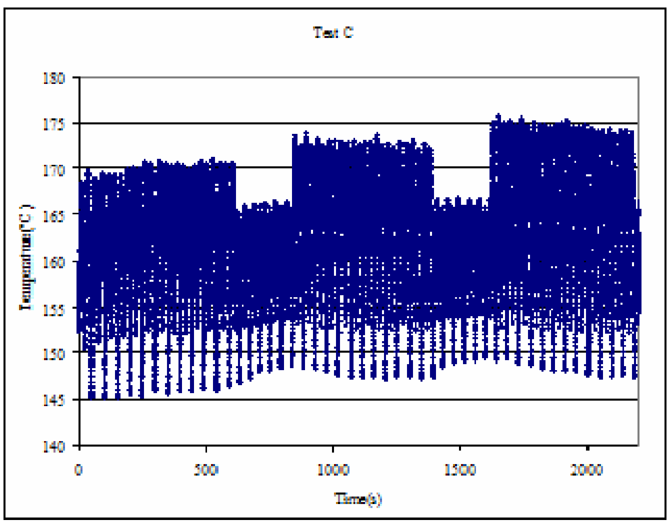


FIGURE VI
SINTERING OF DISCS AT 7, 9, 11 W LASER SETTINGS

Because data were taken every 0.04s for Tests C and D, a more detailed view of the sintering process was captured. Figure VII displays the temperature profile of a single layer. Cooler powder from the feed bed creates the valley on the left when spread over the part bed. The piece is struck by the laser and sintered from about 170-180.5 seconds. Next it quickly cools, solidifies, and the temperature stabilizes around 161°C. Finally, the roller again deposits a fresh layer of powder and the temperature drops until this new layer is raised to the part bed temperature. This process repeats until the entire part is built.

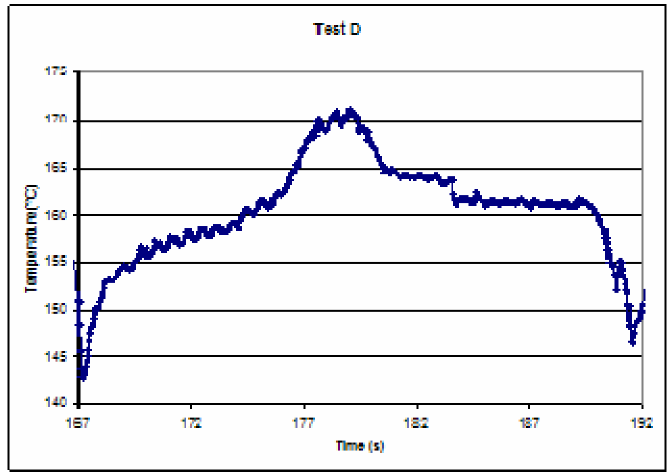


FIGURE VII
TEMPERATURE PROFILE OF THE SINTERING OF A SINGLE LAYER

The significance of what has been accomplished is realized when one looks at what the machine in-built sensors provide, a nearly constant temperature profile without any details of sintering during part build (See Figure VIII). Three layers could be seen but not any intricate details of the sintering process.

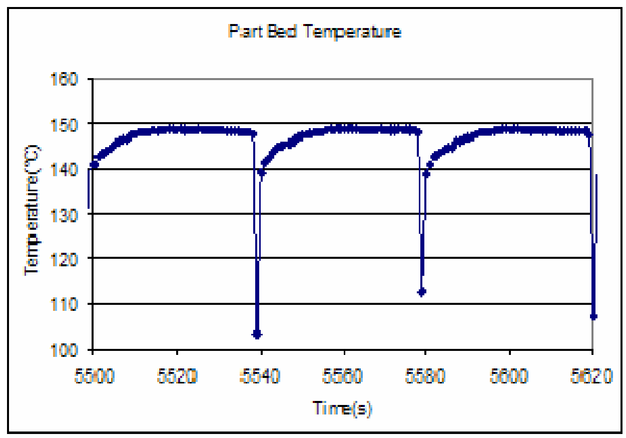


FIGURE VIII
TEMPERATURE PROFILE AS OBSERVED BY THE SLS MACHINE SENSORS

From the temperature data, it is possible to determine the relationship between laser power and change in temperature experienced by the powder when struck by the laser. All experiments show a linearly increasing slope, as would be expected. Increasing laser power results in raising the powder temperature by an increasing amount. Figure IX shows this trend line obtained from Test C. Each data point represents the data from one disc and is thus the average temperature rise of 25 individual layers sintered at that specific laser power.

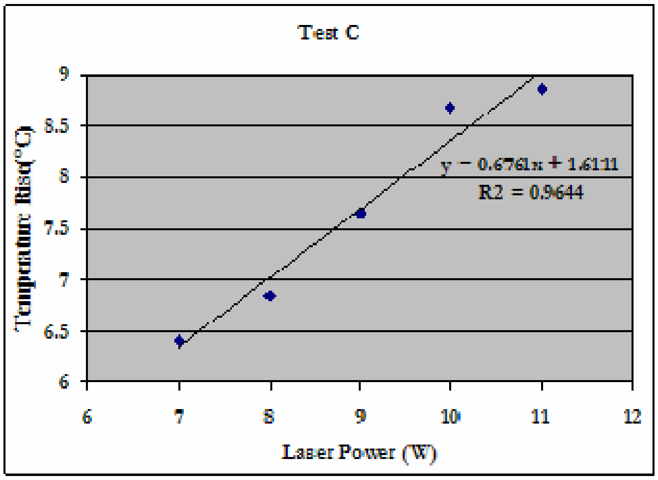


FIGURE IX
EFFECT OF LASER POWER ON TEMPERATURE RISE

One problem encountered during this process was the IRt/c spot size. The IRt/c has a 4:1 field of view, so that mounted 7.5-10cm from the powder, it measures the average temperature of an up to 2.5cm diameter circle. The laser has a diameter of 0.025cm meaning that a much smaller field of view would be necessary to fully capture the sintering process. The measurements indicate the powder never reaches its melting point near 184°C. This is due to the fact that although the temperature reaches 184°C at the precise location where the laser hits, the IRt/c also factors in the temperature of the immediately surrounding powder which is significantly cooler. Even during Test D the spot size was not small enough to capture the melting temperature of the powder. It did, however, result in the temperature readings being a few degrees higher than those in Test C.

CONCLUSIONS AND FURTHER WORK

This research work initiated 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 not been accomplished before, this research has explored ways to do that, and has investigated and solved many possible problems with this type of testing. Through this research a greater understanding of the dynamic sintering process was reached. The temperature profile during part building was seen in greater detail than ever before. It was also clearly seen that increasing laser power affected sintering by increasing the temperature of the powder by a greater amount. The research was limited by the spot size of the IRt/c. This may be resolved with more precise sensor or use of a thermal imaging camera. Then the variations in temperature at a single point would become more clearly visible.

Overall, this research is a significant milestone for the rapid prototyping industry due to the clarity it brought about the temperature dynamics of the sintering process. Now, with 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.

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.

ACKNOWLEDGMENT

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