Real-time Process Monitoring and Temperature Mapping of a 3D Polymer Printing Process

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ABSTRACT

An extended-range IR camera was used to make temperature measurements of samples as they are being manufactured. The objective is to quantify the temperature variation of the parts as they are being fabricated. The IR camera was also used to map the temperature within the build volume of the oven. The development of the temperature map of the oven provides insight into the global temperature variation within the oven that may lead to understanding variations in the properties of parts as a function of build location within the oven. The observation of the temperature variation of a part during construction provides insight into how the deposition process itself creates temperature distributions, which can lead to failure.

Keywords: 3D Printing, Fused Deposition Modeling, Thermography, Temperature Mapping, Soda Lime Glass.

1. INTRODUCTION

Computer designed 3D-models and parts can be printed using plastic as the “ink” resulting in rapid prototypes, models, and useful parts. Fused Deposition Modeling\(^1\) (FDM) is a specific manufacturing process in the general class of additive manufacturing, also known as 3-D printing. In FDM a thermoplastic filament is fed into a heated extrusion tip in the liquefier head. The liquefier head is moved under computer control in the X- and Y-plane as the molten polymer is extruded from the heated tip. The first printed layer is deposited on a disposable plastic build sheet held in place on the build platform by a vacuum. The build platform moves in the Z-direction and contains a grid of small holes through which a vacuum is applied to hold the release sheet in place. After each layer of thermoplastic is printed, the build platform is lowered by a small increment to allow the deposition of the next layer. As the molten thermoplastic is deposited on the thermoplastic below, it fuses to it making a solid bond. This process continues until the final model or part has been manufactured. The liquefier head contains two extrusion tips. The first one, as discussed above, is used to extrude the thermoplastic, which makes up the desired part. The second extrusion tip operates at a different temperature and is used to deposit fragile and dissolvable polymer used as support material. Support material is needed when the next layer to be printed would otherwise not have thermoplastic below to support it (i.e., overhangs, tubes, inverted bevels, etc.). The entire FDM process takes place inside a temperature controlled convection oven to help reduce thermal stresses in the parts being printed.

The FDM process is inherently a thermal process and thus lends itself nicely to study using infrared (IR) cameras. Of particular interest are temperatures within the oven, temperature mapping of parts during deposition, and extrusion temperatures as a function of tip design. In this paper, all thermal imaging was performed on the Fortus 900mc Fused Deposition Modeling Production System manufactured by Stratasys, Ltd. Shown in Figure 1. For this study the thermoplastic filament used was 0.254 mm diameter (0.010 in.) ULTEM 9085\(^2\), which has a glass transition temperature of 186°C. Heated air recirculates through the convection oven of the Fortus 900mc. When using ULTEM, as in these studies, this temperature is set to 185°C. The build envelope size is 914 x 610 x 914 mm (36 x 24 x 36 inches).

2. EXPERIMENTAL SET-UP

Since the internal oven temperatures exceed the safe operating temperatures of IR cameras, it is clear that the camera must be stationed outside of the oven. There are two locations from which IR imaging is practical. First, the Fortus 900mc is equipped with a large window in the oven door (See Figure 1), which allows a straightforward view of the...
build envelope. Second, there is a flexible baffle across the top of the oven to keep the hot air in while allowing the liquefier head to translate in the X- and Y-directions. This baffle material can be disconnected from the front of the liquefier head, and the narrow gap filled with an infrared transparent window. From this vantage point, a close-up view of the liquefier head is possible. Both approaches are discussed below.

![Figure 1. The Fortus 900mc FDM Production System.](image)

### 2.1 Imaging Through the Front Window

The window system in the oven door of the Fortus 900mc consists of a double panes of soda lime glass window on the inside of the door and a pane of decorative clear plastic on the outside. The type of plastic used for the outside window is unknown, but it is extremely opaque in the infrared. So, this plastic pane was removed during IR imaging. The double panes of glass (22 x 22 in.) also offer challenges to the thermography. Soda lime glass is only transparent\(^3\) up to approximately 2.6 \(\mu\)m. While this will allow infrared imaging with a near-IR camera, sensitive from 0.9 to 1.7 \(\mu\)m, there is very little temperature information in this wavelength range at 185°C. Imaging a blackbody cavity set to 185°C, our NIR camera (Indigo Phoenix NIR Camera) was to just discern the cavity above the background noise. As such, there was not enough dynamic range for temperature measurements with this camera at these temperatures. While it is possible to image very hot objects (>600°C) through a room temperature soda lime glass window with a Midwave IR camera (3.0 to 5.0 \(\mu\)m), in this case the objects to be imaged were not that hot. Further, there are 2 panes of glass and the inside pane is at the same temperature as the objects inside. Since the glass is radiating IR energy very effectively above 2.6 \(\mu\)m, IR imaging of the interior of the oven was poor with very little dynamic range.

The best sensitivity to the oven interior temperatures was obtained by using an extended range IR camera manufactured by Indigo. The Indigo Phoenix\(^4\) extended range camera is sensitive from 1.5 to 5.0 \(\mu\)m, and has a 640 x 512 InSb focal-plane-array. The camera was equipped with a 50 mm, f/2.3 lens, also transparent from 1.5 to 5.0 \(\mu\)m (Janos Technology, Inc., NYCTEA Series lens). A warm 1.0” diameter lowpass filter, with a cutoff wavelength of 2.6 \(\mu\)m, was mounted on the back of the lens (Spectrogon SP-2600 Filter). This combination of camera and optics results in system sensitive from 1.5 to 2.6 \(\mu\)m. During some imaging set-up situations, this lens is required to be within a few inches of the hot windows. So, in order to maintain the lens at ambient temperature a small fan was positioned to pass air over the lens body without cooling the windows. This prevented a drift in the temperature calibration, which would otherwise occur if the lens were allowed to warm due to its proximity to the hot windows.
The camera was calibrated for temperature using an ULTEM part, which was instrumented with a type-K thermocouple. By using an ULTEM part, which was printed on this same machine, we could be sure the surface finish, and thus its emissivity, would match that of future parts as they were manufactured. By imaging this calibration target in the oven and through the double pane window, we could be sure the calibration conditions matched as exactly as possible the conditions of future testing. Figure 2 shows the linear calibration obtained with the set-up described above. This calibration equation was used to convert the raw IR signal coming from the camera to temperature in order to map the internal oven temperatures, part temperatures during printing and extrusion temperatures. The calibration curve is only good for objects printed using ULTEM thermoplastic.

![Calibration Curve](image_url)

**Figure 2.** Calibration curve for ULTEM thermoplastic for imaging with the extended-range Phoenix Indigo IR camera with an integration time of 1.2 ms, equipped with a 50 mm f/2.3 lens and lowpass filter with a cutoff wavelength of 2.6 μm. The error bars are ±1%.

2.2 Imaging From the Liquefier Head

The best view of the extrusion tip is from an IR camera mounted on the liquefier head. This would keep the tip fixed in the field-of-view of the camera and allow higher resolution than a camera positioned outside the oven door. However, space and weight restrictions require a small, lightweight camera. The FLIR A35 is an uncooled, 14 bit, 320 x 256 pixel, 60 Hz, IR camera which weighs only 0.2 Kg (0.44 lbs.). The size of the camera without a lens is 106 x 40 x 43 mm (4.2 x 1.6 x 1.7 in.). This radiometric camera is factory calibrated from -40° to +550°C, is equipped with a 19 mm lens with a FOV of 24° x 18° and possesses a minimum focus distance of 153 mm.

The Fortus 900mc was used to print a camera bracket to allow mounting the IR camera to the liquefier head. A window holder was also printed and fitted with a NaCl window, transparent in the long wavelength of the camera. The size of this window is 50 x 25 x 6 mm. A mirror bracket was also printed and fitted with a gold front surface mirror. This mirror bracket was mounted on the liquefier head inside the oven, just below the NaCl window. A gold mirror was chosen for it’s exceptional IR reflectance properties. The entire optical path was less than 200 mm. Figure 3 shows a schematic diagram of the set-up on the left and a photo of the IR camera mounted on the liquefier head on the right.

3. RESULTS

3.1 Mapping the Oven Temperatures

Since hot air rises, it is difficult to maintain a perfectly uniform temperature throughout the 0.51 m³ (18 ft³) volume of the convection oven. Since large variations in temperatures can lead to thermal stresses, it is of importance to understand the thermal profile throughout the build envelope. This thermal profile was measured using the extended range IR camera.
camera, imaging through the double pane window as described above. Nine ULTEM targets were specifically printed for this task. Each target consisted of a face 6 inches high and 1 inch wide attached to a mounting bracket on the back to keep it vertical. A small 50.8 x 25.4 mm (2 x 1 in.) target was equipped with a type-K thermocouple to spot-check the IR temperature calibration for drift. The arrangement of these nine 152.4 mm (6 in.) high targets and the 50.8 mm (2 in.) high target can be seen in Figure 4 below. Lights inside the oven were turned off during the test since the extended range IR camera could detect their light. Room lights appeared to have no effect on the temperature measurements, probably because very little room light could get directly into the oven.

![Fortus 900mc Liquefier Head with IR Camera Modification](image1)

**Figure 3.** Left) CAD drawing of the liquefier head with the FLIR A35 IR camera mounted on top, imaging down through a NaCl window at a gold mirror, which aims the camera at the extrusion tip, and Right) Photo showing the IR camera mounted on the liquefier head, aimed down into the oven.

![Fortus 900mc oven interior](image2)

**Figure 4.** Photo of Fortus 900mc oven interior. The liquefier head is the black box at the top-center of the photo. Six-inch tall ULTEM calibration targets are distributed at nine locations on the build platform. A 2-inch high calibration target is located in the front right quadrant of the build plate and is instrumented with a type-K thermocouple.

The series of measurements began with the build platform raised up to bring the ULTEM targets to within 25.4 mm (1.0 in.) of the top of the furnace. Then the vertical temperature profile of each target was measured and recorded. The build platform was then lowered 5 inches, allowing a 1-inch overlap of data. The targets were then allowed to come into equilibrium with the local air temperature for a period of 1 hour. Then the temperature profile was repeated. This process
continued until the entire build envelope was thermally mapped. Some of the results are shown schematically in Figure 5, and all of the data is shown in the plot in Figure 6. At each level, the hottest area is on the right side. Also, the temperatures drop as the platform moves lower in the oven. From the plot in Figure 6 we see a discontinuity in the temperature profile in the overlap areas. This is due to the presence of the build platform and it’s effect on airflow. On the left side of the discontinuity (closest to the top of the oven), the overlap area on the target is the 25.4 mm (1.0 in.) area closest to the platform, while on the other side of the discontinuity; the overlap area on the target is 6 inches above the platform. In most of these discontinuities (overlap areas) we see that the area of the target 6 inches above the platform is a few degrees cooler than the area of the target, which is only 1 inch above the platform. From the data plotted in Figure 6, we can see that the largest temperature difference within the build envelope is 28°C.

Figure 5. Fortus 900mc Temperature (°C) maps of the build envelope; a) One inch from the top, b) eleven inches from the top of the oven, c) 21 inches from the top of the oven, and d) 31 inches from the top of the oven.

Figure 6. Plot showing the temperature profile at various locations inside the build envelope.
3.2 Mapping Part Temperatures During Deposition

In order to demonstrate the usefulness of thermal imaging parts as they are being printed, a single solid cone was produced while imaging with the extended wavelength IR camera, equipped with a lowpass filter and imaging through the double-pane window, as discussed above. The ULTEM cone was printed to 75 mm (3.0 in.) high with a 25 mm (1.0 in.) base when completed. During the printing, it quickly became evident that a temperature gradient was developing from top to bottom and also from left to right. The top to bottom temperature gradient is expected because the ULTEM is extruded at a temperature approximately 200°C hotter than the build platform onto which the part is printed. However, the horizontal temperature gradient was not expected and may be the cause of the very small geometric distortion in the final part. Figure 7 shows this thermal gradient as it was recorded across the top of the cone, every 12.5 mm (0.5 inches), as it was being printed.

![Figure 7](http://proceedings.spiedigitallibrary.org/)

Figure 7. Plots showing the horizontal temperature profile across the top layer of a solid cone while being printed. Notice at every level there is a temperature gradient with the hottest side on the right.
The magnitude of this temperature gradient varied between 25 and 90°C because of the variable amount of time elapsed between when printing a particular layer was completed and when the thermal image was recorded. However, the temperature is not of primary interest in this situation, but the existence and consistency of the temperature gradient. The magnitude of this temperature gradient was also enhanced by the fact that only one small part was being printed and by not allowing sufficient time between layers for the temperature gradient on the previous layer to dissipate. It is believed that this temperature gradient forms on this particular part because it was designed to be printed in such a way that the liquefier head began and ended each layer on the right side of the part, as viewed by the IR camera. This means that the hot liquefier head remained over this area longer and thus overtapped this region, both radiatively and convectively. This condition can be reduced or eliminated by choosing a random start/end location for each layer, or by rotating this position around the part to average out this effect.

3.3 Measuring Extrusion Temperatures

In a never ending effort to constantly improve the performance of their products, Stratasys designs and tests modified extrusion tips. While the details of these modifications are proprietary, the extrusion temperatures recorded can be discussed as an illustration of the importance of thermography in additive manufacturing. In order to compare the performance of the three tip designs, each was used to print a 76.2 mm (3.0 in.) tall solid cone, with a 25.4 mm (1.0 in.) diameter base. ULTEM thermoplastic was used as the printing medium. The extrusion temperatures were measured through the double pane window using the extended range Indigo Phoenix IR camera, as discussed above. A photo of the three printed cones is shown on the left side of Figure 8. On the right side of Figure 8 is shown a plot of extrusion temperatures of the three experimental tips while printing five layers of the cone when the cone height was approximately 19 mm (0.75 in.). From this data, it is clear that experimental tip #3 extrudes the thermoplastic at a cooler temperature than the other three, while tip #1 results in the hottest extrusion temperatures. Comparing the data for the fifth layer shown in Figure 8 we see the average extrusion temperatures of Tip #1, Tip #2 and Tip #3 are 335°C, 312°C, and 296°C, respectively. This information helps design engineers verify their models, which are used in designing improved extrusion tips.

![Image of ULTEM cones with three experimental tips](image)

![Graph of extrusion temperatures](graph)

Figure 8. Left) ULTEM cones printed with three different experimental tips. Right) Extrusion temperatures of the three experimental tips while printing the cone layer 19 mm (0.75 in.) above the build platform.

3.4 View of Liquefier Head

With the recent addition of an IR camera mounted on the liquefier head, new studies of extrusion temperatures and the temperature gradients of deposited layers can begin. An image recorded by this camera is shown in Figure 9. Future studies with this camera will include the study of new materials, the temperature decay time for the deposited...
thermoplastic, the effect of the temperature of previously deposited layers on the deposition temperature, and the effect of extrusion tip modifications on the extruded temperature.

Figure 9. View of the extrusion tip and liquefier head from the IR camera mounted on top of the liquefier head.

4. SUMMARY

Two different approaches have been developed to allow infrared imaging of the FDM process in the Fortus 900mc Production Printer. In the first approach an extended range IR camera equipped with a lowpass cutoff filter is used to image directly through a double pane soda lime glass window. This allows a view of the entire build volume and measurements of the temperature uniformity of the oven, as well as, individual parts as they are being printed. In the second approach, a small lightweight uncooled longwave IR camera is mounted on the liquefier head and focused onto a close-up view of the heated extrusion tip. This view allows higher resolution imaging and temperature measurements of the thermoplastic as it is extruded and begins to cool on contact with the layer of material below.

Temperatures throughout the build envelope were measured using ULTEM targets mounted on the build platform. The temperature of these targets was measured as the platform was lowered. Using this technique it was observed that the hottest temperatures are typically located on the right side of the oven and the oven is cooler as you move from top to bottom. The maximum temperature difference was measured to be 28°C.

Thermography of parts while they are being printed also allows the detection of thermal gradients within the part, which can lead to thermal stresses and geometric distortions. The detection of horizontal temperature gradients on the printed parts motivates designers to consider more carefully how each layer is deposited.

Thermography was used to evaluate three experimental tips. The temperature of the thermoplastic extrusion was measured for each tip during the printing of solid cones. It was found that small design modifications have a large impact on the extrusion temperatures. This data is useful in model verification and development.

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[2] ULTEM 9085 is a trademark of SABIC (Saudi Basic Industries Corporation) Innovative Plastics IP BV, principal corporate offices and headquarters are in Riyadh, Saudi Arabia.


[4] Indigo Systems was sold to FLIR in 2004 and is now FLIR’s Santa Barbara facility. Phone: 805-690-6617.