Infrared Imaging of the Polymer 3D-Printing Process

Ralph B. Dinwiddie*, Vlastimil Kunc, John M. Lindal, Brian Post, Rachel J. Smith, Lonnie Love, and Chad E. Duty

Oak Ridge National Laboratory, Manufacturing Demonstration Facility, 2370 Cherahala Blvd., Knoxville TN 37932-1563

ABSTRACT

Both mid-wave and long-wave IR cameras are used to measure various temperature profiles in thermoplastic parts as they are printed. Two significantly different 3D-printers are used in this study. The first is a small scale commercially available Solidoodle 3 printer, which prints parts with layer thicknesses on the order of 125μm. The second printer used is a "Big Area Additive Manufacturing" (BAAM) 3D-printer developed at Oak Ridge National Laboratory. The BAAM prints parts with a layer thicknesses of 4.06 mm. Of particular interest is the temperature of the previously deposited layer as the new hot layer is about to be extruded onto it. The two layers are expected have a stronger bond if the temperature of the substrate layer is above the glass transition temperature. This paper describes the measurement technique and results for a study of temperature decay and substrate layer temperature for ABS thermoplastic with and without the addition of chopped carbon fibers.

Keywords: Thermography, 3D-Printing, Additive Manufacturing, Temperature Decay, Extrusion Temperature, Fusion Deposition Modeling, ABS, Carbon Fibers.

INTRODUCTION

In the 3D-printing process the part is built one layer at a time. Each layer is deposited onto the previous layer, which can be referred to as the substrate layer. The first layer is deposited onto a build plate or build platform. In some cases this build plate may be heated to reduce residual stresses in the part. The thermoplastic material is typically in a filament or pellet form. This material is fed into a heated extruder where it is heated beyond the melting temperature and the viscous material is extruded through a small orifice and onto the heated substrate or substrate layer[1, 2]. While the material is hot and sticky it can bond with the previous layer. This bonding mechanism no longer takes place once the material cools below its glass transition temperature, T_g. Therefore, the longer the material is kept above its T_g the better the bond between layers. The direction perpendicular to the layer plane is referred to as the z-direction. Thus the longer the extruded material is above the T_g, the better the expected z-strength[3, 4, 5]. In addition, the z-strength is also expected to be improved if the previous layer is above the T_g during deposition of the new layer. One practical consideration is that if the temperature of the thermoplastic is too high, and the viscosity too low, the part may distort or collapse under its own weight.

This paper is part of a study to quantify and understand the relationship between the temperatures during deposition and the z-strength of the final part. The scope of this paper covers the temperature measurement of the extruded material, the substrate layer, and the decay temperatures under typical build conditions. Two different 3D-printers were used in this study in order to compare the effect of the filament aspect ratio. The first printer is a small scale, commercially available Solidoodle 3 printer, which prints parts with layer thicknesses on the order of 125μm (0.005 in). The second printer is a large scale custom built printer called the BAAM (Big Area Additive Manufacturing) printer which uses pellets and extrudes a bead approximately 4.06 mm (0.160 in.) in diameter. Thus, the two printers extrude beads with very different ratios of surface area to volume, and should exhibit significantly different cooling dynamics.

The tensile data for the specimens discussed in this paper will be published in a future paper.

*dinwiddierb@ornl.gov; phone 1-865-335-0118; fax 1-865-574-3940; html.ornl.gov/contacts.shtml

Thermosense: Thermal Infrared Applications XXXVI, edited by Fred P. Colbert, Sheng-Jen (Tony) Hsieh, Proc. of SPIE Vol. 9105, 910502 · © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2053425

EXPERIMENTAL SET-UP

Solidoodle Printer

A commercially available Solidoodle 3 printer was used to print 2 different simple shapes in order to study how the newly deposited layer cools as a function of time. For simplicity, this will be referred to as the decay temperature. The first simple shape printed was a 101.6 mm (4-inch) square. Five-layer squares were printed using ABS-Neat, ABS + 10 wt% carbon fibers, 20 wt% carbon fibers, and 30 wt% carbon fibers. The second simple shape printed was a 25.4 mm (1-inch) hexagon (the distance between opposite faces). The hexagons are 300 layers tall and will be later cut up into tensile specimens to measure the z-strength. As with the squares, four hexagons were printed using ABS-Neat, ABS + 10 wt% carbon fibers, ABS + 20 wt% carbon fibers, and ABS + 30 wt% carbon fibers.

Temperatures were measured using a FLIR SC-7600 mid-wave IR camera (640 x 512 Focal-Plane-Array)[6]. The camera was equipped with a fixed focus macro lens with has a horizontal field of view of approximately 9.9 mm. This results in an instantaneous field of view of 15.5 µm/pixel. The approximate distance from the lens to the target is 305 mm (12 inches). The set-up is shown in Figure 1. No filters or extender rings were used in this study. The integration time was set to 135 microseconds.

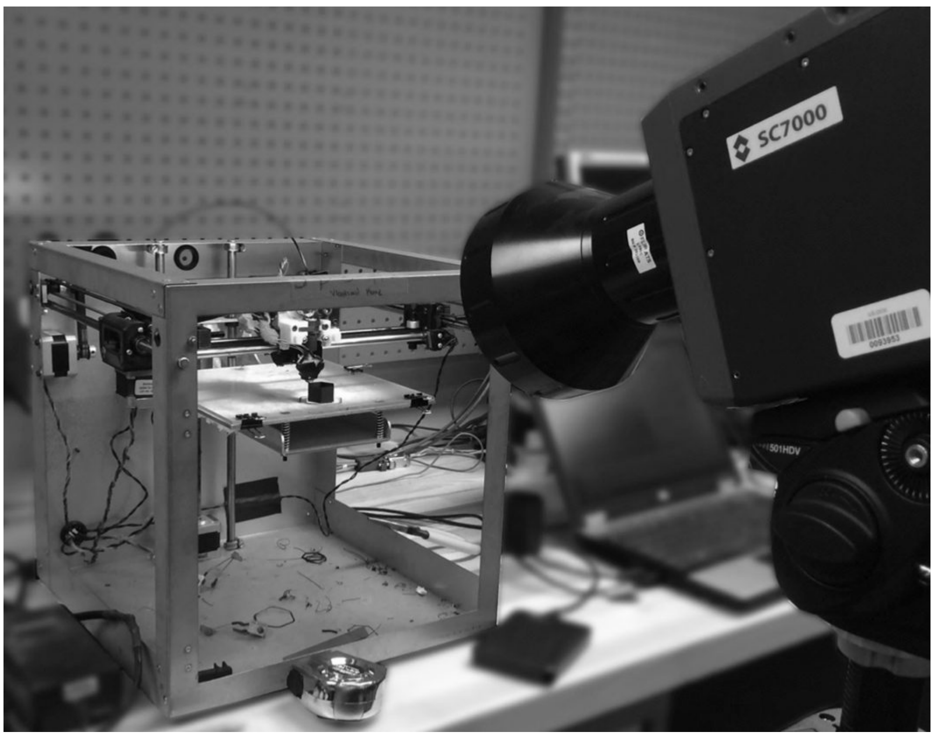

Figure 1. Experimental set-up showing the Solidoodle 3 printer and the FLIR SC-7600 IR camera equipped with the fixed focus macro lens.

Big Area Additive Manufacturing (BAAM) Printer

The BAAM printer (see Figure 2) is a unique custom built 3D printer, designed and constructed at Oak Ridge National Laboratory. This gantry-based printer is capable of printing parts 2.4m wide by 2.4m long by 2.4m high. The extruder is mounted on the bottom of a vertically oriented post, which moves in the x-, y-, and z-directions. The extruder is equipped with a z-tamper, which vibrates up and down, compressing the newly deposited layer onto the substrate layer. This improves z-strength by increasing the contact area between layers. The material is in the form of small pellets, which are continuously transferred to the extruder from a storage hopper by compressed air through a flexible hose. In this study, the material used was ABS + 13 wt% carbon fibers. A series of 3 different sized hexagons were printed (see

Figure 3). The size of the hexagons, as measured by the diameter of an inscribed circle, is 43 cm, 86 cm, and 173 cm (17 in., 34 in., and 68 in.). The size of the hexagons was chosen to double the time required to make a layer (lap time). The lap times for the 43, 86 and 173 cm hexagons were 29.8, 59.5, and 119 seconds, respectively. Each hexagon was printed 34 layers high. The hexagons will later be cut into tensile specimens to compare z-strength with the substrate layer temperature.

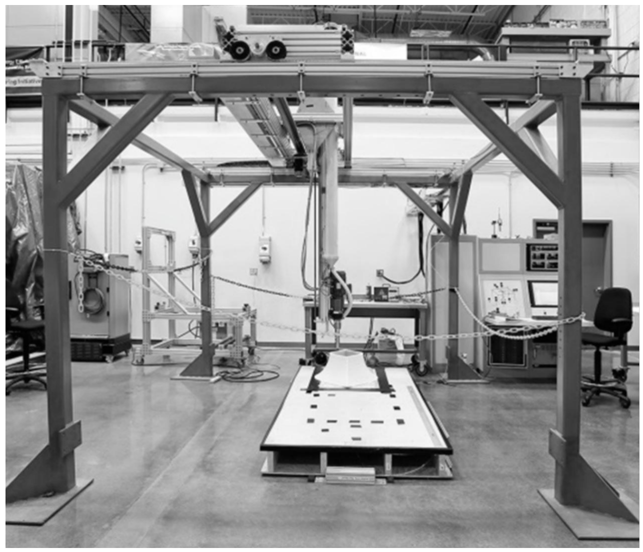

Figure 2. The BAAM 3D-Printer located at Oak Ridge National Laboratory.

Figure 3. Three hexagons printed on the BAAM 3D-Printer.

Temperatures were measured using a FLIR A35 long-wave uncooled microbolometer camera[7]. The A35 weights just 7 ounces and is equipped with a 28 mm lens. Images were taken at a rate of 30 Hz. The lens to target distance was approximately 42 cm (16.5 in.). The experimental set-up showing the BAAM extruder on the right, equipped with a Z-Tamper device, and the FLIR A35 longwave IR camera on the left, is shown in Figure 3.

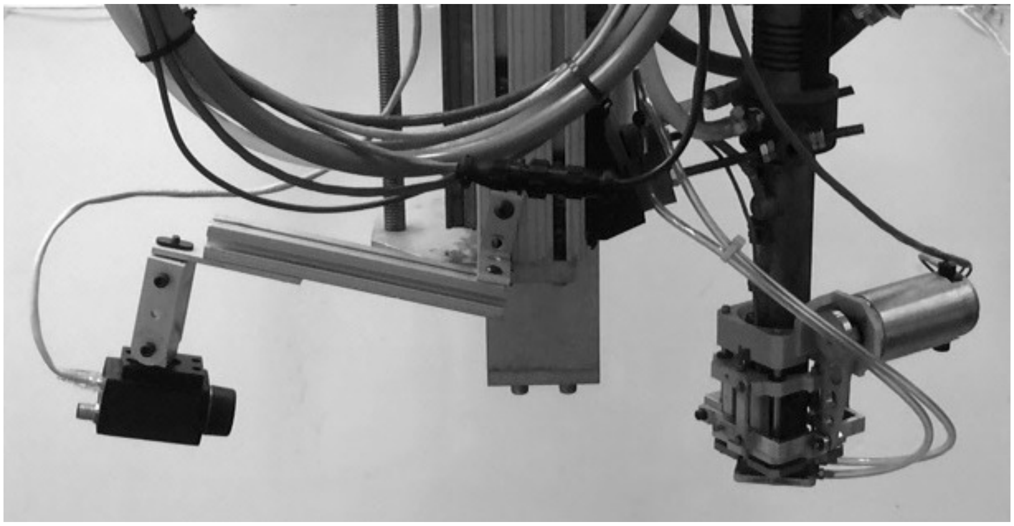

Figure 3. Experimental set-up showing the BAAM extruder on the right, equipped with a Z-Tamper device, and the FLIR A35 longwave IR camera on the left.

RESULTS AND DISCUSSION

2.1 SolidDoodle Printer

During the printing of the simple squares by the Solidoodle printer, a temperature profile was recorded for each layer of newly deposited material. This temperature profile is in units of °C/pixel. This profile can be converted into a decay temperature using the spatial calibration of 15.5 μm/pixel and the translational speed of the printhead, 25.07 mm/s. The decay temperatures for ABS-Neat are shown in Figure 4. Although the set-point temperature of the extruder is set to 255°C, the first layer is actually extruded at 170°C. This material is being deposited onto a glass substrate heated to 85°C. This first layer cools down to 115°C in 0.30 seconds. The second layer follows nearly an identical pattern. Layers 3 and 4 are extruded at 174°C and remain hotter than the previous 2 layers. The extruder temperature controller unexpectedly shut off after layer 4, and thus we were unable to get useful data from layer 5.

Figure 5 shows a comparison of ABS-Neat to ABS with various amounts of carbon fibers. The ABS + 10 wt% carbon fibers had an actual extrusion temperature of 200°C, and remained significantly hotter than the ABS-Neat material. This is expected to result in a higher z-strength, since the longer the material stays above its T_g, the better the bond between layers. The ABS + 20 wr% carbon fibers had an actual extrusion temperature of 222°C. This material remained hotter than the ABS + 10 wt% carbon fibers for the first 0.21 seconds when they reached an equal temperature of 150°C. The ABS + 30 wr% carbon fibers had an actual extrusion temperature of 220°C. this is within the 1% accuracy of the calibration, and thus, is statistically identical to the ABS + 20% carbon fiber material. The decay temperature remained between the other carbon fiber containing material for the first 0.2 seconds. After which the temperature dropped slightly below that of the material containing 10% carbon fiber for the next 0.1 seconds. Although there is noise in the data, it generally appears all of the carbon fiber containing materials have similar decay temperatures in the short term, with the exception of the lower extrusion temperature of the ABS + 10 wt% carbon fiber material.

The Solidoodle printer was also used to make 25.4 mm (1-inch) hexagon (the distance between opposite faces). These hexagons are 300 layers tall and each face can be machined into a tensile specimen for the measurement of z-strength.

The extrusion temperature and previous layer temperature was measured for each layer between 130 and 170, since tensile specimens are expected to break near the center. Three integration (exposure) times were used in a High Dynamic Range (HDR) imaging mode, in order to measure the temperature range between 50° and 230°C. The results for the ABS-Neat extruded at 205°C are shown in Figure 6. While extruder set-point was set for 205°C, the actual extruded temperature ranged from 198° to 211°C.

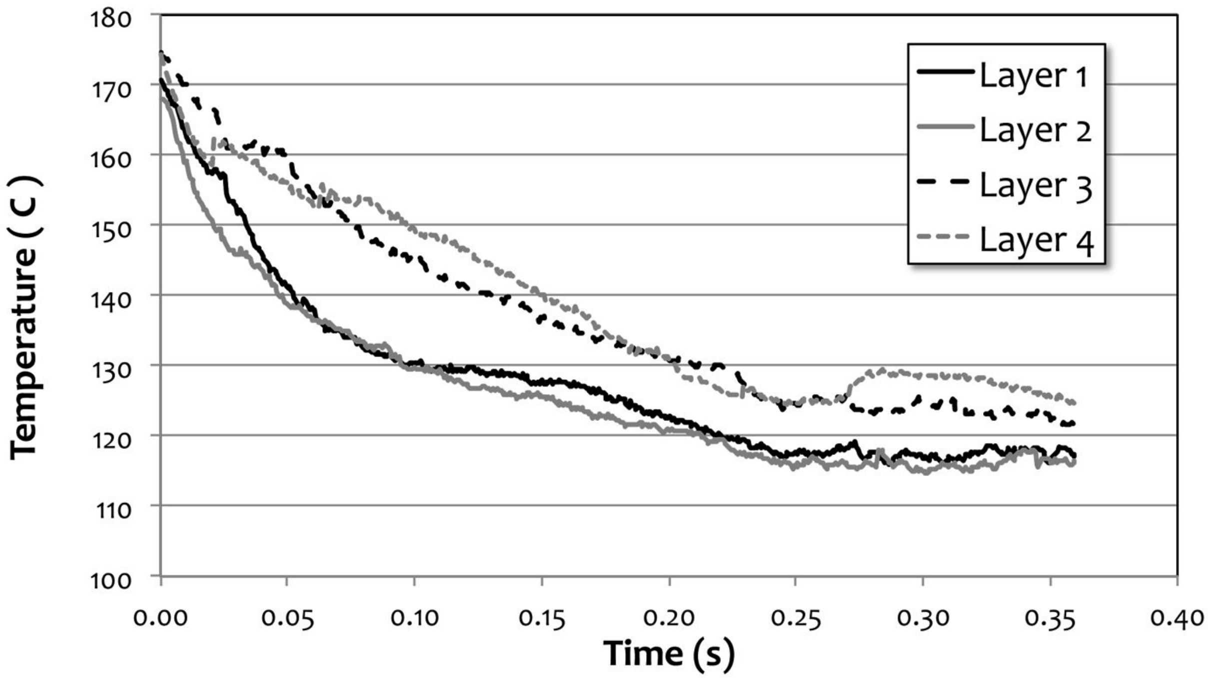

Figure 4. Decay temperatures for ABS-Neat 4-inch square printed on the Solidoodle.

Even though the build plate was heated to 85°C, the layers near the center of the part cooled down to temperatures in the range of 58° to 68°C before the next layer was deposited. These temperatures are significantly below the T_g for ABS, which is in the range of 95 to 105°C.

Figure 7 shows the temperatures of the center region for ABS-Neat extruded with a set-point of 225°C. The actual extruded temperature ranged from 203° to 228°C. The extruded temperature varies with a sinusoidal modulation with a period of approximately 2 minutes. This is probably due to the temperature controller of the Solidoodle not being able to maintain a constant temperature at this high set-point. The layers cooled down to temperatures in the range 56° to 62°C before the next layer was deposited. Again, all of these cool-down temperatures are significantly below the T_g of ABS.

The process temperatures for the center section of the small hexagon made with ABS + 13wt% carbon fibers is shown in Figure 8. The set-point for the extruder temperature was 205°C, while the actual extruded temperatures were 197° to 206°C. As with the ABS-Neat, the layers cooled to a temperature range of 57° to 70°C, which is below the T_g of ABS.

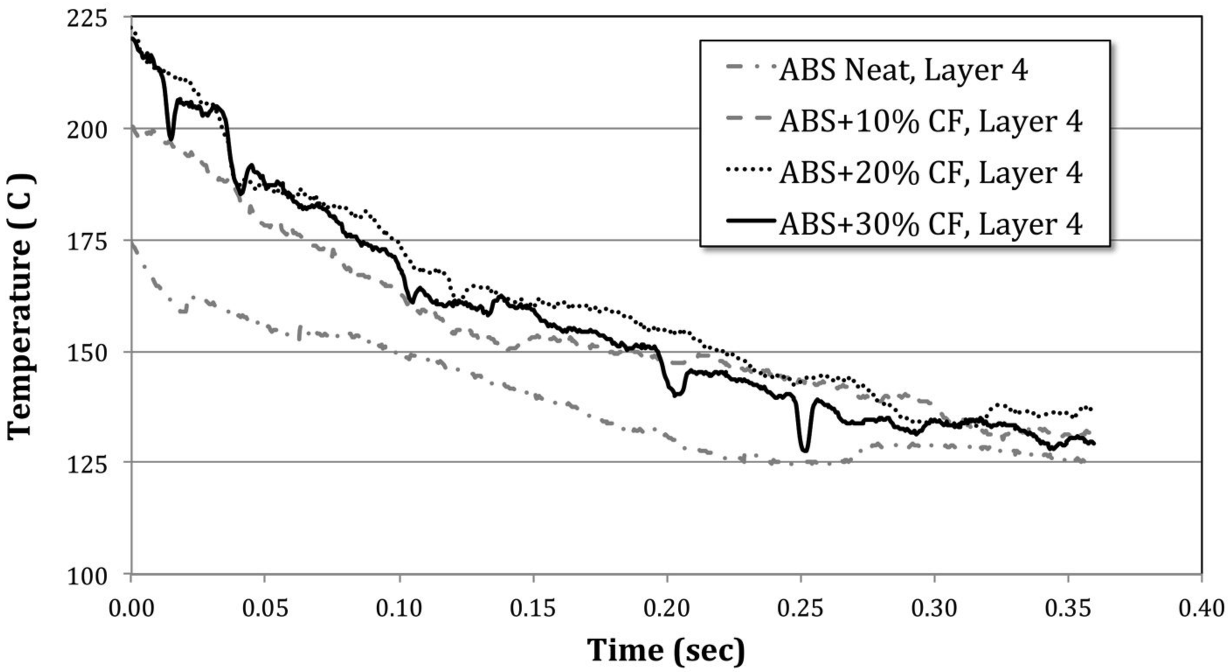

Figure 5. Decay temperatures for ABS-Neat compared to ABS with various amounts of carbon fibers, during the printing of a 4-inch square on the Solidoodle.

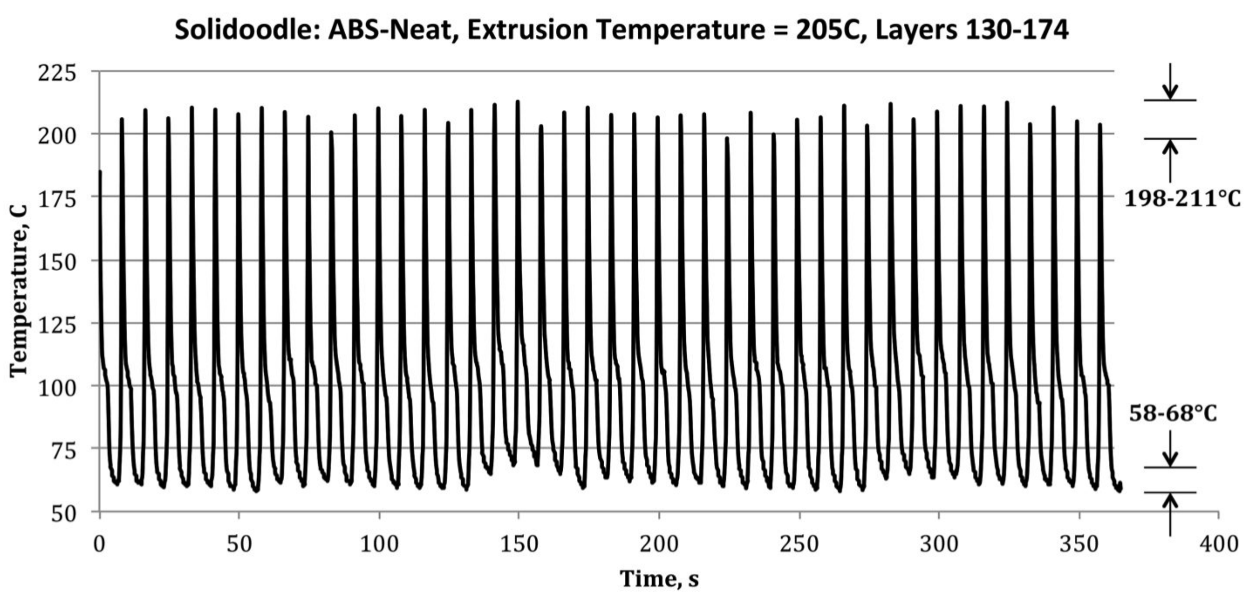

Figure 6. Temperature of the top-most layer during the printing of a 25.4 mm ABS-neat hexagon on the Solidoodle 3D-Printer. Extrusion temperature = 205°C.

Figure 9 shows the process temperatures for center section of the small hexagon made with ABS + 13 wt% carbon fibers. The extruder set-point was 225°C. As in the case of ABS-Neat extruded at 225°C, we see a sinusoidal modulation of the extruder temperature with a 2 minute period. The actual extruded temperature ranged from 209° to 234°C. This hexagon was the only case where porosity was observed forming during printing. The circles in Figure 9 labeled A and B indicate the layers between which the porosity formed. Images of the porosity are shown in Figure 10. While the smaller pores appear between layers, some of the larger pores appear to span an entire layer.

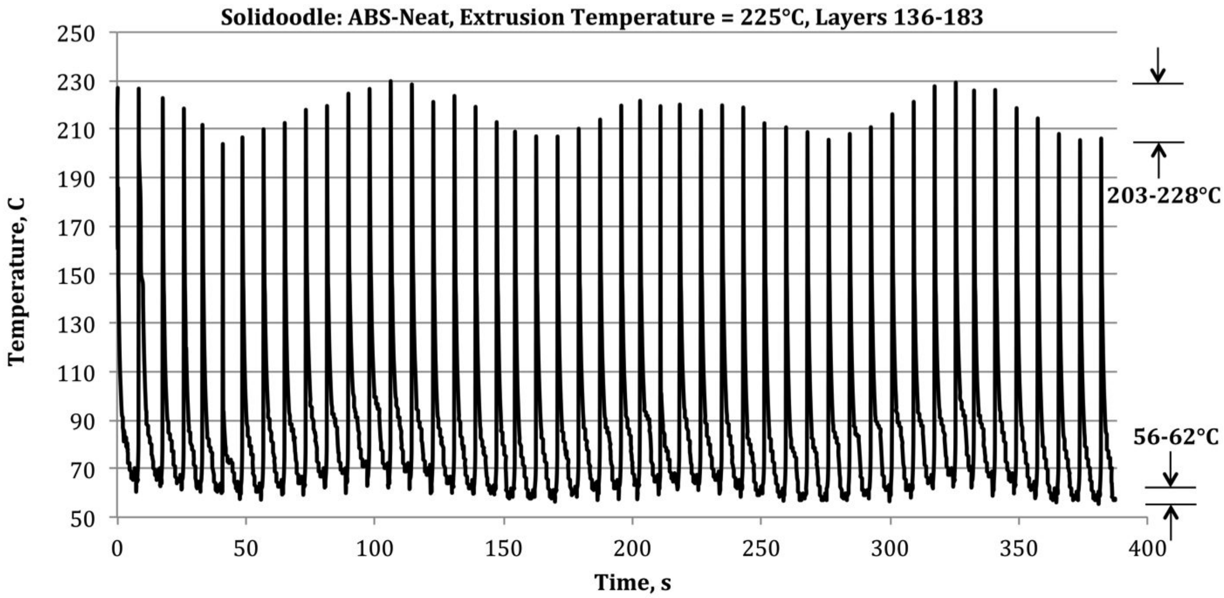

Figure 7. Temperature of the top-most layer during the printing of a 25.4 mm ABS-neat hexagon on the Solidoodle 3D-Printer. Extrusion temperature = 225°C.

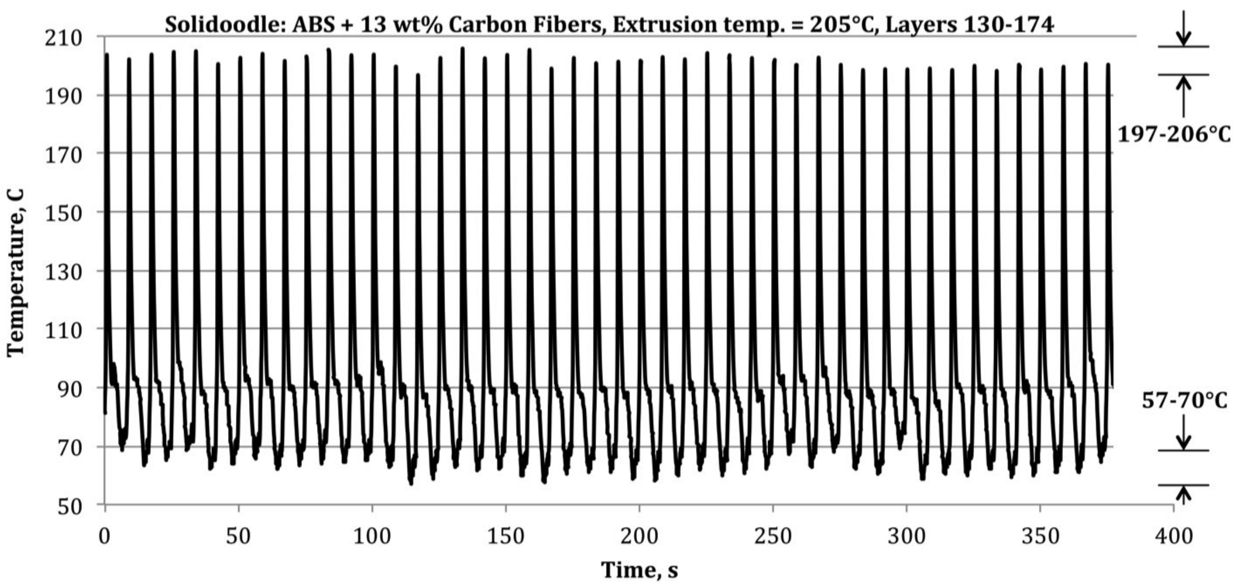

Figure 8. Temperature of the top-most layer during the printing of a 25.4 mm hexagon made with ABS + 13 wt% Carbon Fibers on the Solidoodle 3D-Printer. Extrusion temperature = 205°C.

The exact cause of this porosity is currently unknown. The only unique commonality between these two regions of porosity is that they started to form about 3 layers after the extruded temperature exceeded 230°C. However, this may be a coincidence, and the porosity may have resulted from flaws in the starting material.

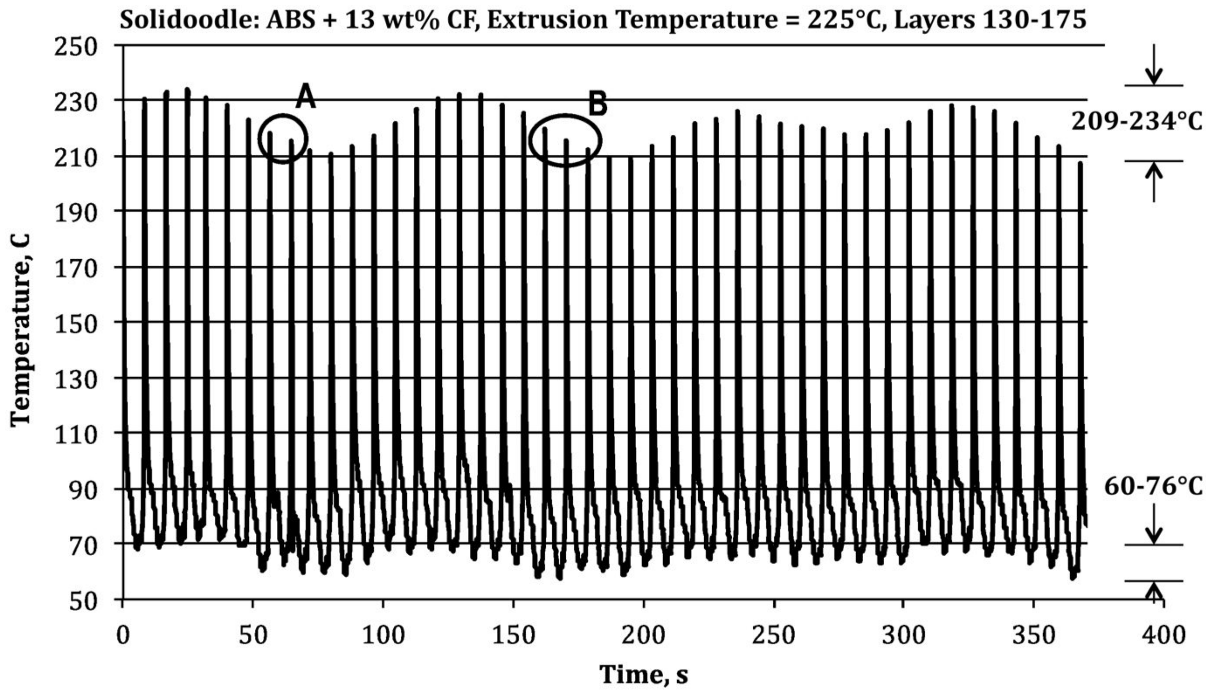

Figure 9. Temperature of the top-most layer during the printing of a 25.4 mm hexagon made with ABS + 13 wt% Carbon Fibers on the Solidoodle 3D-Printer. Extrusion temperature = 225°C.

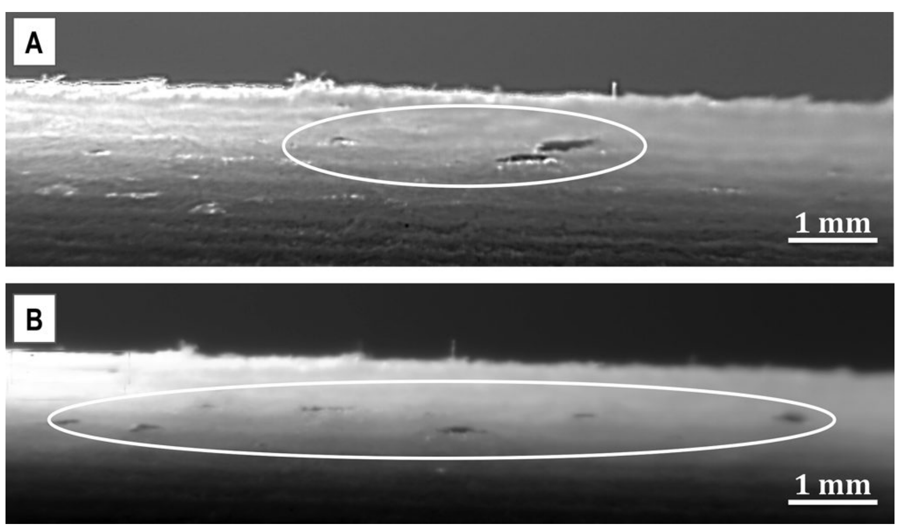

Figure 10. IR Images showing porosity in the hexagon made with ABS+13 wt% carbon fibers and extruded at 225°C. Image A shows porosity between layers 136 and 139 as indicated in by the circle labeled "A" in the above graph. Image B shows porosity between layers 149 and 152 as indicated in by the circle labeled "B" in the above graph.

2.2 Big Area Additive Manufacturing (BAAM) Printer

The BAAM printer was used to manufacture 3 hexagons, each of a different size, designed to double from the previous hexagon, the lap time needed to print one layer. This means that the 86 cm hexagon has twice the cool-down time for each layer than the 43 cm hexagon, while the 173 cm hexagon has twice the cool-down time as the 86 cm hexagon. All hexagons were produced using the Z-Tamper mechanism. Figure 11 shows layer 15 being printed for each of the 3 hexagons. In the images, layer 15 is the brightest layer, running from the center of the image as it is extruded and extending to the left edge of the image. Layer 14 is slightly lower and is measured from the center of the image to the right edge. In this manner, the extruded temperature is measured, as well as, the previous layer temperature.

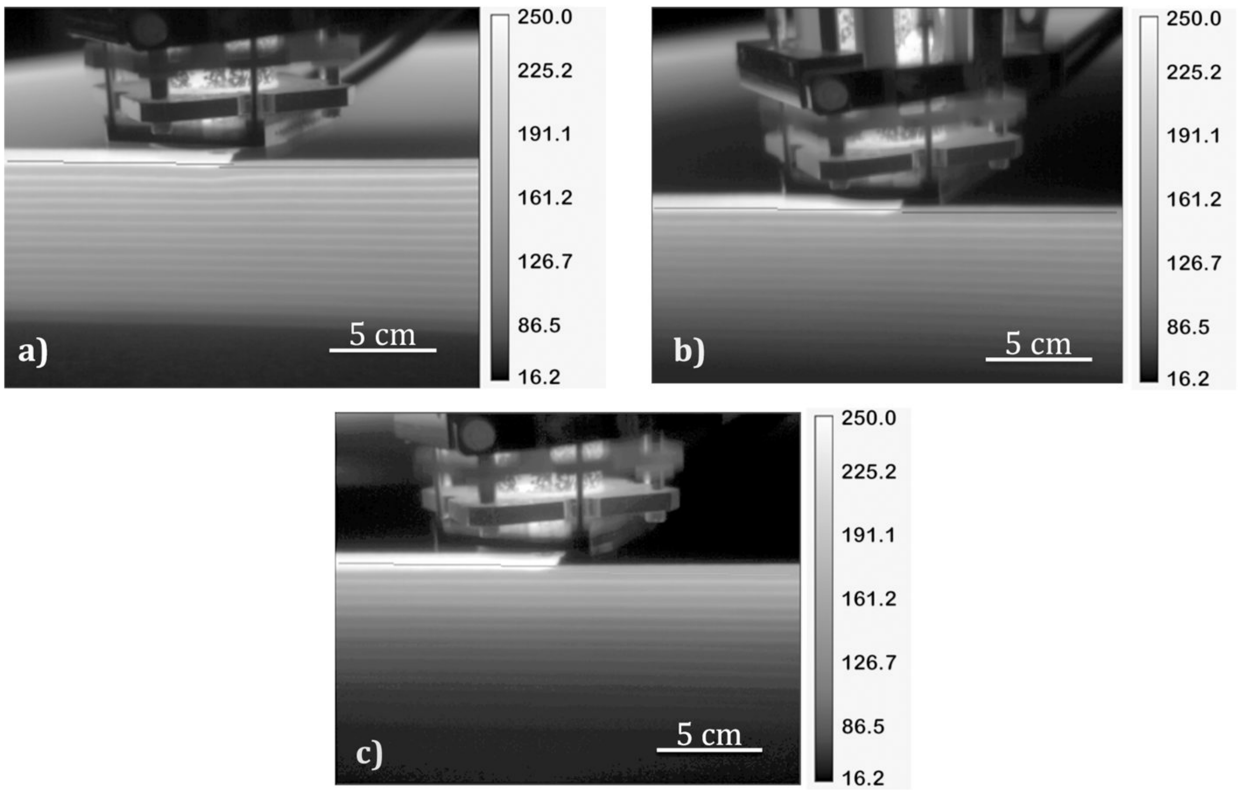

Figure 11. Infrared images of layer 15 being deposited onto layer 14 of the 3 hexagons;
a) 17 inch hexagon, b) 34 inch hexagon, and c) 68 inch hexagon.

Figure 12 shows the temperature profile across layers 14 and 15 for the 43 cm hexagon with a lap time of 29.8 seconds. The actual extruded temperature matches the extruder set-point temperature of 250°C. The temperature of this new layer (layer 15) can be seen to be decreasing away from the extruder. By the time the extruder make one complete lap (29.8 s) the previous layer has cooled to 172°C. Although the temperature cooled 82°C, it is still significantly above the T_g of ABS (T_g ABS = 95° to 110°C).

The results for the 86 cm (43 inch) hexagon, with a lap time of 59.5 seconds, are shown in Figure 13. The temperature profile across layer 15 shows the actual extruded temperature again matches the extruder set-point temperature of 250°C. The temperature of this new layer (layer 15) can be seen to be decreasing away from the extruder. By the time the extruder make one complete lap (59.5 s) the previous layer has cooled to 144°C. This temperature is still significantly above the T_g of ABS.

Figure 14 shows the temperature profile across layers 14 and 15 for the 119 cm (68 inch) hexagon with a lap time of 119 seconds. The actual extruded temperature matches the extruder set-point temperature of 250°C. The temperature of this new layer (layer 15) can be seen to be decreasing away from the extruder. After one complete lap the previous layer has cooled to 110°C. This temperature is right on the upper range of the T_g of ABS.

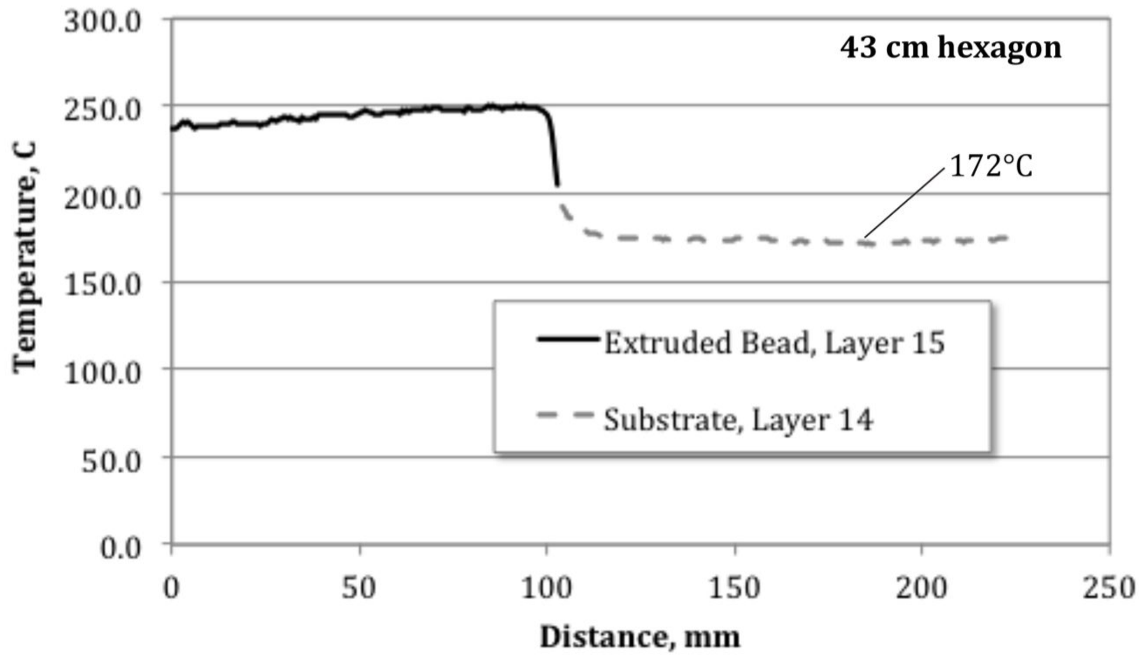

Figure 12. Temperature profile of the 43 cm (17 inch) hexagon, comparing the temperature of the newly extruded layer and the temperature of the layer onto which it is being deposited.

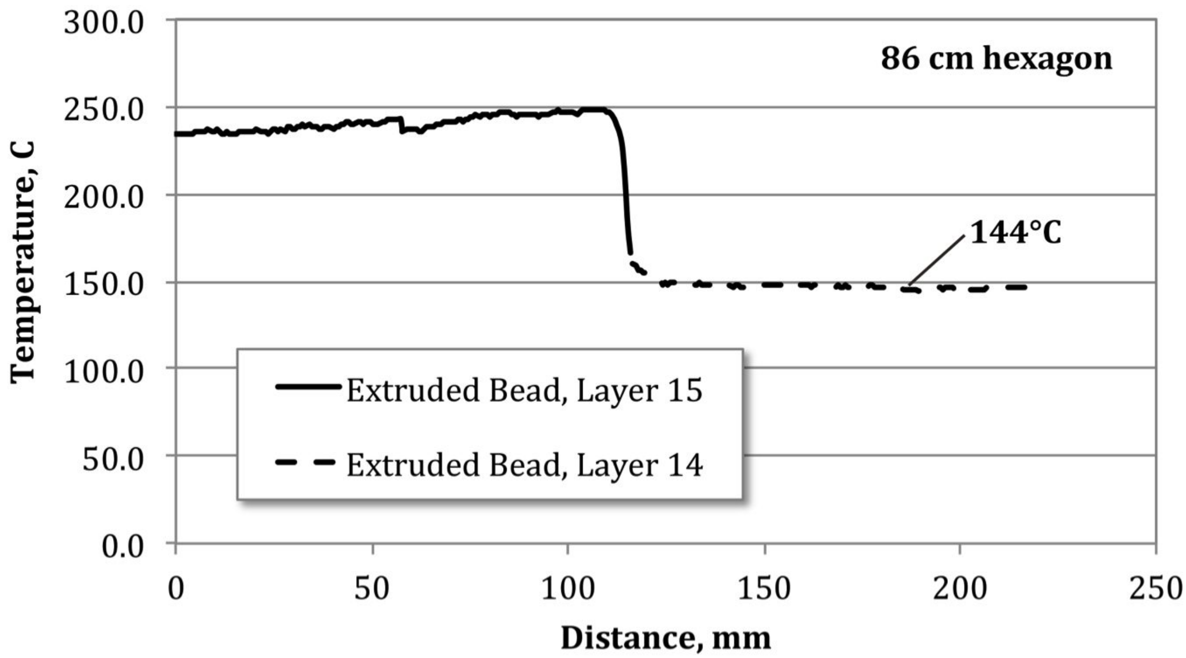

Figure 13. Temperature profile of the 86 cm (34 inch) hexagon, comparing the temperature of the newly extruded layer and the temperature of the layer onto which it is being deposited.

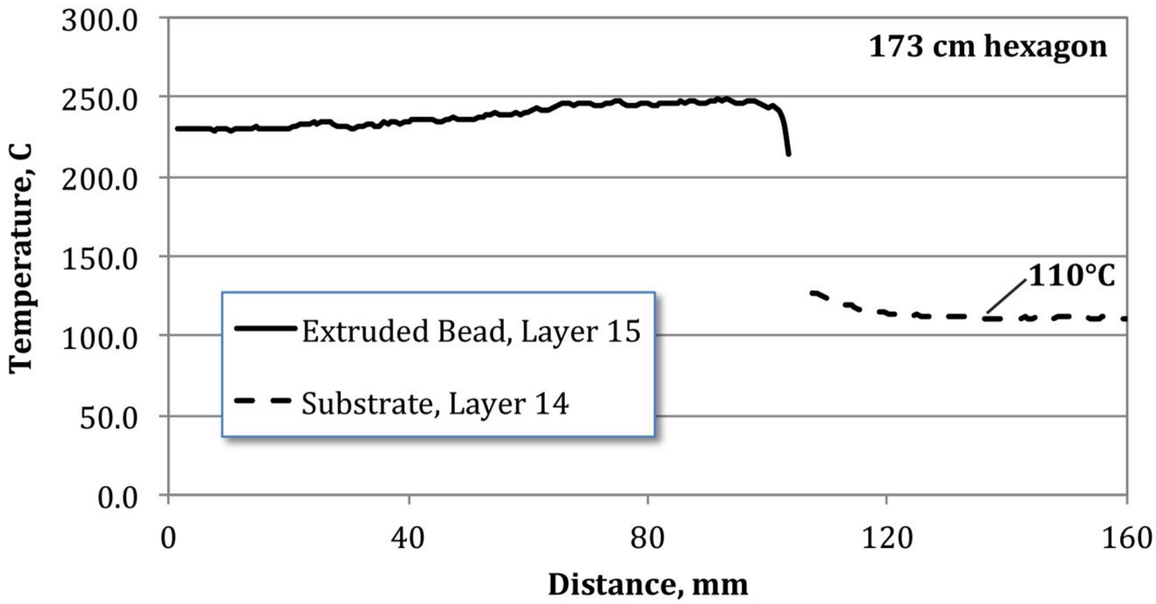

Figure 14. Temperature profile of the 173 cm (68 inch) hexagon, comparing the temperature of the newly extruded layer and the temperature of the layer onto which it is being deposited.

Figure 15 shows the cool-down rate for a typical ABS-Neat part printed on the BAAM. This part is a triangle with a 4-bead thick wall. The temperature was measured from the top and final layer of the part immediately after the extruder lifted out of the way. It can be seen tht the part takes approximately 30 minutes to cool down to a temperature of 60°C. Recall that the same material on the Solidoodle only requires approximately 8 – 10 seconds to cool down to the same temperature when starting at the same extrusion temperature of 250°C.

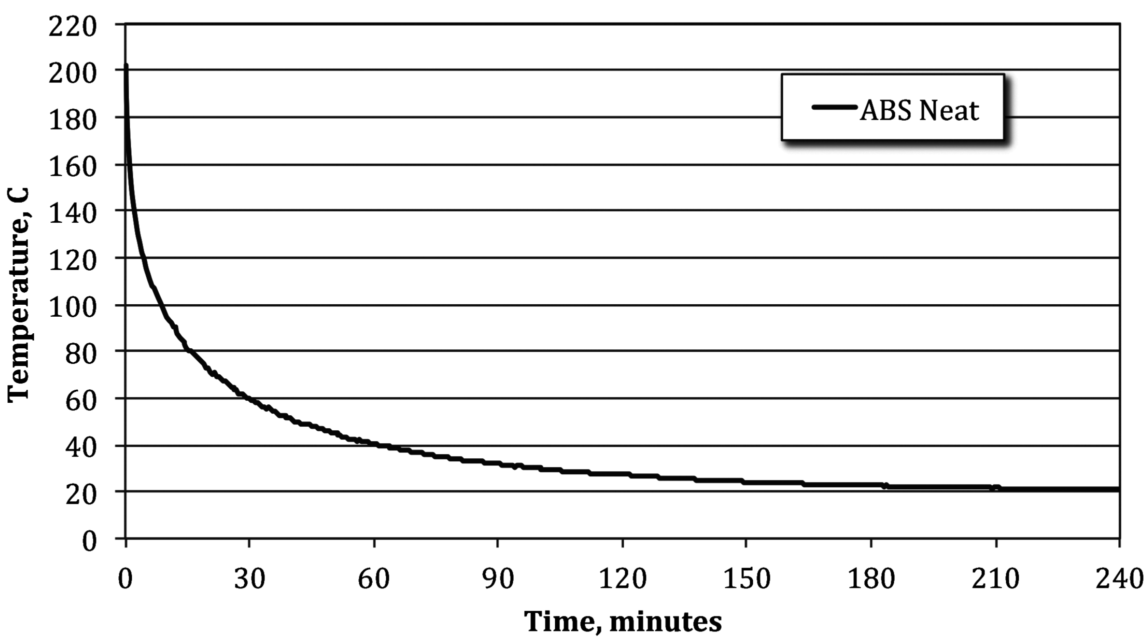

Figure 15. Cool-down time for a typical ABS-Neat part produced by the BAAM printer.

CONCLUSIONS

The temperatures were measured during the printing of simple shapes on the Solidoodle and BAAM 3D-printers. Adding carbon fibers to ABS increases the extruded temperature and keeps the deposited layer hot for a longer time for both the Solidoodle and BAAM printers. BAAM parts require at about 30 minutes to cool-down below 60°C, while Solidoodle layers cool below 60°C in 8-10 seconds. Tensile testing is currently being performed. Porosity is produced in ABS + 13 wt% carbon fibers by the Solidoodle at an extrusion temperature of 225°C. Possibly due to the decomposition of the styrene component.

ACKNOWLEDGEMENTS

Research sponsored by the U.S. Department of Energy, office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

REFERENCES

[1] Crump, S. S., "Apparatus and method for creating three-dimensional objects," US Patent number: 5121329, Filing date: Oct 30, 1989, Issue date: Jun 9, (1992)
[2] Dinwiddie, R. B., Lonnie J. Love, and John C. Rowe, " Real-time Process Monitoring and Temperature Mapping of a 3D Polymer Printing Process," Thermosense: Thermal Infrared Applications XXXV, edited by Gregory R. Stockton, Fred P. Colbert, Proc. of SPIE Vol. 8705, pp 87050K, (2013)
[3] Prager, S., "The Healing Process at Polymer-Polymer Interfaces," J. Chem. Phys., 75 (10), 15 Nov., pp 5194-8 (1981)
[4] Tomari, K., T. Harada, Z. Maekawa, H. Hamada, M. Iwamoto, and A. Ukai, "Fracture Toughness of Weldlines in Thermoplastic Injection Molding," Polymer Engineering and Science, Vol. 33, No. 15, pp 996-1001, Mid August, (1993)
[5] Chen, C-S, Tsyr-Jang Chen, Rean-Der Chien, Shia-Chung Chen, "Investigation on the Weldline Strength of Thin-Wall Injection Molded ABS Parts," International Communications in Heat and Mass Transfer, Vol. 34, pp 448-455, (2007)
[6] FLIR North America, FLIR Systems, Inc., 9 Townsend West, Nashua NH 03063, (866) 477-3687, SC-8000 Datasheet, http://www.flir.com/thermography/americas/us/view/?id=45674&collectionid=530&col=45863
[7] FLIR North America, FLIR Systems, Inc., 9 Townsend West, Nashua NH 03063, (866) 477-3687, Ax5 Datasheet, http://www.flir.com/uploadedFiles/Thermography_USA/Industries/ATS/Products/Ax5_Series_Kits/FLIR-Ax5sc-Kits-Datasheet.pdf