Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

EFFECT OF INFRARED PREHEATING ON THE MECHANICAL PROPERTIES OF LARGE FORMAT 3D PRINTED PARTS

Vidya Kishore[1], Andrzej Nycz[1], John Lindahl[1], Chad Duty[1,2], Charles Carnal[1]

Vlastimil Kunc[1,2,3]

[1]Manufacturing Demonstration Facility, Oak Ridge National Laboratory

[2]University of Tennessee, Knoxville

[3]Purdue University

ABSTRACT

Anisotropy of mechanical properties is characteristic of components printed using processes like extrusion deposition additive manufacturing, wherein the properties along the print direction (x-direction) are superior when compared to the corresponding properties in the build direction (z-direction). This effect, influenced by the bond strength in the z-direction, can be more pronounced for components with longer layer times, as the bottom layers tend cool below the glass transition temperature (T_g) of the material, thereby restricting thermal fusion between the printed layers. The work discussed here builds on the previous work by the authors, demonstrating infrared preheating as a technique to actively control the bond temperature during printing to improve the mechanical properties (z-direction) of parts printed on a large-format extrusion AM system. IR preheating was used on the surface of printed layers just prior to the deposition of the next layer to increase the surface temperature closer to the glass transition temperature. The current study explores the effect of variation in bead surface temperatures (indicative of variations in layer times) prior to and after pre-heating on the mechanical properties in z-direction.

1. INTRODUCTION

1.1 Motivation

Extrusion deposition additive manufacturing, the process where the feed material is melted and deposited layer-by-layer on a build platform, is now being used to print components using a variety of polymers and composite materials on print platforms with build volumes ranging from ~ 10 cm^3 up to ~130 m^3 [1, 2]. Despite several advancements in the development of new materials and printers based on this process, one of the challenges that still exists is the inability to obtain printed components with isotropic mechanical properties [3-5]. There exists a certain level of

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-publicaccess-plan).

anisotropy in the properties of printed parts (mechanical properties being lower in the transverse direction or the print direction when compared to the axial direction) as the layer-wise deposition process makes these properties dependent on temperature history and processing conditions [6-8]. During printing on a large format AM platform (6 m x 2.4 m x 1.8m) [1], without an active temperature control of the entire build volume, increasing part geometry (or layer times) would lead to increased cooling of the deposited bottom layers (or beads) before the next layer gets deposited. If the bonding mechanism between the deposited polymer layers is primarily thermal fusion and polymer inter-diffusion, then the temperature of the bottom layer (or substrate) should at least be above the glass transition temperature (T_g) of the polymer for a sufficient time period to enable good thermal bonding [6, 7]. However, for large-scale system, this condition in not always fulfilled and therefore, there is a need to actively control the bond temperature during printing to obtain better mechanical properties in the print direction.

1.2 Infrared Preheating

As a strategy to address this issue of cooling of bottom beads below T_g before the next bead gets deposited for large-scale AM systems, the authors previously investigated and reported infrared (IR) preheating technique to be an effective method to improve transverse direction mechanical properties (z-direction) [9, 10]. An experimental design feasible for using IR preheating on large-scale printers such as the Big Area Additive Manufacturing system was demonstrated, and this technique was found to be a useful to modify the interlayer bond temperature actively during printing, independent of the material used and part geometry. The previous test set-up comprised of infrared lamps, pyrometers and the extruder all designed to move as a single unit while printing. The lamps were fitted such that they preceded the extruder to heat up the bottom layers just prior to the deposition of the next layer. Two pyrometers, one positioned before the lamp and another after, were used to record the cold bead (substrate) temperature prior to heating (T_{cold}) and the substrate temperature after IR preheating (T_{hot}), just prior to deposition of next layer, respectively. The previously performed mechanical tests results overall indicated the IR preheating technique to be beneficial for print conditions where the cold substrate temperature (T_{cold}) was reduced below T_g (in the range of 75-85 ºC and T_g of the material printed ~ 110 ºC) and when IR preheating increased the substrate temperature closer to or slightly above T_g.

Despite the reported efforts so far by the authors on using the IR preheating technique to actively control the bond temperature, there was a need to refine the experimental set-up and print conditions to have a better control of the substrate temperature before and after preheating to be able to better understand the effect of preheating on the mechanical properties. The previous efforts primarily used variations in print speed, intensity of the lamps (heat input), and extrusion temperature as methods to modify substrate temperature before and after preheating. There was no other active control of substrate temperature before preheating, and there were several cases of excessive heating caused by the lamps which might have led to some possible degradation of the polymer, thereby in turn weakening the z-direction properties. To have a better understanding of the conditions where this technique could be very effective, in the work reported here, print trails were performed by actively controlling the substrate temperature before and after preheating. Printing with a set speed and deposition temperature, artificial cooling was used to create different cold substrate temperatures (by varying the number of cooling cycles) and the intensity of the lamp was constantly controlled to raise the substrate temperature to a certain set value (above T_g) by preheating. This reduced overheating issues as well as provided a way to alter the cold substrate temperature to ranges well below T_g (40 to 80 ºC) unlike the previously reported trials. Also, it should be noted that lower cold substrate temperature is indicative of larger parts or increased layer times, thereby making these studies more useful to understand the effect of preheating in case the of printing very large parts.

2. EXPERIMENTATION

2.1 Experimental Set-up

Figure 1 represents the modified experimental set-up on the large-scale AM system used in this work comprising the IR lamps, pyrometers, extruder, all inter-connected and moving as a single unit, as well as provisions for artificial cooling during printing.

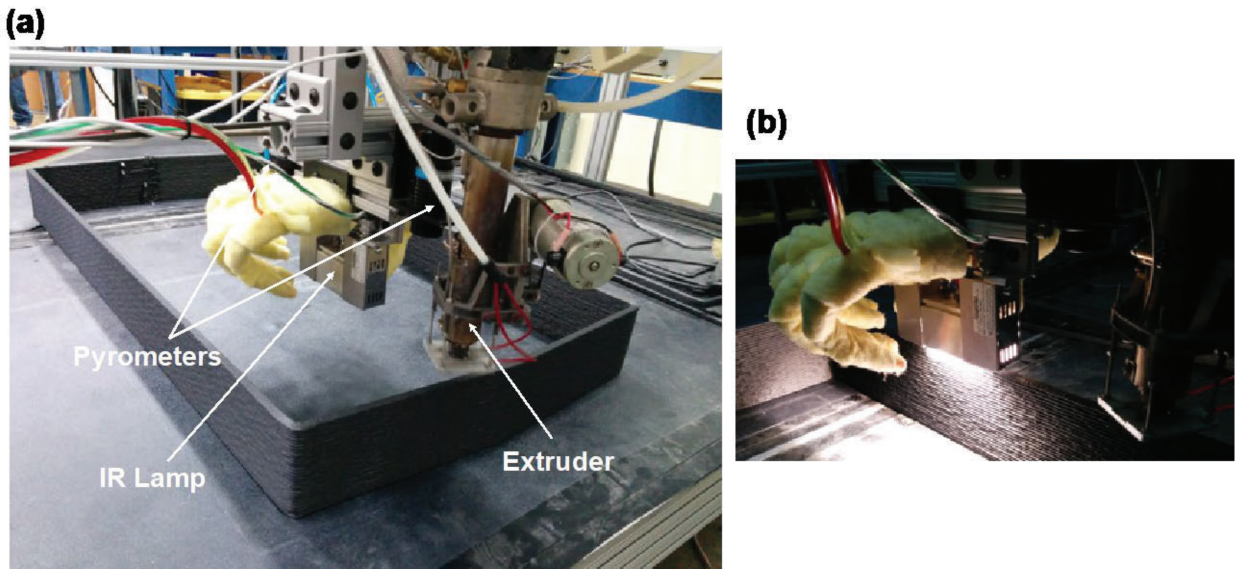

Figure 1. Experimental set-up indicating (a) various key components and (b) IR preheating during printing.

The feed material used for printing was the same as the previous trials, acrylonitrile butadiene styrene (ABS) reinforced with 20 wt.% short carbon fiber. The IR lamp used was a Strip IR model number 5306B-02-1000-01-00 fitted at a standoff distance of 10 mm from the bead surface. Components printed under different conditions were 0.25 m high hexagons with dimensions as shown in Figure 2. Three hexagons were printed, with cold substrate (T_{cold}) target temperatures (i.e. substrate temperature just prior to preheating) being 40 ºC, 60 ºC and 80 ºC controlled by varying the number of active cooling cycles. Active cooling was achieved through forced convection. Eight sets of insulated hoses were used to direct air flow over the printed structure. The target substrate temperature after IR preheating was set to 150 ºC (above T_g) for all the cases. The print speed for all the parts was set to 5.1 cm/s.

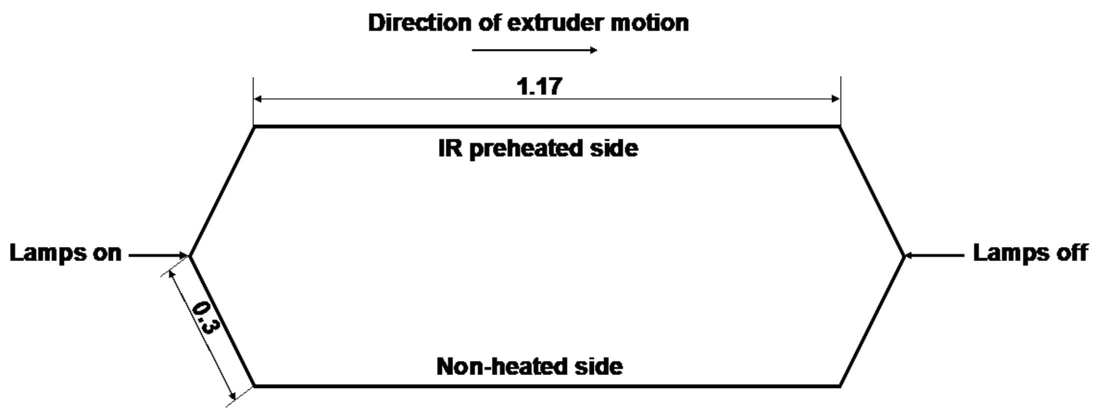

Figure 2. Schematic of the printed hexagonal sample (all dimensions in m), sample height: 0.25 m.

2.2 Tensile Testing

Tensile testing was performed by harvesting samples from both, heated and the non-heated sides (control samples) of the hexagon. Plaques were cut out from the sections harvested and tensile test specimens were milled from these plaques. The target specimen dimensions are shown in Figure 3 and were in accordance with ASTM D638 (Type I). Tensile tests (z-direction of the sample) were performed using an MTS 4.4 kN (1 kip) load cell and MTS 200k micro-stain extensometer at a testing speed of 1.524 mm/min (0.06 in/min) until failure.

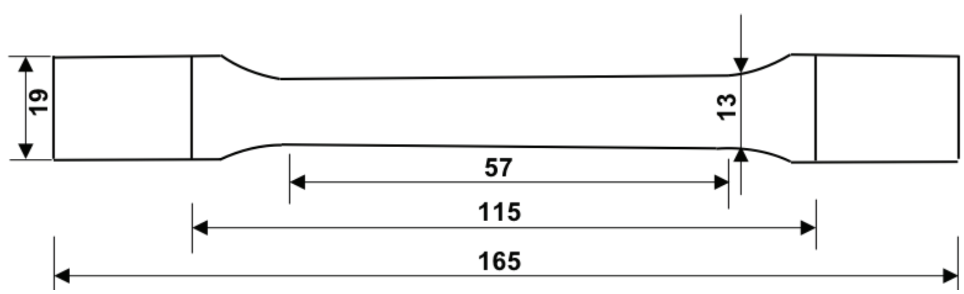

Figure 3. Tensile test specimen dimensions (mm), sample thickness: 6.35 mm.

3. RESULTS AND DISCUSSION

Table 1 summarizes the printing and preheating conditions varied in the previous reported print trials to modify the substrate temperature before and after preheating (T_{cold} and T_{hot}) and Figure 4 summarizes the tensile test results reported for preheating conditions that used a 1kW IR lamp with variations in print speeds and the extrusion temperature [9,10]. In almost all the reported cases, there were no statistically significant improvement in tensile strength due to preheating. In addition, for many conditions, IR preheating lowered the average z-direction tensile strength to some extent which was attributed to the possibility of excessive heating (as the substrate was preheated up to the chosen extrusion temperature) leading to possible degradation of ABS in the process.

The tensile test results for the samples harvested in the present work, with a good control of T_{hot} and T_{cold}, are as shown in Figure 5. The data clearly indicates an increase in the average tensile strength for all the three T_{cold} conditions, with the increase being statistically significant for the case with T_{cold} of 40 ºC. The average z-direction tensile strength for this condition was increased by 81% due to IR preheating. These trends show that IR preheating is a very useful technique for improving bond strength, especially for print scenarios involving long layer times that cool the part down to temperatures significantly below the glass transition temperature of the material.

Table 1. Process parameters varied in previous trials.

Print speed (cm/s)	3.8, 5.1, 7.6
Extrusion temperature (ºC)	215, 235, 250
Lamp power setting	80-90% intensity for 1kW lamp 2 X 500 W lamps (at max intensity)
Standoff distance (cm)	8, 2.5, 1

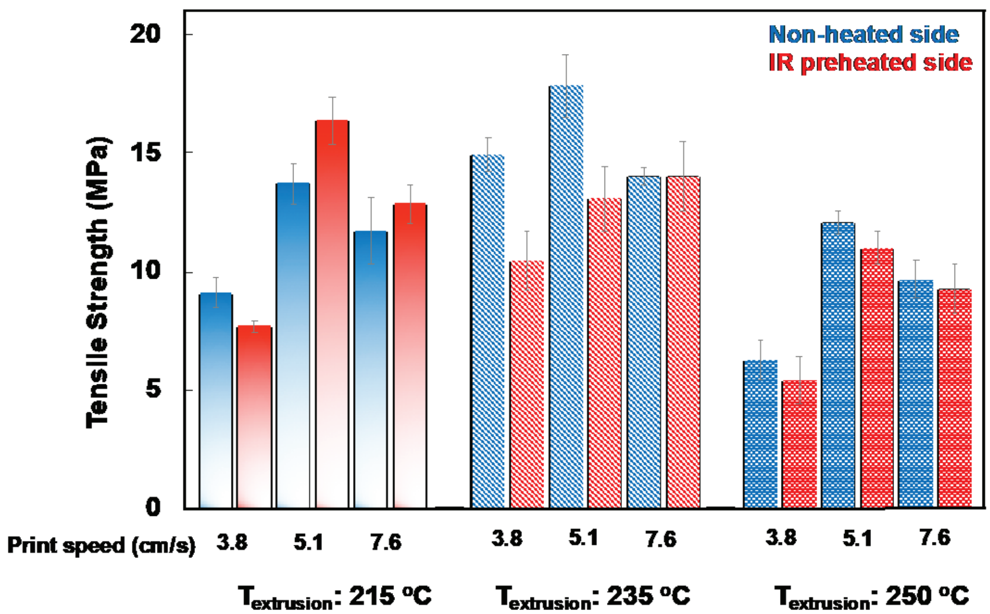

Figure 4. Summary of tensile test results from previous trials [10].

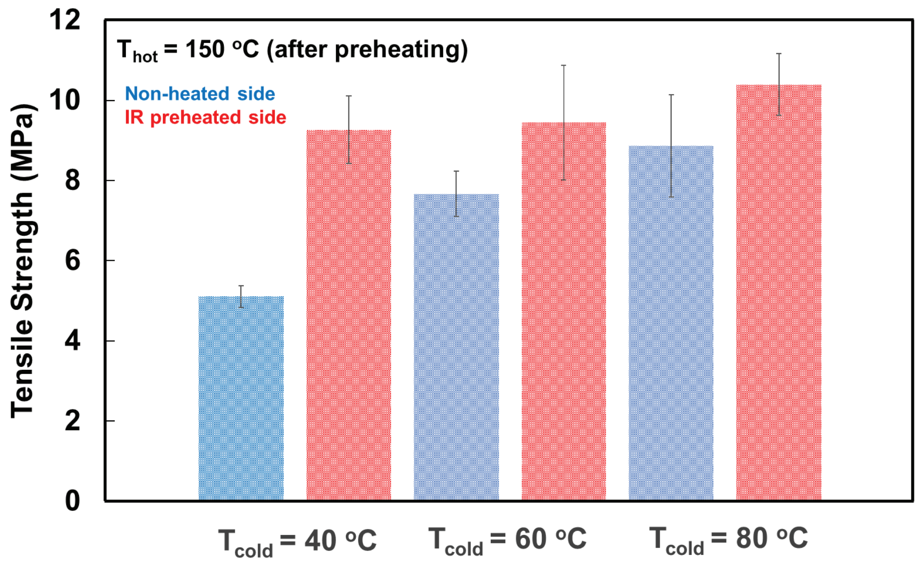

Figure 5. Ultimate tensile strength (z-direction) for the three cooling conditions.

4. CONCLUSIONS

Previous work by the authors demonstrated infrared preheating to be a useful technique to enhance the z-direction mechanical properties of components printed on large-format AM platforms. However, in those print trials, the substrate temperature (bottom beads) before and after preheating was controlled only by varying the print parameters and heat input conditions. The cold bead temperatures obtained by varying these parameters, although below the T_g of the material, were in the range of 75 – 85 °C and excessive preheating in some cases led to the possibility of polymer degradation. In this work, with modifications in the experimental set-up and processing conditions, the authors were able to simulate longer layer times (or larger part geometry) by actively cooling the substrate to chosen temperatures significantly below T_g and then preheating up to a certain temperature well above T_g (also below the extrusion temperature). These conditions enabled better control over the process as well as led to the possibility of printing parts where IR preheating enhanced the tensile strength by even ~ 80 %. Increase in the average tensile strength was observed to be greater as the substrate temperature lowered. This therefore indicates that the IR preheating technique to be advantageous for large-scale prints involving longer layer times. Future work involves experimental trials with multiple preheating temperatures (T_{hot}) as well as validation of the trends in properties by performing mechanical testing using other methods.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge Dr. Donald Erdman at Oak Ridge National Laboratory for the use of lab facilities for mechanical testing and Techmer ES for providing the materials used in this work. Research was 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.

6. REFERENCES

1. Duty, C.E., Ajinjeru, C., Kishore, V., Compton, B., Hmeidat, N., Chen, X., Liu, P., Hassen, A.A., Lindahl, J. & Kunc, V. "What makes a material printable? A viscoelastic model for extrusion-based 3D printing of polymers." *Journal of Manufacturing Processes* 35 (2018): 526-537. https://doi.org/10.1016/j.jmapro.2018.08.008.
2. Brenken, B., Barocio, E., Favaloro, A., Kunc, V. & Pipes, R.B. "Fused filament fabrication of fiber-reinforced polymers: A review." *Additive Manufacturing* 21 (2018): 1- 16. https://doi.org/10.1016/j.addma.2018.01.002.
3. Duty, C.E., Kunc, V., Compton, B., Post, B., Erdman, D., Smith, R., Lind, R., Lloyd, P. & Love, L. "Structure and mechanical behavior of Big Area Additive Manufacturing (BAAM) materials." *Rapid Prototyping Journal* 23 (2017): 181-189. https://doi.org/10.1108/RPJ-12-2015-0183.
4. Shaffer, S., Yang, K., Vargas, J., Di Prima, M.A. & Voit, W. "On reducing anisotropy in 3D printed polymers via ionizing radiation." *Polymer* 55 (2014): 5969-5979. https://doi.org/10.1016/j.polymer.2014.07.054.
5. Perez, A.R.T., Roberson, D.A. & Wicker, R.B. "Fracture surface analysis of 3D-printed tensile specimens of novel ABS-based materials." *Journal of Failure Analysis and Prevention* 14 (2014): 343-353. http://dx.doi.org/10.1007/s11668-014-9844-0.
6. Turner, B. N., Strong, R. & Gold, S.A. "A review of melt extrusion additive manufacturing processes: I. Process design and modeling." *Rapid Prototyping Journal* 20 (2014): 192-204. https://doi.org/10.1108/RPJ-01-2013-0012.
7. Sun, Q., Rizvi, G.M., Bellehumeur, C.T. & Gu, P. "Effect of processing conditions on the bonding quality of FDM polymer filaments." *Rapid Prototyping Journal* 14 (2008): 72-80. https://doi.org/10.1108/13552540810862028.
8. Ahn, S.-H., Montero, M., Odell, D., Roundy, S. & Wright, P.K. "Anisotropic material properties of fused deposition modeling ABS." *Rapid Prototyping Journal* 8(2002):248-257. https://doi.org/10.1108/13552540210441166.
9. Kishore, V., Ajinjeru, C., Nycz, A., Post, B., Lindahl, J., Kunc, V. & Duty, C. "Infrared preheating to improve interlayer strength of big area additive manufacturing (BAAM) components." *Additive Manufacturing* 14 (2017): 7-12. https://doi.org/10.1016/j.addma.2016.11.008.
10. Kishore, V., Ajinjeru, C., Nycz, A., Post, B., Lindahl, J., Kunc, V. & Duty, C. "Infrared Preheating to Enhance Interlayer Strength of Components Printed on the Big Area Additive Manufacturing (BAAM) System." *SAMPE Technical Conference Proceedings.* Long Beach, CA, May 2016. Society for the Advancement of Materials and Process Engineering.