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UNCERTAINTY IN THERMAL BEHAVIOR ANALYSIS OF POLYMER-MELT EXTRUSION ADDITIVE MANUFACTURING

Azhdari, S[1]*, Sharifan, M[2], Genest, M[3], G. Cole, R[3], Avalos, A[4], Milani, AS[2], and Kravchenko, S[1]
[1] Department of Materials Engineering, The University of British Columbia, Vancouver, BC, Canada
[2] School of Engineering, University of British Columbia Okanagan, Canada
[3] National Research Council Canada (Canada)
[4] AON3D, Montreal, Quebec, Canada
* Corresponding author (soroush.azhdari@ubc.ca)

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ABSTRACT

The cooling history of polymers in melt extrusion additive manufacturing (3D printing) depends on the printing process parameters (material deposition temperature, speed of nozzle, build plate temperature, and chamber temperature) as well as the temperature-dependent thermal properties of the printed material. Using infrared thermography, we measured the temperature evolution at various points along the printed path, with the printing parameters expected to be nominally the same. Time-temperature profiles exhibit notable variation within the sample due to the presence of inherent uncertainties. In this paper, we employ an experimental framework to explore how the uncertainty in process parameters and material properties contributes to uncertainty in the local thermal history of Acrylonitrile Butadiene Styrene printed by the AON-M2 3D printer.

1 INTRODUCTION

During manufacturing, the variability and uncertainty in material response arise from the unavoidable inherent variability in process parameters and material properties. The printing quality of polymers in fused filament fabrication (FFF) is influenced by the printing speed, filament size, nozzle and chamber temperatures, build plate temperature, as well as the thermal properties of a polymer – all of which collectively control the thermal history of the material [1], as schematically summarized in Figure 1(a). The variables influencing the local cooling history of the polymer must be understood, as they directly affect its microstructural development and, consequently, the mechanical properties and dimensional stability of the 3D printed product. Heat transfer analysis of the 3D printing process is a useful tool to study cooling history, but it typically assumes a steady-state temperature for the material near the build plate, a uniform deposition temperature, and uniform convective boundary conditions at the model's faces, e.g. [2, 3]. These assumptions do not fully reflect the dynamic and complex nature of the physical printing process; the true thermal response of the material may vary between these bounds due to the non-uniform distribution of heat transfer boundary conditions around complex parts [4]. Previously, infrared (IR) thermography have shown that the temperature of the extruded material frequently diverges from the extruder's set-point temperature [5, 6]. The build plate undergoes a warm-up process, leading to a surface temperature lagging behind the heater underneath, resulting in non-uniformity, as has been reported by some of the co-authors in [7]. In addition, non-uniform cooling can occur due to variations in the air flow and temperature around the part, particularly at corners where the nozzle movement is slower [8]. Additionally, polymer thermal properties constitute another source of variability in heat transfer dynamics during FFF 3D printing process. Even the most advanced 3D printers are not exempt from these variabilities. Consequently, our task is to quantify these effects, which will enable the development of probabilistic 3D printing process models.

In this study, the effect of variabilities in printing process parameters and material properties on the local thermal history variability of Acrylonitrile Butadiene Styrene (ABS) is examined. A state-of-the-art, large-format, high-temperature industrial 3D printer, instrumented with additional thermocouples and an IR system, was used to collect the temperature measurements; thermal conductivity and specific heat were measured using standard techniques.

2 VARIABILITY IN LOCAL COOLING HISTORY OF 3D PRINTED MATERIAL

An ABS wall prototype, measuring 100 x 1.4 x 40 millimeters (X-Y-Z) and consisting of two layers in thickness (Y direction), was printed using an AON-M2 printer with a nozzle size of 0.6 mm. Figure 1(b) shows the printed wall consisting of 133 layers, each measuring 0.3 mm in height, along with the printing direction, and the inspection line and points. The filament used was AON3D ABS Prime, and the printing speed was set at 15 mm/s. The printing process was conducted with a chamber temperature of 90 °C and a build plate temperature of 100 °C. The thermal profile of the part during printing was captured by IR measurements using a Jenoptik IR-TCM HD infrared camera equipped with a 30mm (32x24 degrees) lens. The radiometric data was captured by the thermal camera at a rate of 30 Hz and was processed using custom made MATLAB® code, enabling the analysis of temperature changes over time; an example of IR image is shown in Figure 1(c). The printer door was modified and fitted with an infrared window to enable IR measurements without disrupting the printing process. A set of thermocouples were attached inside the printer. IR images and readings from both thermocouples built into the AON-M2 and those attached by the authors were used to measure variation in printing process parameters.

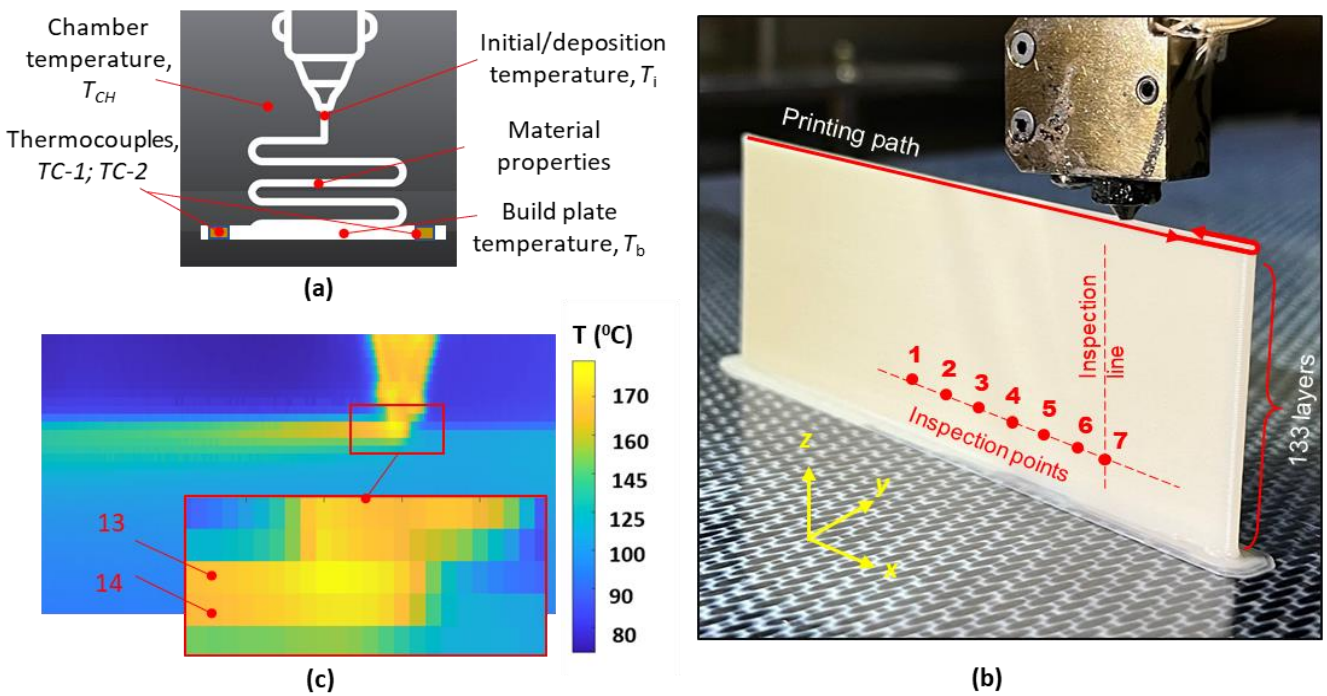

Figure 1. (a) Sources of variabilities in printing process, (b) inspection article, (c) example of IR image.

During the IR measurement, the IR camera remains stationary, focusing on fixed points, while the printed part moves down by adjusting the build plate level (Z axis). Low observation angles, less than 30 degrees with respect to the build plate, were considered non-ideal for the IR camera as despite high emissivity, significant reflections were observed on the surface of the build plate. These reflections adversely affected the accuracy of temperature measurements [7]. We conducted more than seven measurements using two different angles (37° and 0°) to analyze the thermal profile of the printed wall. The 0° measurements were performed to monitor the Z-plan temperature profile during the print. High-resolution IR images are recommended to better capture temperature variations. In IR images, the resolution is determined by the number of pixels along the X-axis (width) and Y-axis (height) and a color scale is used to represent different temperatures. In the MATLAB parula colormap used in Figure 1(c) yellow indicate areas of higher temperatures, while blue pixels signify cooler areas. In our measurements multiple pixels are suspected to be representative of the newly deposited layer. Due to differences in pixel size and the height of printed layers, the pixels may represent temperature measurements including that of previously printed layers, the background wall, or show the nozzle passing through the pixel. For example, pixels in line 13 of Figure 1(c) cool to approximately 80 °C, which is lower than both the chamber (T_{CH}=90 °C) and build plate temperatures (T_b=100 °C) yet matches the temperature of the printer's chamber walls (measured 80 °C by thermocouple). Despite this, pixels in line 13 exhibit a higher extrusion temperature compared to pixels in line 14. This discrepancy necessitates the consideration of average temperatures with the assignment of varying weight factors to accurately assess the thermal profile.

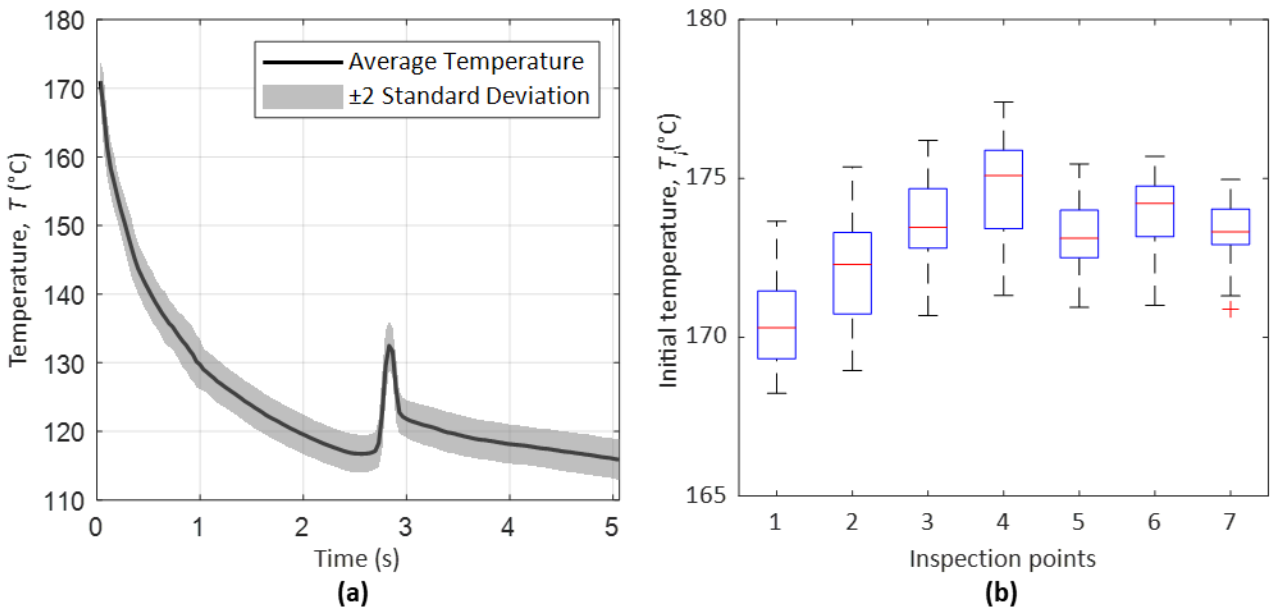

Figure 2. (a) Variations in the cooling history at point 7 (as indicated in Figure 1(b)) and across 50 printed layers at that point (refer to the inspection line in Figure 1(b)), (b) variations in extrusion temperature (T_i) measured at 7 different points.

3 VARIABILITY OF PRINTING PROCESS PARAMETERS

The variability of build plate temperature (T_b), extrusion temperature (T_i), and chamber temperature (T_{CH}) in the AON-M2 were explored. The T_i was set to 210 °C, and IR measurements indicated average extrusion temperatures ranging from 168 °C to 177 °C along the printing direction. T_i variations were reported at seven points along the printing direction, and over 50 layers were printed at those points in Figure 2(b). Additionally, Figure 3(a) shows the variability in T_i at the specific points, identified as points number 2 and 7 in Figure 1(b). The printed wall consisted of 133 layers, and we focused on analyzing the thermal profiles of layers numbered from 40 to 120 to ensure that we were observing temperatures unaffected by the build plate.

To investigate the uncertainties in T_b, two tests were performed. In the first test, two thermocouples were installed on the build plate to create a benchmark comparison against measurements made by the AON-M2's built-in thermocouples which are located beneath the build plate. As the PolyEtherImide (PEI) build plate used has a thickness of 7.5 mm, discrepancies occur between temperature reported by the two sets of thermocouples due to the convection and radiation heat transfer modes between the build plate and the chamber, as well as delays caused by conduction heat transfer from the heater mounted beneath the plate. This discrepancy was demonstrated in steady state by holding the T_{CH} constant at 80 °C while commanding different build plate temperatures. A build plate temperature of 80 °C, 140 °C, and 180 °C was reported by the built-in thermocouples. However, the author-installed thermocouples reported temperatures of 80 °C, 117 °C, and 133 °C. These differences are amplified with increased temperature differences between the build plate and chamber. An additional series of tests was conducted to assess temperature variability at various locations on the build plate during the printing process, with T_{CH} set to 90 °C and T_b to 100 °C. This was accomplished using two thermocouples attached to either ends of a printed ABS wall. Figure 3(b) illustrates how the installed thermocouples, positioned in different locations, exhibited a temperature variance of 2 °C. TC-1 and TC-2 are thermocouples attached to the left and right ends of the printed wall, respectively.

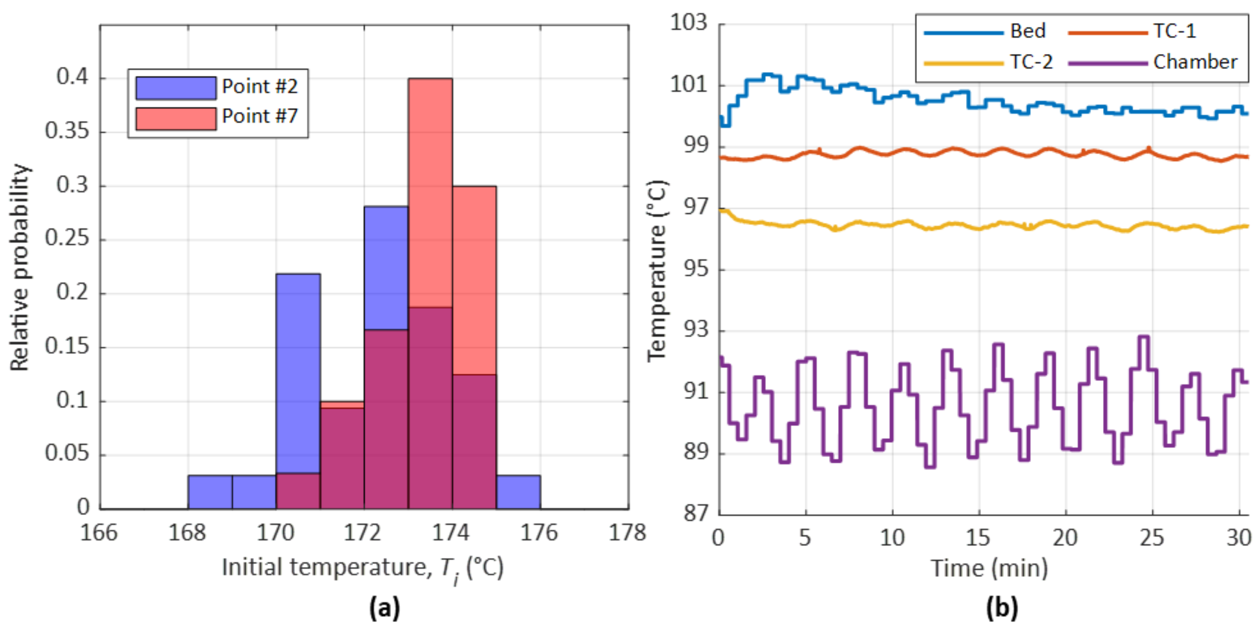

Figure 3. Variation of (a) initial temperature (T_i) at points 2 and 7, (b) printing process temperatures.

The T_{CH} fluctuates between 88 to 92 °C due to the heater's efforts to maintain a constant temperature at 90 °C according to the printer's readouts. This temperature is reported by a built-in thermocouple located at the back of the printing chamber. Due to the thermcouples distance from the build plate, the effects of 1) heat convection due to air between the printing chamber and heated build plate and 2) the nozzle printing speed, must also be consided. In future experiments, additional thermocouples will be attached near the nozzle/build plate surface to examine differences in reported T_{CH} based on thermocouple location.

4 VARIABILITY OF MATERIAL THERMAL PROPERTIES

In heat transfer phenomena of amorphous polymers, two temperature dependent material properties play important roles: thermal conductivity, and specific heat. These properties influence how heat is transferred within the polymer material during printing processes.

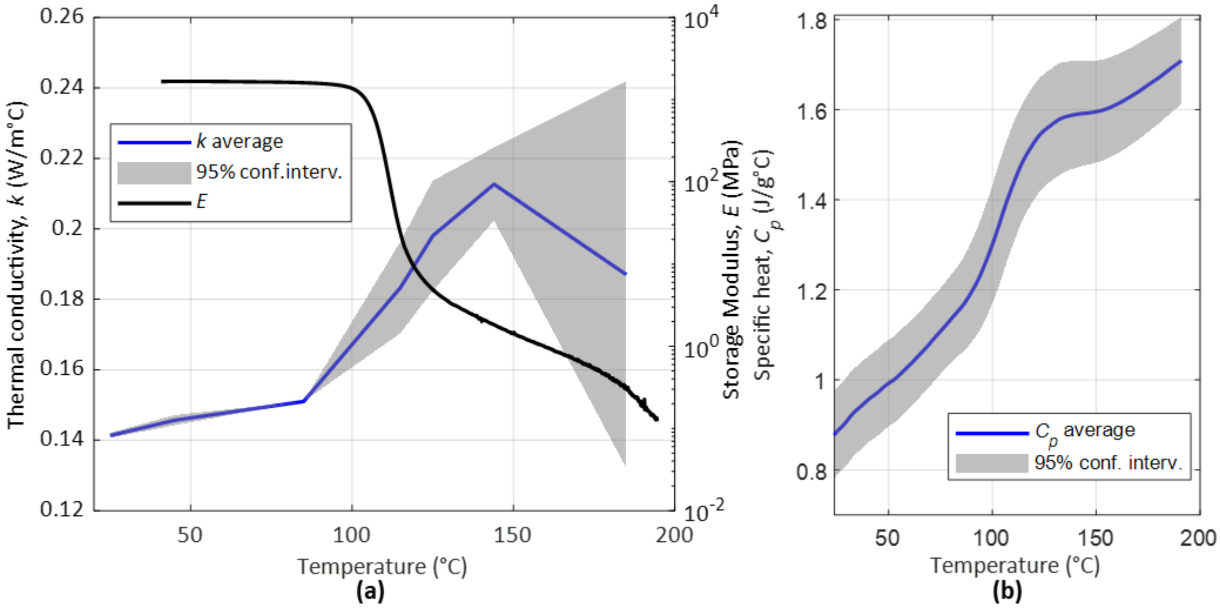

Figure 4. Variability of measured (a) thermal conductivity vs. temperature and (b) specific heat capacity vs. temperature of ABS prime material.

We conducted the thermal conductivity measurements of the ABS material using the FOX heat flow meter by Laser-Comp, which utilized a steady-state technique in accordance with ASTM C518-04 [9]. Additionally, we used the NETZSCH LFA 467 HyperFlash instrument, employing a transient-state technique, following ASTM E1461-13 guidelines [10]. Figure 4(a) shows Thermal conductivity versus temperature with 95% confidence interval. As temperature increases, distinct transitions are observed in amorphous polymers from a glassy state to a rubbery state and then to a viscous flow state, as evidenced by the DMA test results depicted in Figure 4(a). These transitions in behavior lead to a non-linear relationship between thermal conductivity and temperature, potentially causing a shift from an increasing trend to a decreasing trend at higher temperatures. We can see that measurements from two different devices show greater discrepancies above the glass transition temperature (Tg), which is around 100 °C. This necessitates additional measurement temperature points above the Tg to accurately capture the variations in thermal conductivity data in rubbery and viscous flow states.

The specific heat capacity of ABS versus temperature was measured using Differential Scanning Calorimetry (DSC). For these measurements three different instruments: Perkin Elmer DSC 4000, NETZSCH DSC 214, and TA Instruments DSC were used. We followed the ASTM E1269-11 guidelines for these tests [11]. The heat ramp was set at 20 °C/min. ABS samples were obtained from two sources for testing: directly from the ABS filament and from parts that were printed. Some samples underwent repeated testing, where the same sample was used multiple times to collect additional data. This analysis was crucial in identifying any potential discrepancies in specific heat capacity data. Figure 4(b) shows specific heat capacity versus temperature with a 95% confidence interval.

5 CONCLUSIONS

Our study demonstrated variability in the local cooling history of 3D printed ABS material, variability in printing process parameters (such as changes in build plate temperature, chamber temperature, and extrusion temperature) and filament material thermal properties (such as specific heat and thermal conductivity). High-resolution IR images were employed to examine the thermal history of each newly printed layer. The higher pixel density in these images allows for more detailed and accurate tracking of temperature changes at specific points in the 3D printed part. This accuracy is crucial for avoiding errors in identifying the correct locations of printed layers. The discrepancy between the set point temperature for the build plate and the temperature indicated by the thermocouples installed by the author above the 3D printer build plate necessitates including the build plate during numerical heat transfer analysis. These differences became more pronounced as the temperature difference between the build plate and the chamber increased. Different methods and devices were used to measure the material properties, aiming to improve data reliability. The measured data for specific heat capacity and thermal conductivity of ABS material exhibited significant variations.

During the printing process, with the chamber temperature set at 90 °C and the build plate at 100 °C, the extrusion temperature estimated by IR measurements fluctuated between 168 °C and 177 °C. The chamber temperature oscillated by 4 °C, ranging from 88 °C to 92 °C. The thermocouples attached by the author above the 3D printer's build plate showed a temperature difference of 2-4 °C from the build plate's set point temperature of 100 °C, depending on the location. The combination of some or all of these variabilities causes uncertainty in the local cooling history of the printed part. This study emphasizes the importance of incorporating these variabilities into heat transfer modeling of 3D printing to enhance model reliability

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