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Thermal Simulation and Experiment Validation of Cooldown Phase of Selective Laser Sintering (SLS)

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Abstract

Thermal stresses, induced by inhomogeneous temperature distribution inside a part during the cooldown phase of selective laser sintering, can be a major cause of part rejection for geometric deviation from its as-built specification. A validated cooldown simulation can provide predictions of temperature distribution in both parts and part cake which may enable alternative cooling profiles to reduce the likelihood of such rejections. This work describes experiments and comparative simulations developed to validate a sample tool for developing cool down control profiles in an SLS machine. In the experiments, thermocouples were inserted inside the part cake to monitor temperature at preselected locations during cooldown. The results from initial experiments and simulations were compared at these locations, to obtain improved estimates of uncertain powder conductivity and convective heat transfer parameters. The resulting simulation was then compared with independent experiments to evaluate the accuracy of such simulations. Though diffusion time in the part cake prevents active closed loop control in cooldown based on thermal measurements at the part, the simulation can be used to determine an open loop control profile for the build box heaters based on temperature gradient and resultant stresses inside the part.

Introduction

In the selective laser sintering process, polymer powder material is contained in a build box. The powder surface of each layer is first heated to just below its melting point. After heating, the surface layer of powder is scanned by a laser above with the desired geometry path to be melted. Then a new layer of powder is placed on the top of the previous powder layer, and the laser scans this new powder layer. This layer by layer 2-D scanning process of powder results in a 3-D solid part. After the building process completes, the built part is surrounded by a powder part cake and is cooled down to room temperature before it is removed from the cake. Due to uncontrolled heat transfer during the cool down process, the temperature distribution inside the part/part cake is usually not uniform, and thermal stresses can build up. The thermal stresses lead to warpage, shrinkage, or other types of geometric deviation.

Norrell, Wood, and Crawford designed in-bed structures built along with the part to affect the heat transfer, such as tortillas, and thermal walls. The geometries and porosities of the parts with/without in-bed structures are examined after the experiments. The results show that adding in-bed structures help to avoid geometry deviations and reduce porosities in the part [1]. Their method is a practical way to quickly solve the problem, but building a large in-bed structure means a longer build time and a higher manufacturing cost.

Another way to affect the heat transfer in the part cake is having control inputs on the boundary of the part cake. The prerequisite for determining desired control inputs is a good understanding of the temperature distribution inside of the part cake. A temperature measurement system is set up to determine the temperature distribution history in the part cake in their SLS machine. Thermocouples were inserted into the part cake, and recorded the temperature history at selected locations. A 3-D temperature history map was plotted upon dense data points got from different experiments [2]. Calibration of the temperature history map of a certain geometry takes many experiments to achieve.

This work takes a step further by developing a verified simulation model that can be used to predict the part cake temperature history for future builds. A temperature measurement system is added to LAMPS (Laser Additive Manufacturing Pilot System), an SLS machine at the University of Texas at Austin's research campus. Because of the prediction capability of simulations compared to that of experiments, control inputs can be determined in the simulations ahead the part build, and be applied into actual cool down process to resolve thermal stresses problems.

Machine Overview and Modification

Machine Overview

The LAMPS machine was designed and built at the University of Texas at Austin for experimental testing purposes. Detailed features and specifications of the machine are discussed and documented in Wroe's work [3]. A section view of the LAMPS machine is shown in Figure 1, and major components are marked on this figure. The design considerations for the LAMPS machine are based on the purpose of manufacturing thermoplastic polymer materials. The general SLS manufacturing process is discussed in the previous section. The visual camera and the IR camera monitor the physical and thermal situations of the build surface during the building process. Compared to commercial machines, the build volume of the LAMPS machine is smaller, and thus shorter time is required for cooldown process. In the experiments and simulations, the cooldown time is set to 12 hours. As verified in experiments and simulations discussed in later sections in this paper, the part cake temperature is close to room temperature after 12 hours of cooldown.

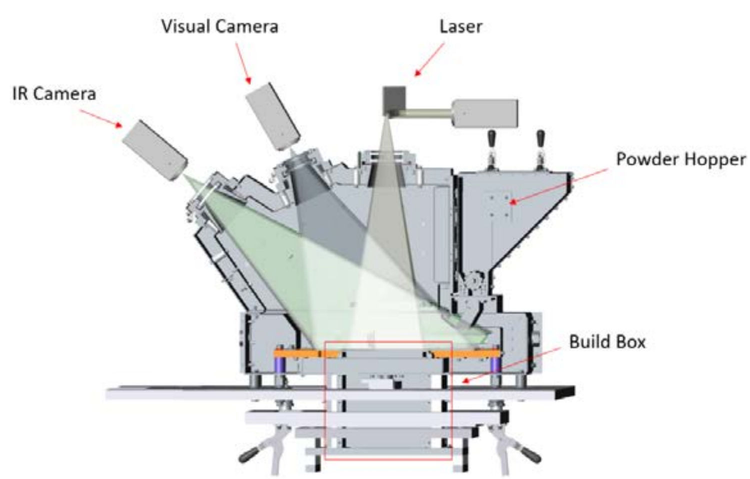


Figure 1: A Section View of the LAMPS Machine

Figure 2 shows a top view of the build surface. Geographically, the powder is dropped from the powder hopper on the west side of the machine, and a roller feeds the powder to the build surface in the direction from west to east. This geographic direction reference is taken for all the directional indications in this paper. For instance, heaters on the north side wall of the build box are names as north wall heaters.

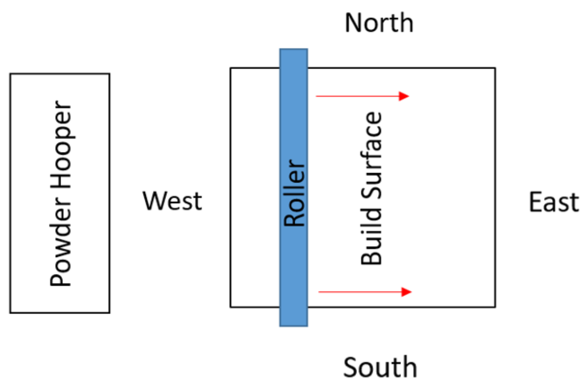


Figure 2: Geographic Direction Reference for the Build Box

Machine Modification

The original build box on the LAMPS machine did not have accesses for probe thermocouple insertions. Thus, a new build box was designed, fabricated, and installed for this project and future work. A section view of the new build box and piston is provided in Figure 3. The key characteristics of the build box are:

1. 20.3 cm cube build volume
2. Set up for Nylon 12 processing for this work
3. Accessible build box from under and side of machine
4. Open source software controls enabling direct measurement to heater closed loop capability for 3 depths of the build box and the piston

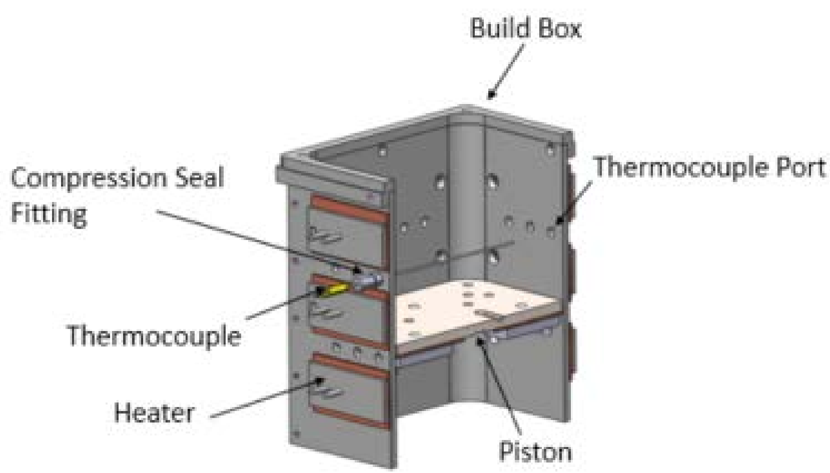


Figure 3: Build Box and Piston Allowing Thermocouple Access to the Part Cake

Measurement Process

Once the build was completed (all layers spread and selectively melted with the laser), the build chamber was maintained at an elevated temperature. Because the builds in the experiments are shallow, the piston was lowered 7.5 cm to enable insertion of the thermocouples at a level 1.3 cm from the top surface of the build. This process usually took 20 minutes. Thermocouples were then inserted and reached preselected positions. The associated thermocouple positions depend on the different build and are shown later in this report. Once the thermocouples were in positions and temperature readings of the thermocouples were steady, which typically took 10 minutes, cooldown control profiles were read in the software, and cooldown process started. Temperature readings were recorded every certain amount of time at these locations. Figure 3 shows the relative positions of the part and the part cake to the thermocouples during the cooldown process. The control volume of the heat transfer problem is marked in yellow.

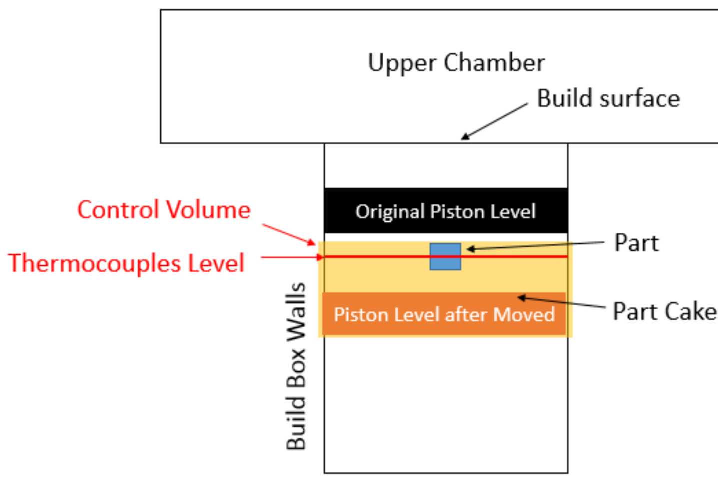


Figure 4: Relative Positions of the Part and Part Cake in the Cooldown Process

<u>Simulation Assumptions and Setup</u>

Material Properties

The data collected in the experiments were compared with results of a simulation. Several assumptions were made in the simulation including material and thermal properties, initial conditions, and boundary conditions. The material used in the experiment is Nylon 12, Griehl' work [4] determined the density of solid nylon 12 is about 1000 kg/m^3, and Kruth's work [5] suggested the density of powder nylon 12 is about half of solid nylon.

During the cool down process, the top surface of the part cake in the build box was open to the environment in the upper chamber, and convection and radiation happened at the build surface to the surroundings. Heat conduction happened among the part, the part cake, the build box walls and the piston, and outside environment. Values of thermal conductivity, specific heat capacity, convective coefficient, and emissivity were assumed ahead. Yuan’s work [6] determined minimum and maximum effective thermal conductivity of nylon 12 is about 0.04 W/m-K and 0.15 W/m-K. The research also stated that the thermal conductivity of the powder increases with an increase in temperature from 40 Celsius to 170 Celsius. The initial value of thermal conductivity of powder was set to a high value as 0.15 W/m-K due to the high temperature in the part cake. The material for the build box and the piston is stainless steel 304. Because the density, the specific heat capacity, and the thermal conductivity do not vary much among different type of steels, the default values were taken from ANSYS material database.

Table 1 shows the material and thermal properties discussed above for powder nylon 12, solid nylon 12, and steel.

	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)
Nylon powder	500	1640	0.15
Nylon solid	1000	1640	0.7
Steel	8030	502	16.27

Table 1 – Material Properties Used in the Simulation

Governing Equations and Boundary Conditions

Boundary conditions in the simulation needed to be determined as functions of time. As described in the equation of conduction $q''_{cond} = k\nabla T$, where q''_{cond} is the rate of heat transfer per unit area due to conduction,∇T is the temperature gradient, and k is the thermal conductivity. The boundary temperature conditions for the conduction are the surface temperatures of the build box walls and the piston. In the experiment, the surface temperature on the build box walls and the piston were only measured at some locations via surface mounted thermocouples. Because steel is a highly thermally conductive material, the average temperatures of these thermocouples' readings were used as bulk boundary temperature of the build box walls and the piston.

The next boundary condition needs to be determined is the convention boundary conditions at the top surface of the part cake. The equation of convection is stated as $q''_{conv} = h(T_S - T_\infty)$, where q''_{conv} is the rate of heat transfer due to convection per unit area, $h$is the convection heat transfer coefficient, T_S is the surface temperature, and T_∞ is the surrounding temperature. A thermocouple suspended in the upper chamber monitored the surrounding temperature. Though the thermocouple is 5.63 cm above the build, it is the closest thermocouple in the current LAMPS machine from the build surface. Also, during the cooldown process, the gas mixed quickly due to small space above the build surface. The temperature in the space above the build surface tends to be uniform in a relative short amount of time. Thus, the reading of this thermocouple is a reasonable assumption as the surrounding temperature of the convection. Dong' research work in modeling the convection at the surface in a SLS machine determined the convective coefficient as 25 W/m^2-K [9]. This value is taken in the simulation model.

Another boundary condition at the surface of the part cake is the radiation boundary conditions. The equation of radiation is stated as $q''_{rad} = \epsilon\sigma(T_S^4 - T_\infty^4)$, where q''_{rad} is the rate of heat of transfer due to radiation per unit area, ϵ is surface emissivity, and σ is Stefan-Boltzmann constant. During the cool down process, heat energy in the part cake radiates out to the surround through the surface. Same surrounding temperature is used as in the convection. Sih and Barlow modelled and estimated the emissivity of the powder bed is very close to 1 [8].

Initial Temperature

The initial temperature of the part cake was estimated after probe thermocouple inserted into the part cake at the beginning of the cooldown process. Because there was already a temperature gradient inside of the part cake, it was not possible to get the exact temperature distribution at the beginning of the cool down process. A preliminary assumption was using the reading from a thermocouple in the part cake to represent the initial temperature in the part cake. As the simulation running, the temperature in the part cake was driven by boundary conditions, and a temperature gradient developed inside the part cake. A more sophisticated way by assigning different regions in the part cake with different initial temperatures is discussed later in the paper. The initial temperature of the part cake was assumed as same as the temperature reading of a thermocouple that was very close to the part at the beginning of the cool down process.

Rectangular Part Build and Lesson Learned

The geometry of the first part build was chosen as a rectangular bar with a dimension of 7.5 cm by 2.5 cm by 2.5 cm because the part had a simple geometry and certain amount of thermal mass that can affect heat transfer in the part cake. The part cake had a dimension of 20.3 cm by 20.3 cm by 5 cm. In the experiment, the part is placed at the top center of the part cake.

Since the build box walls and piston were made with the same material, and the piston did not move relative to the part cake during the cooldown process, they can be modeled as an open-top box, rather than separate walls and a piston. Different boundary temperatures were assigned to the walls and piston. To improve simulation efficiency, the model in the simulation was 1/4 of the original model due to the symmetry in the build box/part/part cake geometry being examined. Figure 5 demonstrates ¼ symmetry of the CAD model. The inner surfaces of the part and part cake were insulated due to the symmetry. Thermocouple positions during cooldown for this build are shown in Table 2.

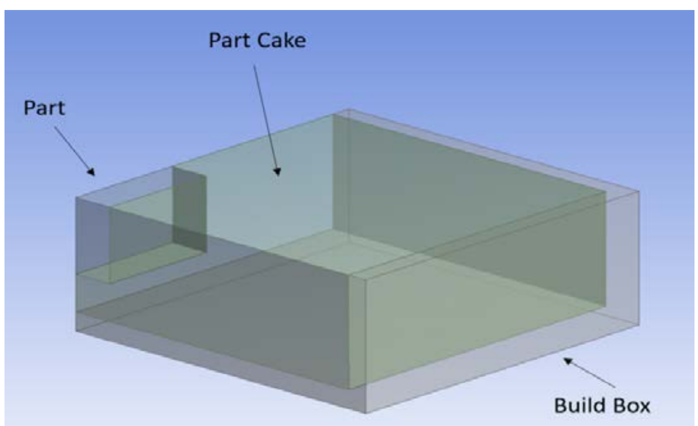
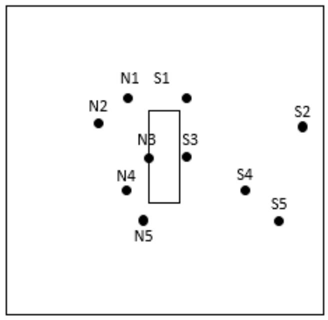


Figure 4 –CAD Model for rectangular bar build with 2 symmetry planes



Port #	Distance From Wall (cm)	Distance From Part (cm)	Initial Temperature (C)
S1	8.25	0.64	134.6
S2	1.27	7.62	91.7
S3	8.25	0.64	136.2
S4	3.81	5.08	117.8
S5	2.54	6.35	106.1
N1	7.62	1.27	130.9
N2	5.08	3.81	122.7
N3	8.89	0	134.7
N4	7.62	1.27	128.3
N5	8.23	0.64	127

Table 2 Thermocouples insertion positions (Top View)

Once the thermocouples were in position, the heaters in the build chamber, on the walls of the build box, and on the piston, were commanded to a specified temperature vs time problem. A plot of this temperature vs time for the cooldown used in this early build is shown in Figure 6. The heaters in the build chamber were remained on in for the first five hours and then turned off. In testing the fastest cooldown case with control on the wall and piston heaters, the wall and piston heaters were turned off, and the temperature plotted was the resulting temperature measured. Trendline functions are used to fit the curves in Figure 5. Then fitted functions are plugged into the simulation as UDF (user defined functions) to define the boundary conditions in the simulation.

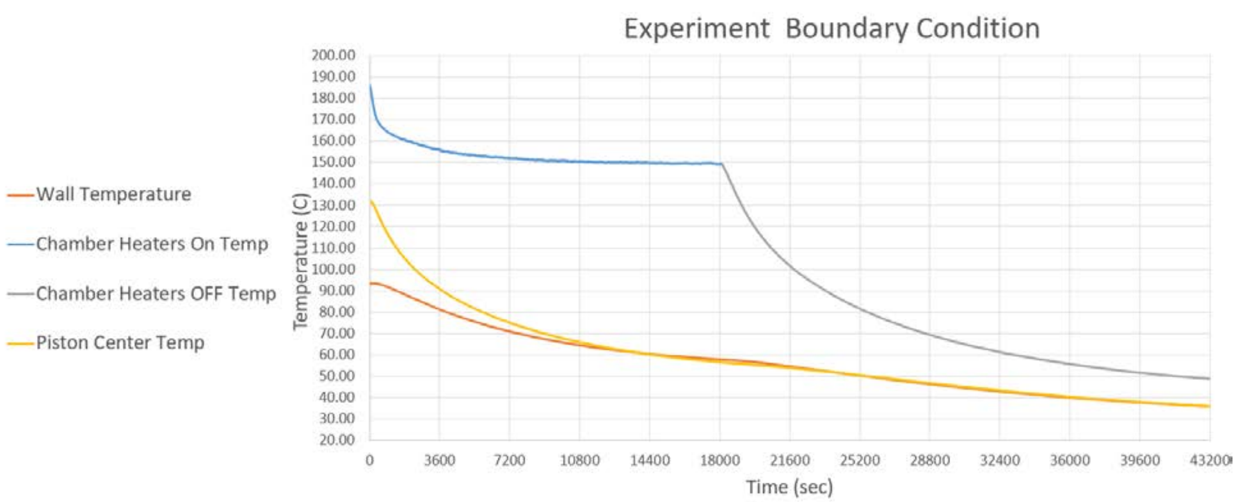


Figure 5: Boundary Temperature in the Cooldown process of Rectangular Bar Build

After the experiment was complete, the temperatures measured in the experiment were used as the initial and boundary conditions in the simulation. As shown in Figure 5, the part cake is modeled in one single piece, and only one temperature can be assigned to this block. The temperature at S4 was chosen as the initial temperature of the part cake. Similarly, the temperature at N3 was chosen as the initial temperature of the part because N3 was right on the edge of the part. The results of the post-experiment simulation and the experiment at locations S3 are plotted in Figure 6.

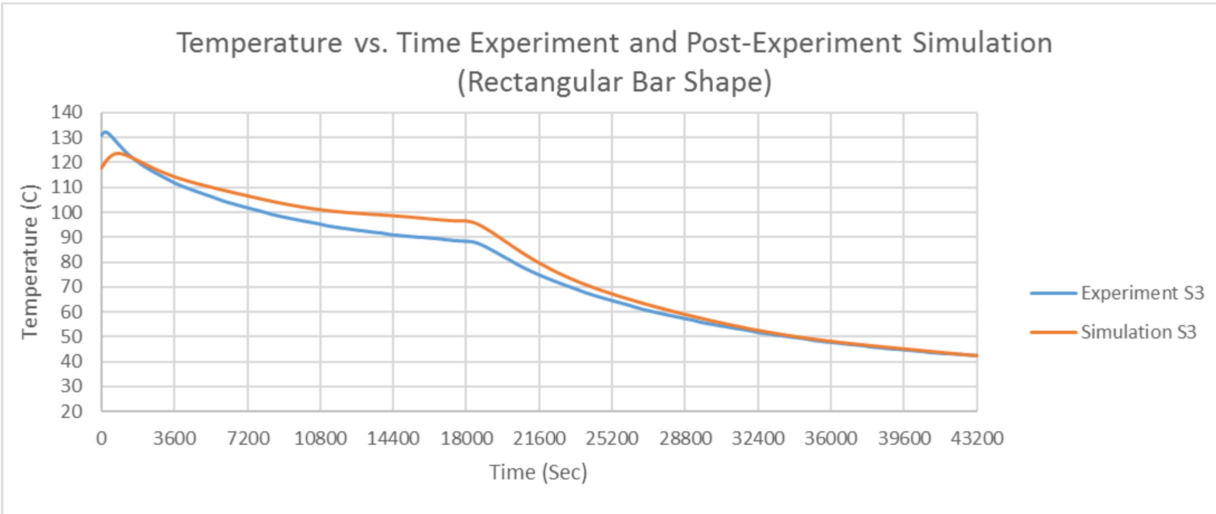
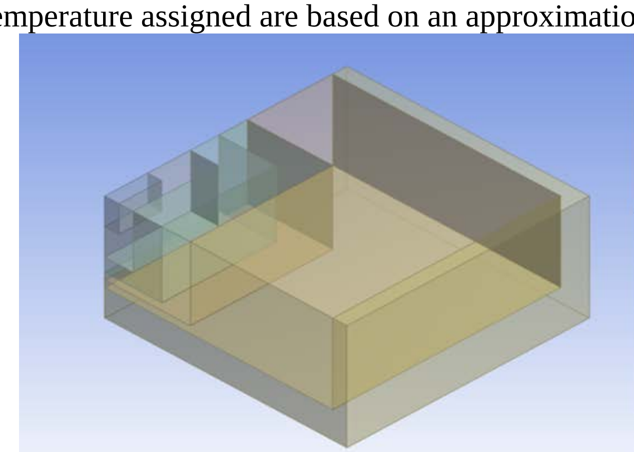


Figure 6: Comparison of Experiment and Simulation Temperature History at S3

The results for S3 was close to the experiment temperature but still did not match very well. At the beginning of the cooldown, the initial temperature at S3 (136.2 Celsius) was higher than the temperature at S4 (117.8 Celsius). That is, at the beginning of the cooldown, the temperature in the simulation at S3 was lower than its actual temperature in the experiment. To solve this problem, the part and the part cake were divided into different segmented regions and different initial temperatures are assigned to these regions. This change could not reflect the exact temperature gradient in the part and part cake, but could quickly fix the unmatched temperature profiles at the beginning of the simulation. The improved model is shown in Figure 7. The temperature assigned are based on an approximation of the actual thermocouple measurements.



Block No.	Part/Part Cake	Initial Temperature (C)
1	Part	140
2	Part	145
3	Part Cake	130
4	Part Cake	120
5	Part Cake	105

Figure 7: Segmented part and part cake with assigned initial temperatures

With a lower initial temperature, the temperature at S3 was still higher than experiment temperature between 2 hours to 7 hours. There are two possibilities that caused the temperature inflation. One is that the hot gas above the build surface transferred too much energy to the part and the part cake through convection, or convective coefficient h was set too high. Another possibility is that the thermal conductivity was too low so that energy was conducted from the part and part cake to the cold build box walls and piston too slowly. However, the thermal conductivity of Nylon 12 was already assumed at its high value 0.15 W/m-K as discussed before, so it was not realistic to have a larger value of k. After running some testing in the simulation, changing h from 25 W/m^2-K as assumed to 15 (W/m^2-K) made temperature profile at all thermocouple locations agree more to the experiment results. Figure 8 shows the simulation results with improved initial temperature assignments and improved convection heat transfer coefficient.

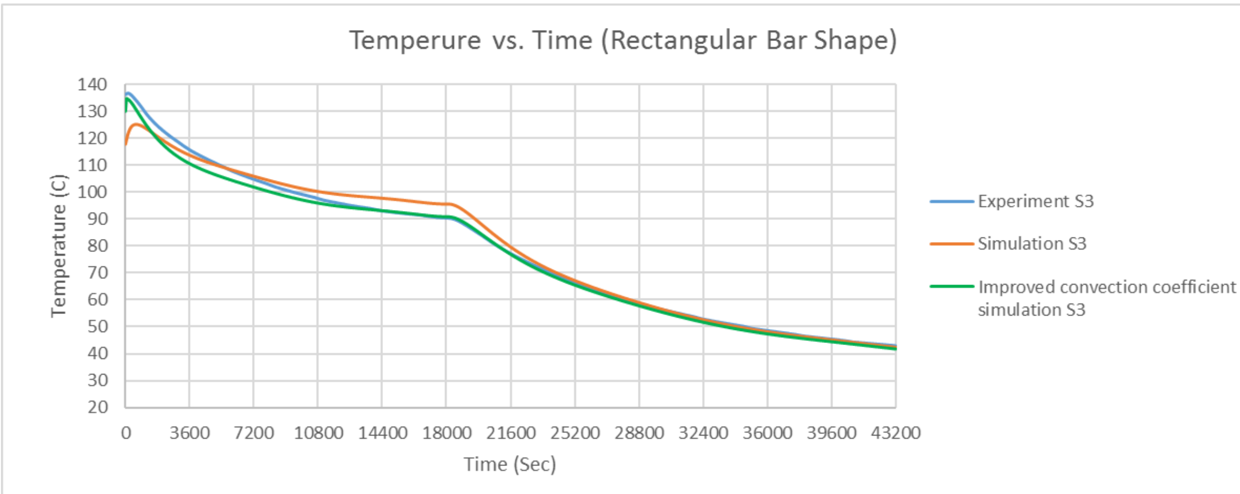


Figure 8: Comparison of experiment and simulation temperature history at S3

T-Shape Part Build and Lesson Learned

A larger "T" shaped Part was designed to enable more thermal heat transfer interaction with the walls and more thermal mass in the simulation. The CAD model of the T-shape is shown in Figure 9. One side of the T was close to the build box wall, and thus the heat energy exchange between the build box wall and the part was quicker at this region because of a short diffusion distance. The other side of the T-shape was treated as an extension of the rectangular part discussed in the previous section, and it took longer time and distance for the heat energy exchange from the build box wall to the center of this region. Table 3 shows all the locations of thermocouple insertion.

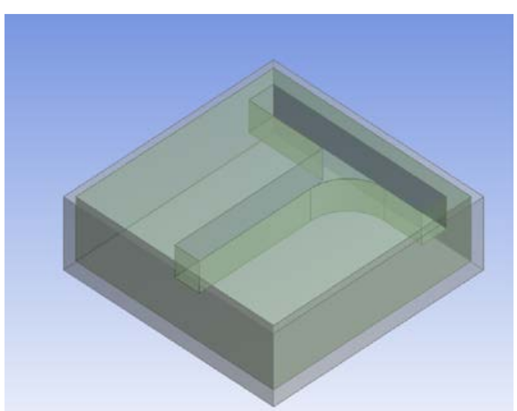
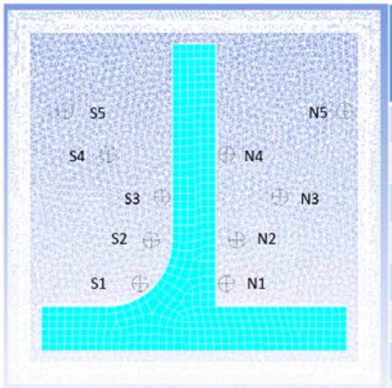


Figure 9 CAD model for the T-shape part simulation



Port #	Distance From Wall (cm)	Initial Temperature (C)
S1	6.98	127.3
S2	7.62	126.8
S3	8.26	128
S4	5.08	122.8
S5	2.54	115.4
N1	8.26	134
N2	7.62	130.1
N3	5.08	124.8
N4	8.26	129.2
N5	1.27	110.5

Table 3 Thermocouples locations in the cooldown process of the T-shape part experiment

Before attempting to run a simulation as a prediction ahead of the experiment, boundary temperature constraints and initial temperature needed to be assumed. Boundary temperatures are usually not affected by the geometry, but they largely depend on users' control commands of the heaters on the machine. In the T-shape part experiment, all heater on the machine was intended to be turned off at the beginning of the cool down process. Thus, the boundary temperatures were assumed the same as from other builds if the heaters are turned off (i.e. no control) at the beginning of the cool down process. The boundary temperatures of the T-shape simulation are plotted in Figure 10 below.

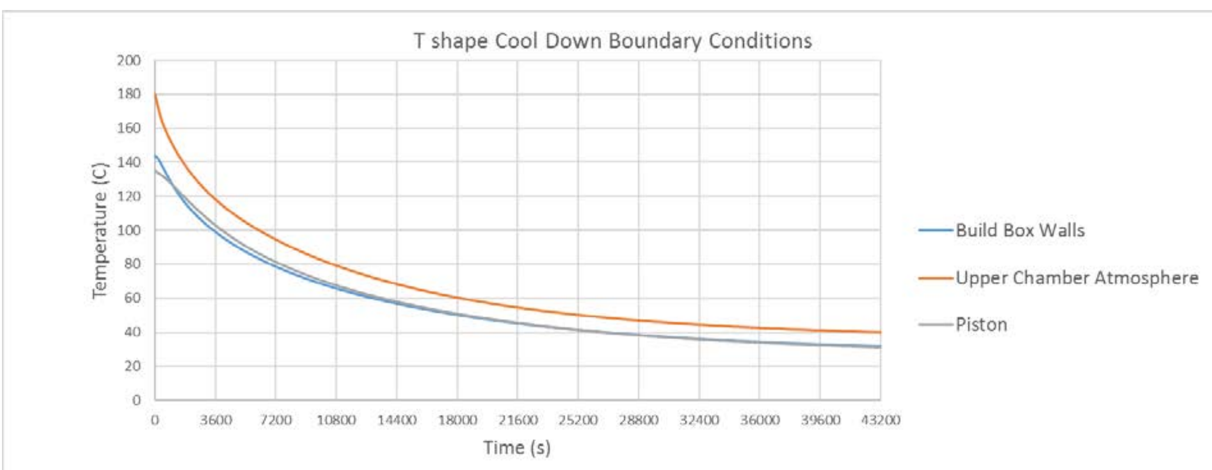


Figure 10 Boundary temperature for the cooldown process of the T-shape part simulation

The experiment procedure was almost the same as the previous experiments. In the pre-xperiment simulation, an average temperature of 125 Celsius was assigned as the initial temperature of the part cake. Accordingly, the initial temperature of the part was assigned as 130 Celsius as the initial temperature at N2, at a location very close to the part. The thermal parameters remained the same as in the tuned rectangular bar shape simulation, where h (convection heat transfer coefficient) equals to 15(W/m^2-K) and k (effective thermal conductivity of Nylon 12 power) equals to 0.15 (W/m-K). Figure 11shows the temperature history after 12 hours of cooldown at the N1 position.

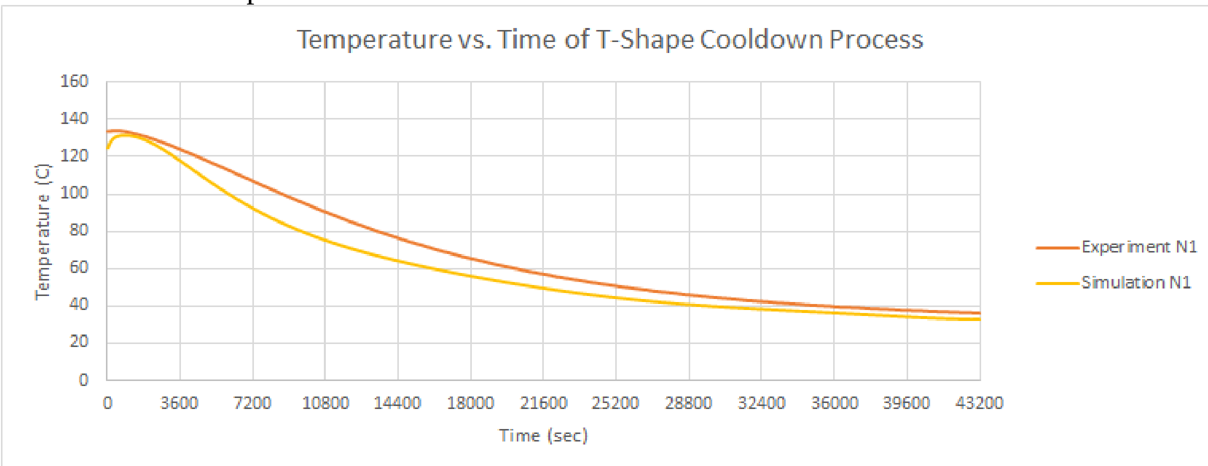


Figure 11 Comparison of experiment and simulation temperature history at N1

The actual initial temperature at N1 was close to the assumed average part cake temperature. The major problem that caused the disagreement between the simulation and experiment was that the heat energy conducted too fast to the build box walls and the piston. A lower thermal conductivity k should slow down the rate of heat conduction. After some testing, a thermal conductivity k as 0.05 (W/m-K) made the simulation results at N1 and other locations closer to the experiment results. 0.05 (W/m-K) is in the range of value of effective thermal conductivity of Nylon 12 as discussed before. The actual initial temperature at a location (e.g. N5) closer to the build box walls was lower than the assumed initial temperature in the simulation. Thus, the higher temperatures in the simulation overall were not surprising. To better represent the powder temperature observed in the experiment, the part cake in the simulation was divided into three regions, the region closer to the T-shape part remained its assumed initial temperature in the previous simulation, while the two regions closer to the build box walls were assigned with lower initial temperatures. The results of the updated simulation at N1 are shown in Figure 12. The temperature history at all positions showed better agreement with results in the experiment with this gradient powder initial condition near the part imposed.

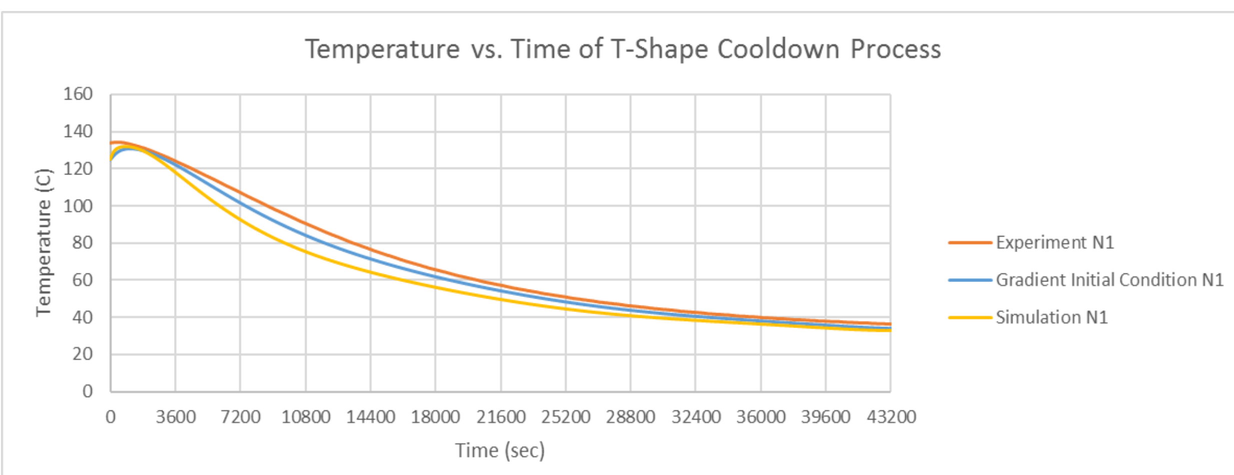


Figure 12 Comparison of experiment and gradient initial condition simulation temperature history at N1

Several lessons were learned from the simulations and the experiments described above with two different geometries. Fundamental simulations working as predictions of the temperature history of the part and the part cake in the cool down process require the knowledge of temperature constraints on the boundary, and the initial temperatures in the part cake. The highest uncertainties in the simulation are the initial temperature at different regions in the part cake, and the thermal parameters (h and k). An accurate simulation needs to be updated by adjusting thermal parameters and segmenting the part cake into regions with appropriate assigned initial temperatures to make the simulation results agree with experimental results.

Controllability of Build Box Heaters

As the goal is testing the controllability of the build box heaters, the SLS machine follows an operator prescribed temperature control profile for the cooldown process. The profile was used to control the temperature of the heaters on the build box walls and the piston. This controlling method did not allow direct control of temperature of the powder part cake, because the thermal response time is too long in this powder to enable practical close loop feedback control. For instance, a change of temperature on the build box wall heaters takes a long time to change the temperature at the center of the part cake.

Theoretically, in 1-D conduction, the diffusive distance and the diffusive time is associated by the equation $d \approx \sqrt{\alpha t}$, so that $t \approx d^2/\alpha$. The diffusive distance d is about 2 inches and thermal diffusivity $\alpha = \frac{k}{\rho C_p}$. The calculated diffusive time is about 4 hours. This is a rather rough estimation, because the model is 3D, and other heat transfer modes involved. However, the order of the answer shows a long diffusive time for heat diffusion in Nylon 12. As discussed earlier in the paper, the LAMPS machine has a smaller build volume compared with a commercial machine. That means, it takes even longer for the change of temperature on the boundary to take effect on the part at the center of the build volume in commercial machines.

Another way to test the response time is running a simple simulation. In the simulation of the cooldown of the rectangular bar part, ambient temperature on the top surface was held as constant, while a sudden temperature drop after 5hours of the cooldown was applied on the build box wall heaters. Figure 13 shows the boundary conditions in the simulation.

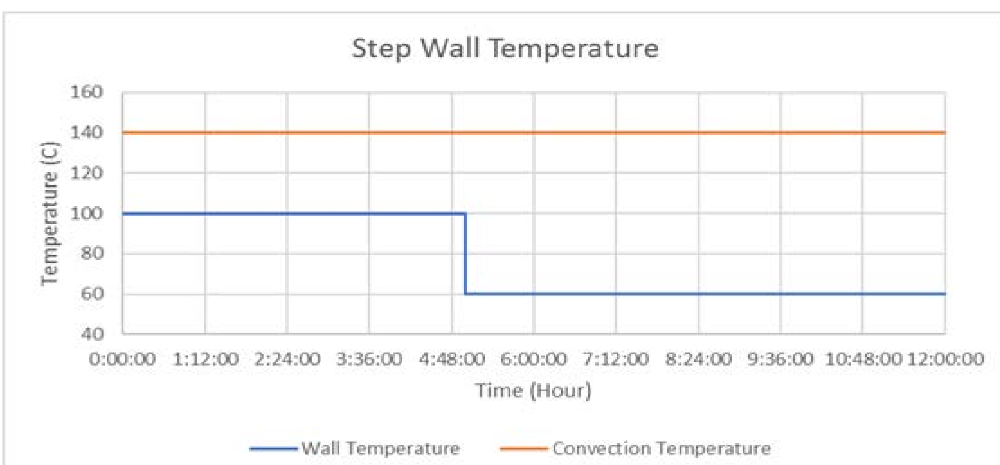


Figure 3: A Step Temperature Drop at the Wall Temperature

The response of temperature at a location (S3) close to the center of the part cake is shown in Figure 14. As shown in the figure, the temperature at the location took about 2 hours to drop to a steady state temperature after the sudden drop in the temperature of the build box wall heaters.

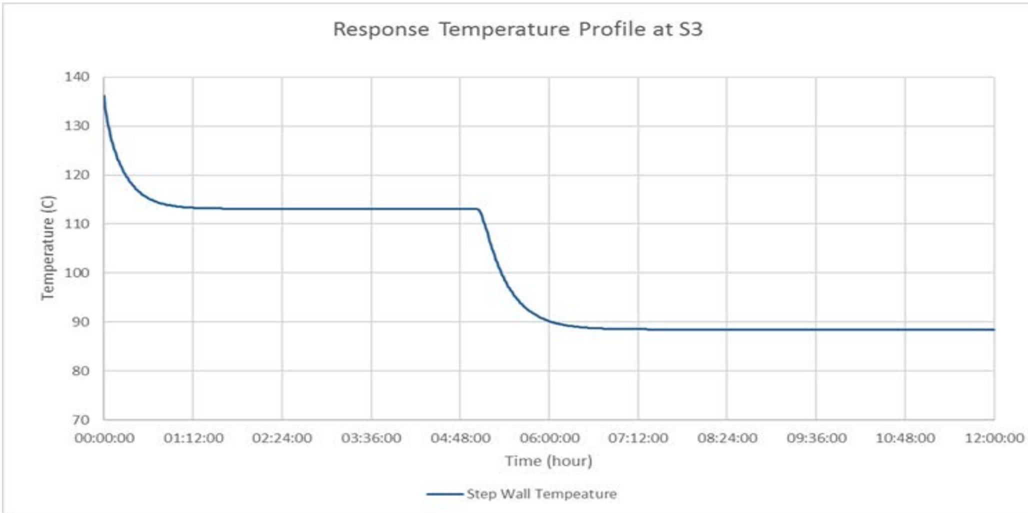


Figure 4: The Response of the Temperature Inside Part Cake to the Step Temperature Drop

A conclusion was drawn that real-time feedback control of the part/part cake temperature is not feasible by controlling wall heaters on the build box. However, the temperature in the part/part cake does respond slowly. In other words, a non-real time feedforward control is possible.

Simulations models were designed to compare the first two hours' temperature history of the cooldown process of the T-shape part build with and without build box wall heaters control. To get the boundary temperature on the build box walls, a separate experiment was done. At the beginning of the cool down process, a control command of dropping the temperature from 145 Celsius to 135 Celsius was sent to the build box wall heaters. At the end of the first hour, another control command of dropping the temperature from 135 Celsius to 125 Celsius was sent. Figure 15 below demonstrates the actual build box wall temperature monitored by surface mounted thermocouples.

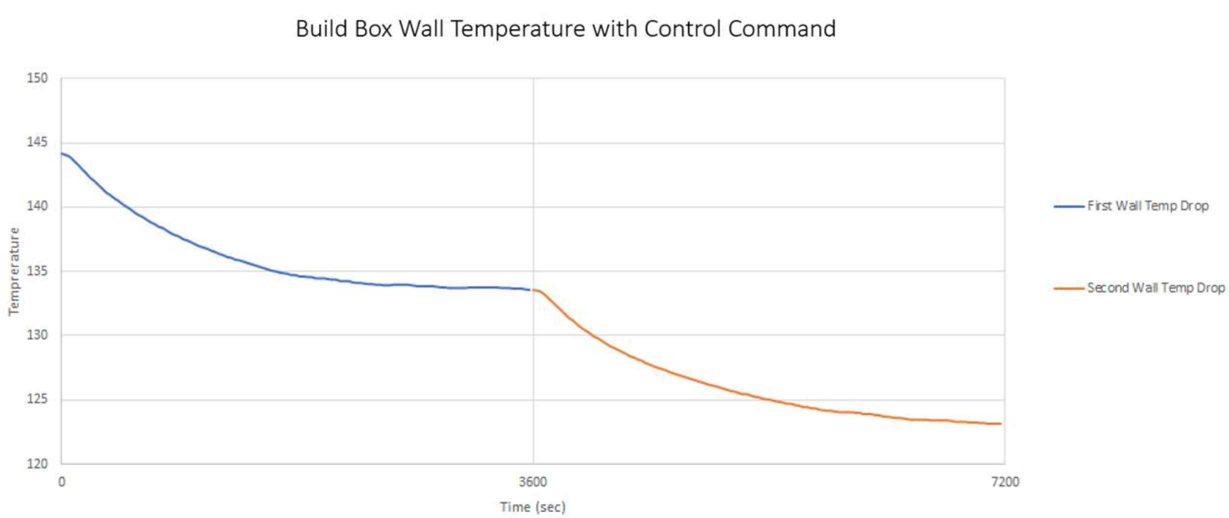


Figure 5: Temperature response at the surface of the walls with step control inputs

Though the temperature control command was sent instantaneously to the wall heaters, the surface temperature of the build box walls took more than 30 minutes to reach the set temperature. The boundary temperatures on the build box wall surface with control inputs and with heaters turned off are plotted in Figure 16.

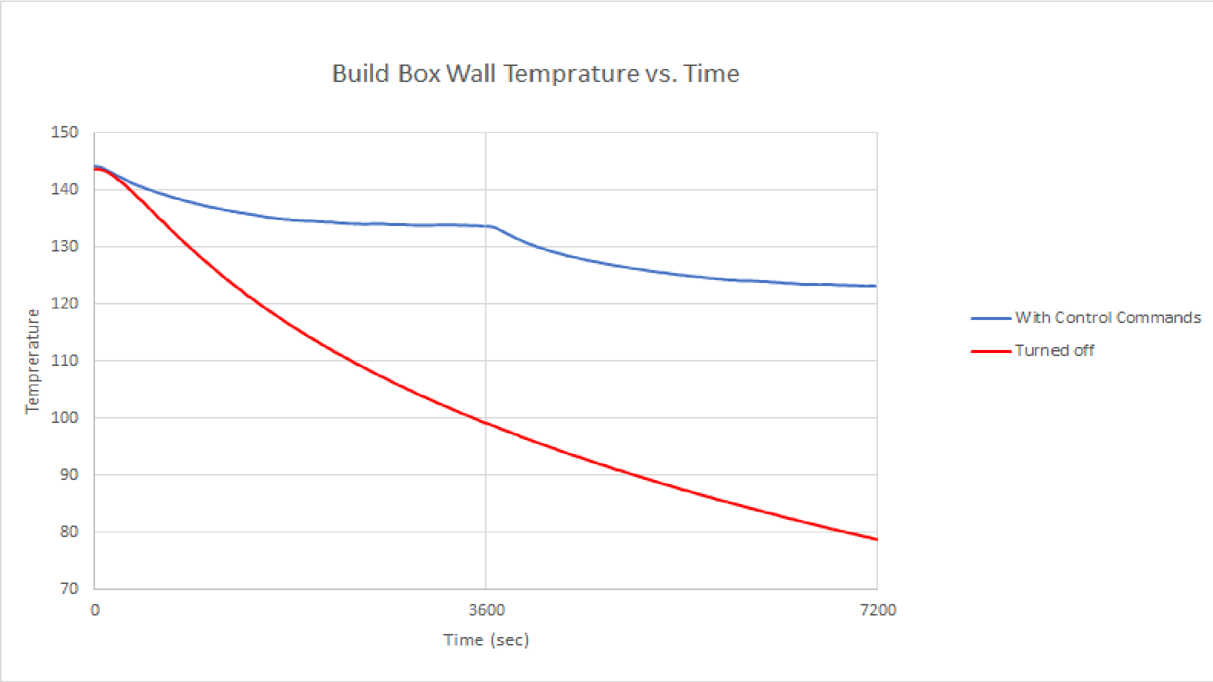


Figure 6: Boundary temperature with different control inputs at build box walls

Temperature maps at a ½ depth of the part were compared with this two control inputs. Figure 17 shows the temperature maps with wall heaters turned off 2 hours after the cooldown process starts, and Figure 18 shows the results with wall heaters control. The unit for the temperature map is Kelvin. The maximum and minimum value of the temperature scales were forced to be the same.

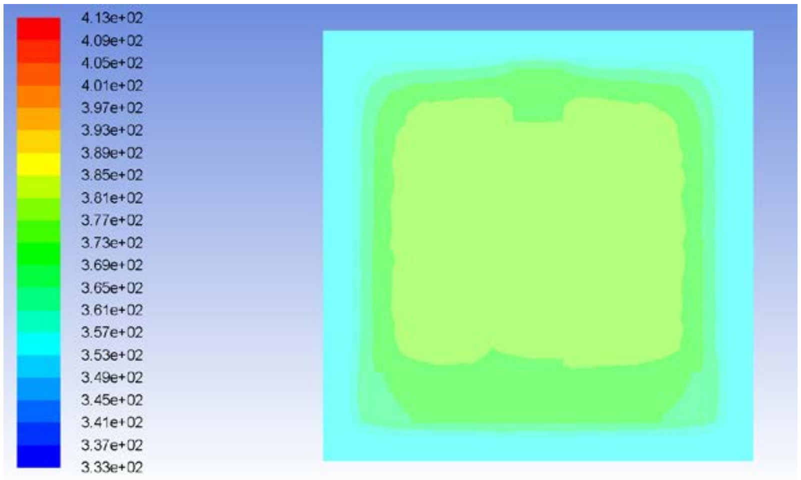


Figure 7: Temperature map after 2 hours of the cooldown with heaters turned off

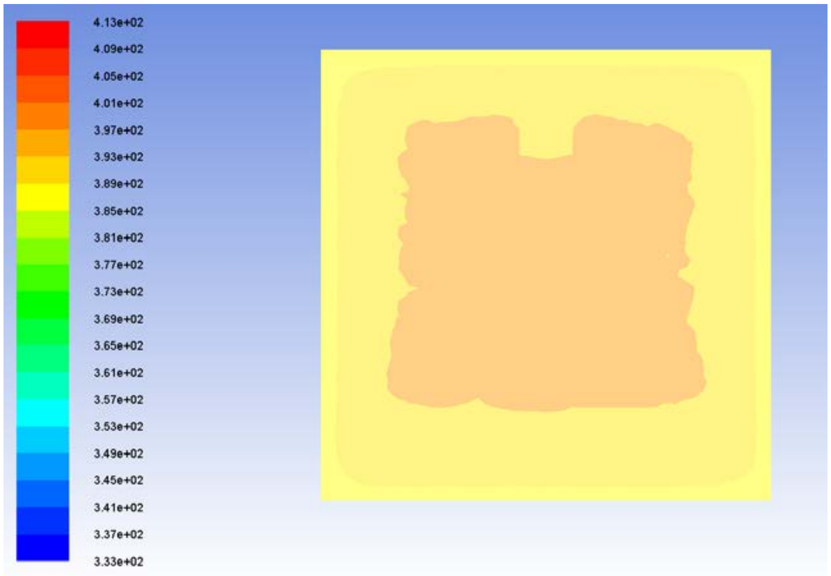


Figure 8: Temperature map after 2 hours of the cooldown with heaters controlled

As Shown in Figure 27, and 28, though the controlled heaters affected the heat transfer inside the part cake, this implementation only reduced the cool down rate, and did not resolve the uneven temperature distribution issue in the part cake. It is hard to learn from comparing the results with different control inputs and make improvements.

Conclusion and Future Work

Boundary temperature conditions and initial temperature conditions are the necessities to run simulations as fundamental predictions before experiments. For a new control profile used in the cool down process, boundary conditions can be approximated because they largely depend on the control inputs. For a build with new geometry, initial temperatures are known from the initial probe thermocouple readings at the beginning of the cool down. The initial temperature from a thermocouple closing to the part can be used as the initial temperature of the part. Assigning initial temperatures to different regions in the part cake can model the temperature gradient inside of the part cake at the beginning of the cool down. The simulations need to be improved by adjusting thermal parameters to represent accurate temperature history of the part and the part cake in the experiments.

Verified simulation models can predict the temperature history for future builds with the same geometry. When different control inputs applied, simulations save time from running extra builds, and quickly return the temperature mapping inside of the part cake. With accurate and quick predictions, it is possible to control the temperature field inside of the part cake, and then prevent shape distortions and weak points in the parts due to thermal stresses.

Due to a long diffusion time, feedback control with build box wall heaters is not feasible. A feedforward control is possible but hard to determine ideal control inputs that can help resolve thermal stresses problem. The limitation of current systems is a lack of control of chamber heaters.

A more sophisticated method is starting the simulations from the beginning of the build. The temperature history inside of the part cake are simulated from the laser sintering stages, and no assumptions needed to be made for the cool down process because all the constraints needed to be known to solve the transient problem are already included in the simulations. However, the entire machine but not just the build box need to be included in the simulation. The version of ANSYS Fluent used for the simulations is not the ideal tool for this kind of simulation because it does not allow adding material to the control volume.

Thermal stresses are not compared with different control conditions in this paper. To achieve that, temperature distribution map needs to be exported from Fluent and used as thermal loading in a coupled thermal-structural analysis to determine thermal stresses in the part with different temperature distributions.

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