Development and Verification of a Thermal Model for a Novel Automated Composite Fabrication Process: Laminated Object Manufacturing (LOM)

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SUMMARY: The initial framework for a thermal model of the Curved-layer Laminated Object Manufacturing (Curved LOM) process was developed. Curved LOM is a automated process involving layer-by-layer lamination and cutting of sheet materials using a conformable heating membrane and CO_2 laser, respectively. The process is used for fabrication of flat or curved panels made from fiber composites, ceramics, or other advanced materials. A thermal model was developed in order to predict temperature profiles throughout the panel during LOM processing. To verify the model, a 20-layer ceramic panel was built with thermocouples embedded every fourth layer to record temperature during the process.
By adjusting one of the model parameters (heat transfer coefficient of laminator to panel top surface), the model accurately predicted the observed response. Further model refinements and additional capabilities will be pursued.

KEYWORDS: Process Modeling, Near-Net Shape Manufacturing, Prototyping, Ceramic Materials/Composites, Integrated Design and Manufacturing, Emerging Manufacturing Technologies

INTRODUCTION

Rapid prototyping (RP) is an emerging area of technology used to make dimensionally accurate three dimensional (3-D) models directly from computer-aided design (CAD) files, without the use of hard tooling, molds, or dies. This technology is also known as solid freeform fabrication (SFF) or layered manufacturing. There are several commercial versions of the technology, all of which operate under the same principle of building an object in a layer by layer fashion. The process begins by converting a standard 3-D CAD file of an object to an RP standard format and slicing it with a series of horizontal planes. This layerwise geometric information is transferred to a computer controlled machine that physically reconstructs the object, cross section by cross section, using wax, low strength plastic, plastic coated powder, or adhesive paper. RP is widely used in industry to fabricate conceptual models and prototypes for verifying form and fit. Recently, there has been much activity in developing new materials and improving the existing RP processes so that fully

functional articles can be directly constructed from engineering materials such as composites, ceramics, and metals.

One of the leading rapid prototyping techniques is Laminated Object Manufacturing (LOM) (see Fig. 1). LOM is an additive process involving lamination of sheet materials. First, a full layer of material is delivered to the platform via roll or single sheet and laminated to the existing stack. Lamination is performed via heated roller. After each layer is laminated, a CO_2 laser cuts the perimeter of the cross sectional area, one layer deep. The laser also dices or "cubes" the excess material to help with removal of the finished component. The waste material is left in place during the build process to serve as a support. The sequence of laminating and cutting continues, one layer at a time, until the part is complete. The “block” then is removed from the platform and the waste material is manually separated to reveal the three dimensional part.

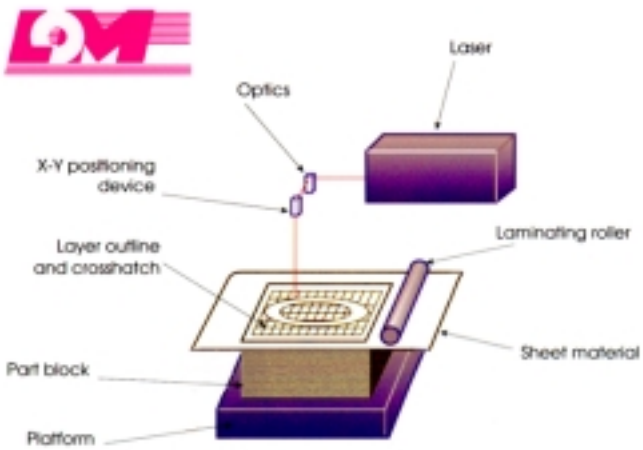

Fig. 1: *the LOM process (courtesy Helisys, Inc., Torrance California, USA*).

Current research and development is directed toward applying LOM for direct fabrication of structural composite parts, including continuous fiber polymer and ceramic matrix composites. To this end, the standard LOM process has been modified to accommodate common feedstock materials such as fiber prepregs and ceramic tapes. In addition to developing new methods for feeding, laminating, and cutting these advanced materials, a fundamentally different building paradigm was required: the curved layer building style. Instead of being limited to building with flat layers, the LOM machine is now capable of building in a curved-layer-by-curved-layer manner. The new curved layer LOM process (“Curved LOM”) allows continuous fiber composites to maintain fiber continuity in the plane of curvature to achieve optimum mechanical performance.

The Curved LOM process is illustrated in Fig. 2. The process can be used to make flat panels or curved panels. If a curved panel is desired, one must supply a matched tool or “mandrel”. This mandrel can be made with the standard (flat layer) LOM process using LOM adhesive paper. The paper mandrel is mounted to the flat building platform in the Curved LOM machine. Sheets of the desired build material (e.g., composite prepreg, 0.25 mm thickness) are loaded onto a rotatable feed table, picked up with a vacuum chuck (integrated with the laminator), and shuttled to the mandrel. A flexible thermoforming mechanism laminates each new layer to the curved mandrel with steady, uniform vacuum pressure and heat. Details of the vacuum laminator mechanism are illustrated in Fig. 3. After the laminator retracts, a

pulsed CO_2 laser cuts each layer, accounting for the sloped surface. The fiber orientation can be varied from layer to layer by programming the rotatable feed table. The process proceeds one layer at a time until the part is finished. If necessary, the laminator can be used to provide additional post cure to the final part. Subsequently, the part is removed from the mandrel and the excess material is manually stripped away ("decubed").

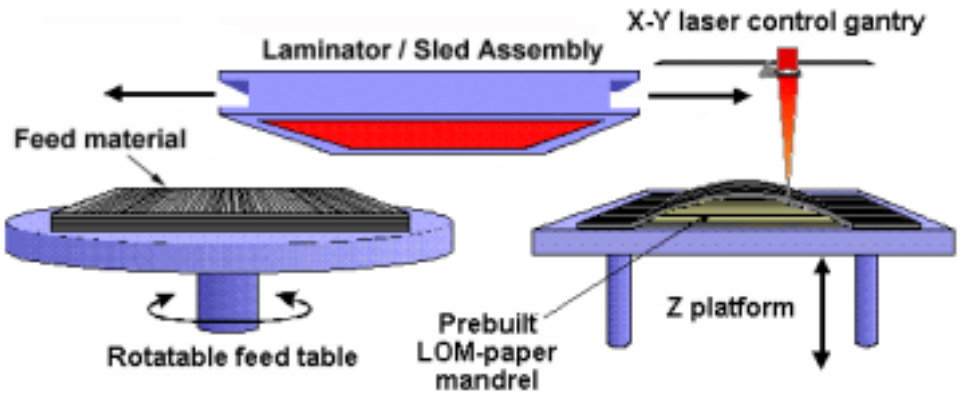

Fig. 2: *Schematic of the Curved LOM Process*.

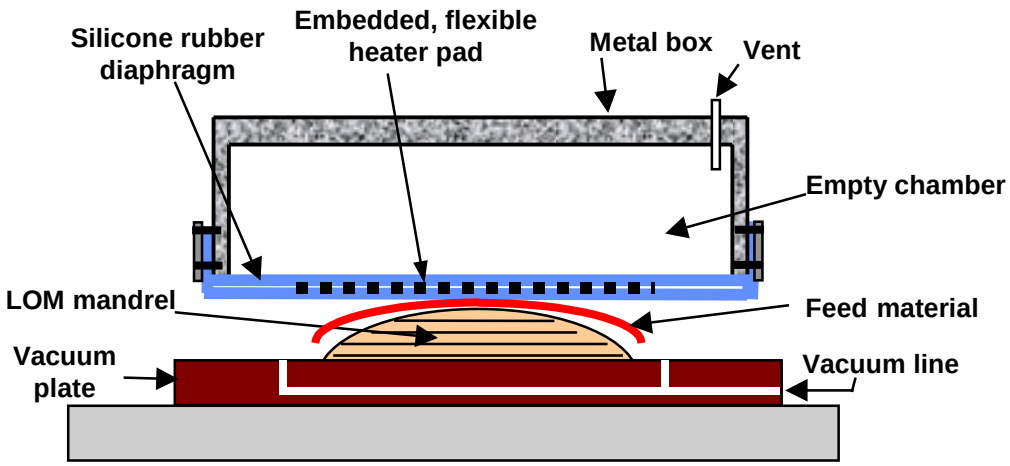

Fig. 3: *Cross sectional schematic (not to scale) of Curved LOM laminator and platform. The Z-platform elevates to close the seal between the rubber diaphragm and the vacuum plate.*

The Curved LOM process is intended to benefit the design and manufacturing of advanced material structures that currently require intensive manual labor assembly. Examples of typical components are aerospace or automotive panels. The primary material types are ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and monolithic structural ceramics. Most of the work to date has been with monolithic ceramic and CMC systems [1, 2, 3, 4]. Additional efforts are underway to combine the LOM process with innovative, computer-based structural design methodologies. The goal of the overall research effort is to provide a new prototyping tool for allowing simultaneous evaluation of new materials, new design concepts, and innovative approaches to structural components.

The rationale for developing a mathematical model of Curved LOM is based on the cyclic thermal environment encountered in the layer-by-layer lamination process. For chemical and physical processes occurring in advanced materials, such as thermoset resin cure and

thermoplastic crystallization, the thermal history of the part plays a key role in determining the mechanical properties of the final parts. Predicting thermal fluctuations in the LOM process is not straightforward. Existing mathematical models for composites [e.g., 5, 6], which are based on batch thermal processing, are not applicable. Thus, it was decided to develop an entirely new, numerical-based mathematical model for Curved LOM.

MODEL DEVELOPMENT

The basis for the model was taken from a model previously developed by the authors for the standard (flat layer) LOM process [7, 8]. The thermal behavior of a LOM part is primarily determined by the heat transfer mechanisms that take place during the LOM build cycle. These mechanisms include:

- heat transfer from the heated laminator to the surface of the partially completed part,
- heat conduction within the part itself, typically away from the heated surface,
- heat loss from the bottom of the part to the paper mandrel and the metal base-plate on which the part is being fabricated, and
- heat loss from the various exposed surfaces of the part to the surroundings via free or forced convection.

A mathematical model describing these mechanisms for a simple rectangular geometry LOM part was developed (see Fig. 4). The difficulties in modeling curved geometry were not addressed in this phase of model development. However, it is thought that existing geometric transformation techniques [9] could be applied once a workable model for rectangular geometry is developed. To further simplify the analysis, heat transfer from the sides of the part was ignored. This assumption, which is valid for thin panels, reduced the problem to a transient, one-dimensional heat transfer problem.

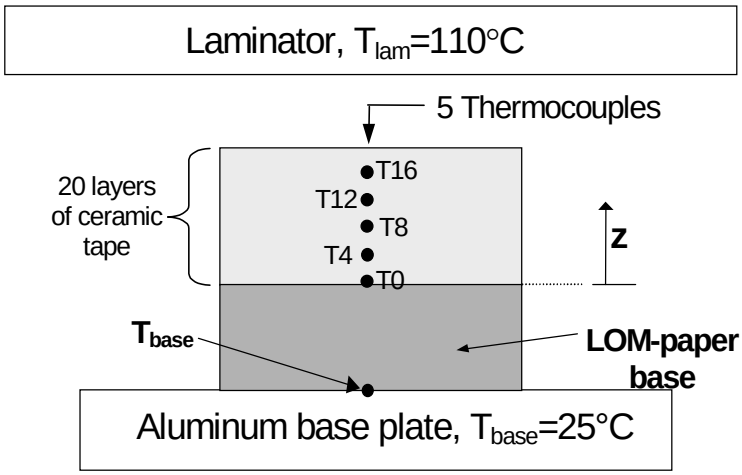

Fig. 4: *Model geometry and experimental set-up (not to scale).*

Heat conduction within the rectangular region of build material (e.g. ceramic tape) was described by the following equation:

$$\rho C_p \frac{\partial T}{\partial t} = k_z \frac{\partial^2 T}{\partial z^2} \tag{1}$$

where T is temperature in the part; t is time; z is displacement in the direction normal to the plane of the layers (see Figure 4); and ρ, C_p, and k_z are the density, heat capacity, and thermal conductivity in the z-direction of the build material, respectively. Note that no energy source term was included in the equation at this stage of development. This assumption is valid for the materials used in this study, as discussed later. Thus, energy addition or loss from the region was handled through the boundary conditions at the top and bottom surfaces.

Boundary conditions for the part were specified using general heat transfer coefficient (convection-type) boundary conditions. For the top part surface when in contact with the surrounding air, the following expression was adopted:

$$k_z \frac{\partial T}{\partial z} = h_{air}(T_{surface} - T_{air}) \tag{2}$$

where T_{air} is the temperature of the air surrounding the part, $T_{surface}$ is the temperature of part top surface; and h_{air} is the heat transfer coefficient of the part top to the surrounding air.

For when the top surface was in contact with the laminator, a similar expression was used:

$$k_z \frac{\partial T}{\partial z} = h_{lam}(T_{surface} - T_{lam}) \tag{3}$$

where T_{lam} is the temperature of the laminator and h_{lam} is the heat transfer coefficient of the laminator to the part top. The use of a convective boundary condition to describe what is essentially a conductive heat transfer process proved successful in a similar model [7, 8]. This approach is simple and allows for experimental tuning of the model to actual lamination conditions, which are inherently difficult to model.

The panel fabricated by the Curved LOM process is supported by a solid mandrel or block. In this study, the boundary between the ceramic part and the LOM-paper block was also accommodated using a heat transfer coefficient boundary condition as follows:

$$k_z \frac{\partial T}{\partial z} = h_{base}(T_{bottom} - T_{base}) \tag{4}$$

where T_{bottom} is the temperature of the panel bottom surface (note T_{bottom} = T0 in Figure 4), and T_{base} is the temperature of the platform supporting the LOM-paper block. The heat transfer coefficient for the paper block, h_{base}, is an effective value that can be estimated or experimentally measured. The base plate temperature was treated as a single, constant value that is essentially equal to room temperature in practice. This modeling approach was also used successfully in a previous effort [7, 8].

A finite central difference approximation was applied to the heat conduction equation (Eqn. 1) and the boundary conditions (Eqn. 2-4). This resulted in a set of simultaneous linear equations that were solved for each time increment and a one-dimensional spatial grid, which grew in size as layers were added at discrete times. The simulated processing cycle for each layer consisted of three phases: new layer placement on the existing stack, layer lamination, and layer cooling during laser cutting. Heat input by laser cutting was not considered, as it was expected to be negligible. Addition of a new layer of material was accomplished by adding additional nodes to the existing spatial grid structure. It was assumed that the new layer of material was at ambient temperature. The temperature discontinuity at the instant of new layer application was handled by simply adjusting the temperature of the interfacial node

to the average of the previous layer's surface temperature and the temperature of the new layer.

EXPERIMENTAL VERIFICATION

In order to perform a build simulation, a number of parameters were determined and input to the mathematical model. These parameters related to the physical and thermodynamic properties of the material being used to construct the part, the LOM machine parameters (laminator temperature, cycle times), physical dimensions of the part, and estimates of heat transfer coefficients to the surrounding air and base plate. The parameters used in this study are presented in Table 1. All parameters were experimentally measured [7, 8, 10] except the laminator-to-part heat transfer coefficient (h_{lam}), which was used as a model tuning parameter.

Table 1: *Data for LOM build simulation*

Material	Silicon carbide ceramic tapes
Thermal Conductivity, k_z	1.25 $W.m^{-1}.K^{-1}$
Density, ρ	1.98 $g.cm^{-3}$
Heat Capacity, C_p	1.05 $J.g^{-1}.K^{-1}$
Layer thickness	0.33 mm
Number of layers	20
Heat transfer coefficient (part to air), h_{air}	13.6 $W.m^{-2}.K^{-1}$
Heat transfer coefficient (part to base), h_{base}	8.5 $W.m^{-2}.K^{-1}$
Air temperature, T_{air}	23°C
Base plate temperature, T_{base}	25°C
Initial temperature of material	23°C
Laminator temperature, T_{lam}	110°C
Build cycle time	90 seconds

A simple experiment was conducted to verify the model performance (see Fig. 4). A twenty-layer ceramic part was built using an off-line, physically simulated Curved LOM building process. An aluminum base plate (85 cm x 63 cm x 2 cm) from a standard LOM2030 machine was placed on a tabletop. A 10 cm x 10 cm x 1.25 cm LOM-paper block was placed on the aluminum plate. A simple laminator was fabricated consisting of a flexible heating pad placed between two pieces of rigid aluminum sheet. The temperature of the pad was controlled electronically via a thin thermocouple sandwiched between the heater pad and the supporting aluminum sheet. To laminate layers of material, the heater assembly was manually placed on the build stack, and an insulated 6.1-kg weight was placed on top of the heater. The resulting pressure was 0.006 MPa (~ 1 psi), which was sufficient to produce good thermal contact between the laminator and the part. To prevent the ceramic tape from sticking to the sheet metal surface, a Mylar film was placed between the ceramic part and the laminator.

A twenty-layer, 10 cm x 10 cm rectangular block of monolithic SiC ceramic tapes was fabricated atop the LOM-paper block using the sequence given in Table 2. This cycle realistically represents the Curved LOM process. Ceramic tapes were comprised of SiC particles embedded in a highly plasticized thermoplastic polymer [1]. The material does not undergo an endothermic

(e.g., melting) transition or exothermic transition in the temperature range investigated here, thus satisfying a key assumption implicit in Equation 1.

Table 2: *Curved LOM process sequence.*

Process Step	Action	Duration
Layer Placement	Place new ceramic tape layer on top of stack	10 seconds
Layer Lamination	Quickly place Mylar film on top of stack; quickly place heater and weight; wait	40 seconds
Laser Cutting	Quickly remove weight, heater, and Mylar film; wait (no attempt was made to add heat to simulate laser cutting)	40 seconds

A thin (0.075 mm diameter) thermocouple was placed in the center of the top surface of every fourth layer beginning with layer 0 (the top of the paper mandrel). A thermocouple was also placed below the paper mandrel to verify that the temperature between the base plate and the mandrel remained steady. Temperature from each thermocouple was recorded every 0.5 seconds through the entire 30-minute build.

RESULTS AND DISCUSSION

The results of the experimental LOM build are presented in Fig. 5. The responses of only three of the embedded thermocouples are shown for clarity. An enlarged view of a portion of a single thermocouple's response (T8) is given in Figure 6. The characteristics of the temperature measurements agreed with expectations. The temperature rose when the laminator was placed on the partially built ceramic part. The temperature rise was sharp initially, and it slowed gradually as the laminator temperature (110°C) was approached. Surprisingly, the ceramic part temperature didn't reach a steady value even after a 40 second hold. When the laminator was removed, the temperature dropped sharply in a negative exponential fashion. The addition of a new layer resulted in another abrupt drop in temperature. As more layers were added, the temperature changes became less pronounced. This behavior was repeatedly obtained for each new thermocouple embedded on the top-most layer. The temperatures at various points in the LOM part eventually oscillated around a steady-state value of approximately 92°C. After all 20 layers were added, the entire block cooled with very little thermal gradient over the part thickness.

The response (not shown) of the thermocouple placed below the LOM-paper block confirmed the boundary condition that the aluminum base plate remained near room temperature throughout the build cycle. This result is not surprising considering that this large piece of metal acts as a thermal heat sink. Actually, T_{base} slowly changed from 22.5 to 28°C throughout the experiment. However, this variation was considered to be negligible, and T_{base} was taken as a constant 25°C.

Model predictions for the system were made using the data given in Table 1. The only parameter not given in this table and not known before the experiment was the heat transfer coefficient of the laminator to the part top (h_{lam}). The value of h_{lam} was adjusted until the model predicted the steady state temperature achieved in the experiment. The result, in which h_{lam} =275 W/m^{2}K, is shown in Fig. 7. Comparing with Fig. 5, a reasonable match of the steady state response was obtained. However, this value resulted in an over-prediction in the temperature rise in the initial layers. Yet, the predictions for other thermocouples and at later times in the process are excellent

(see Fig. 8). These results suggest that the base heat transfer coefficient changes during the build. The cause of this phenomenon was attributed to the temperature increase in the LOM paper mandrel, which affects the heat transfer dynamics.

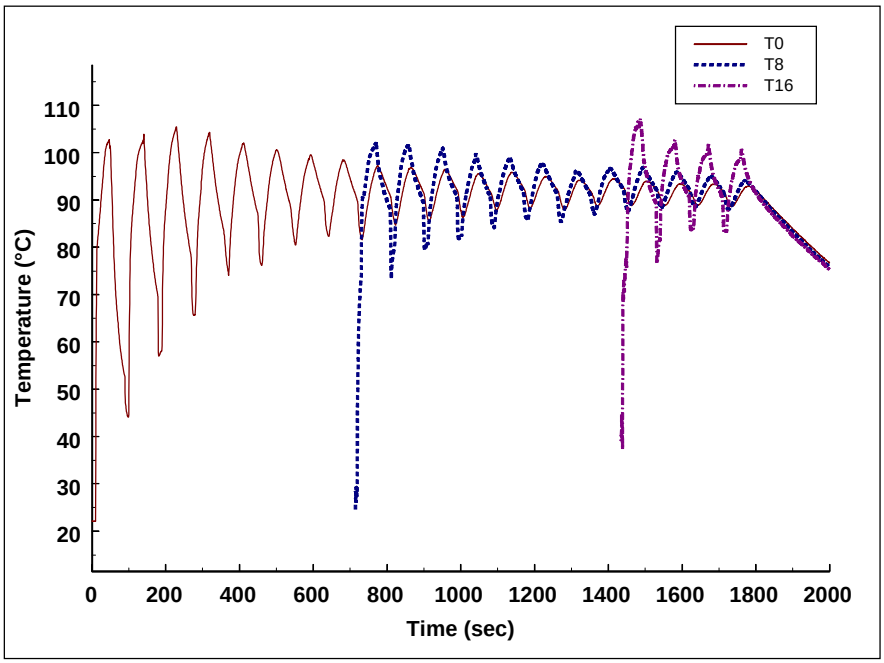

Fig.5 : *In-situ temperature profiles for 20-layer monolithic SiC block laminated with Curved LOM process. Temperature was measured from thermocouples embedded under layer #1 (T0), over layer #8 (T8), and over layer #16 (T16). The cycle time was 90 seconds per layer.*

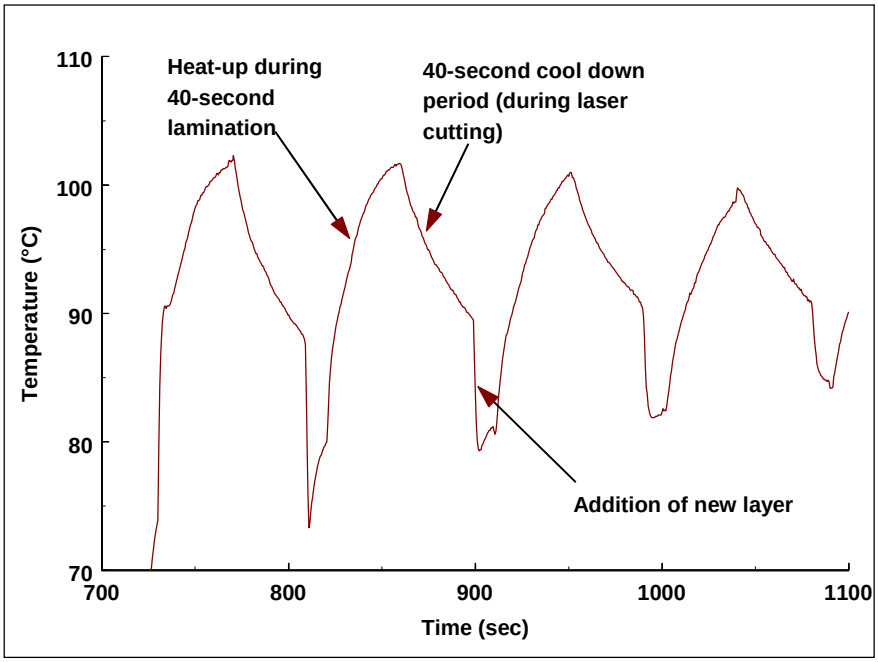

Fig. 6: *Enlarged view of data from thermocouple T8 (embedded above layer #8) as layers #9-12 are added.*

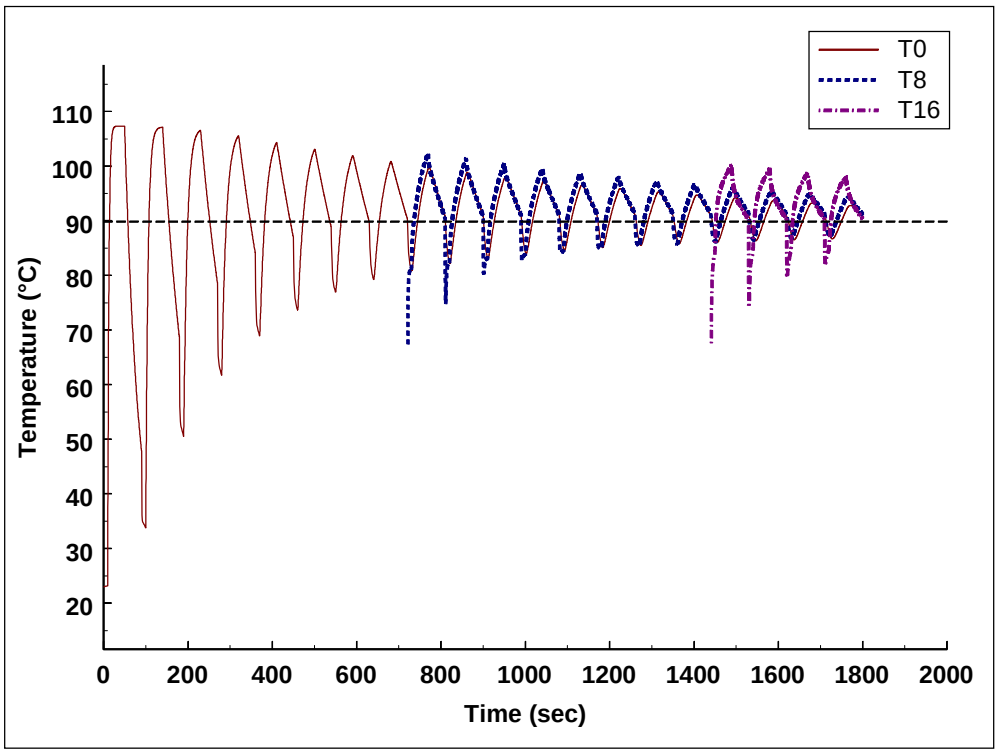

Figure 7: *Model results for all layers using* h_{lam} *= 275 W/m*^{2}*K.*

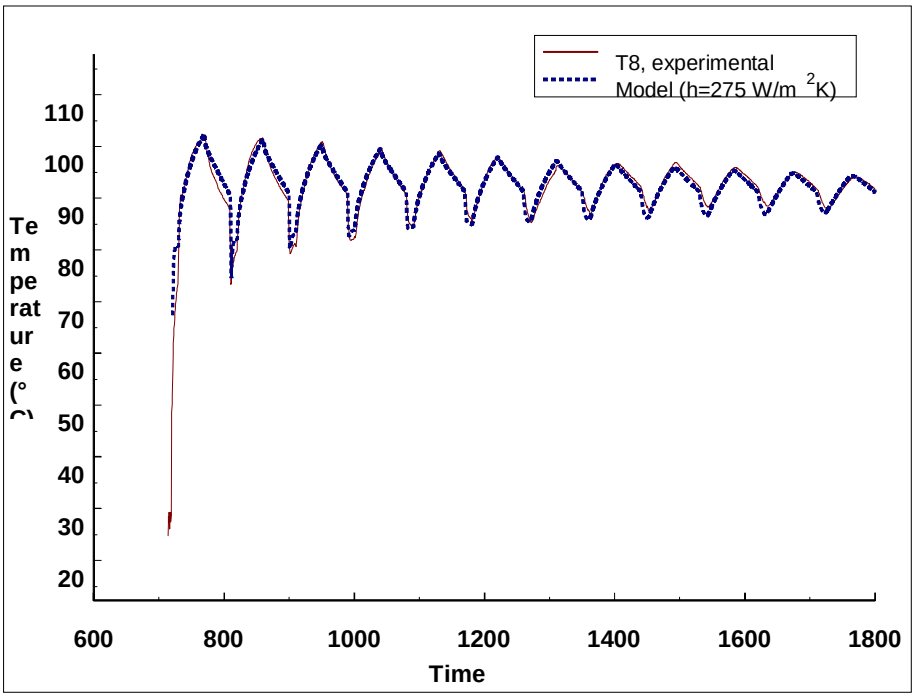

Fig. 8: *Comparison of model to experimental data for thermocouple #8 (T8), using* h_{lam} *= 275 W/m*^{2}*K.*

CONCLUSIONS

The initial framework of a mathematical model for the Curved LOM process was successfully developed. The model, based on one-dimensional transient heat conduction in thin panels, predicts the qualitative features of the observed experimental response. Experimental data collected from an off-line Curved LOM process was used to tune the model parameters. The tuning parameter was the heat transfer coefficient of the heater to the part top surface. Reasonable quantitative agreement with most of the experimental observations was obtained. The next steps planed for this study are:

- Investigate the use of a variable heat transfer coefficient at the base of the part (h_{base}) in order to improve the temperature prediction of the lower layers / initial times.
- Investigate an alternative to the base convection-type boundary condition by incorporating the LOM-paper block into the conduction part of the model. This will increase the mesh size of the finite element grid.
- Include chemical heat of reaction terms in the model in order to predict thermoset cure profiles.

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