A THERMAL MODEL FOR LAMINATED OBJECT MANUFACTURING (LOM)

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ABSTRACT

A thermal model for Laminated Object Manufacturing (LOM) has been developed. The model is based on 3-dimensional transient heat conduction in a rectangular geometry LOM part. Heat transfer from the heated roller to the laminated part as well as heat loss to the surroundings and the base plate are considered. It allows calculation of the transient temperature distribution within the part during the application of a new layer as well as during other periods of the LOM build cycle. To verify the model performance, thermocouples were embedded every 4^{th} layer in a 20-layer ceramic part while it was being built on a standard LOM-2030. The model predictions are in excellent agreement with the measured temperature profiles. In addition to explaining the observed thermal behavior of LOM parts, model predictions also have direct application to on-line control of the part temperature during the build process, to be discussed herein.

INTRODUCTION

The LOM process, illustrated in Figure 1, is described as follows. First, a fresh layer of material is placed on top of the stack. (The first layer is bonded to the platform via double sided carpet tape.) In the case of the standard paper process, this step is automated via a paper roll feeding mechanism; in the case of experimental materials such as ceramic tapes, this step is accomplished by hand. Next, the heated roller makes a forward and backward pass to laminate the layer to the stack. The roller height relative to the stack is maintained such that the roller compresses the top layer by approximately 0.5 mm, thus enabling lamination via pressure. After the roller is retracted, a CO_2 laser cuts the part cross sectional area, the cross hatching, and the boundary box. Any excess material outside the boundary box is removed and a new layer is placed. The process repeats until all layers have been added. Thus, a part is built from the platform up one cross section at a time.

The temperature distribution that develops in a part during LOM fabrication has a significant influence on a number of aspects of the build process. Low temperatures in the upper layers may result in poor adhesion of the individual layers causing delamination of the completed part. On the other hand, excessive buildup of heat in the body of the part may result in a general loss of structural rigidity during the build leading to excessive compression or shearing during application of pressure by the roller. Thus, a knowledge of the transient thermal behavior of the part is essential to successful building and to a more comprehensive understanding of all aspects of the LOM process.

Mathematical models for heat transfer in general tape laying processes have been developed [1, 2, 3, 4], but the majority of these are formulated for pseudo-steady-state situations. As a result, existing models can not accommodate the transient behavior that is observed during the different phases of the LOM build cycle. The mathematical model presented here has been developed to overcome this difficulty. We present the basic model structure, its capability, and some results obtained from the simulation of the build process for a simple ceramic LOM part built from layers of ceramic tape. Ceramic tapes are thin (0.25 mm), flexible sheets of ceramic powder bound together with a thermoplastic binder. The simulation of the building cycle for this ceramic part is compared to actual experimental measurements in an attempt to verify model predictions. Possible applications of model predictions for on-line control of the process are also discussed.

LOM users are fast becoming aware that an understanding of the thermal behavior of the part during the build process is crucial for the fabrication of parts with good lamination characteristics. While this is important for prototype parts made from the standard LOM paper and plastic materials, it has become extremely significant now that the fabrication of high performance, functional ceramic and composite parts is being considered [5, 6, 7, 8]. To address this concern techniques are being developed where the surface temperature of the part is measured (referred to as the part body temperature or PBT) and used in some form of feedback control to adjust roller speed and/or roller temperature [9]. The objective of the control is to obtain a PBT within a certain desirable range. The use of mathematical models with such feedback control would constitute intelligent, adaptive, on-line control which will be discussed later.

MODEL DEVELOPMENT

The thermal behavior of a LOM part is primarily determined by the following:

- heat transfer from the heated roller 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 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.

These heat transfer mechanisms determine the temperature profiles that develop in the LOM part during the various phases of the build cycle, thus the mathematical model developed must describe them as accurately as possible.

A mathematical model for a simple rectangular geometry LOM part was developed. Figure 2 indicates the geometry of the part as well as the coordinate system used for development of the mathematical model. Since all LOM parts are built as rectangular blocks, the model geometry is universally applicable to all LOM parts. At any instant during lamination, the heated roller contacts the surface only through a narrow strip in the x direction, and moves in the y-direction, applying both heat and pressure to the surface. Although the contact surface is three dimensional in nature, it is approximated by a rectangular zone, the "contact strip", that moves along the top surface on the part.

Heat conduction within the rectangular region of material is described by the following equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \bullet (k \nabla T) \tag{1}$$

It should be noted that no energy source term is included in the equation since no heat is generated or consumed within the ceramic part itself. The binder is a highly plasticized thermoplastic resin, therefore, it will not undergo a chemical reaction or melting transition. Thus, energy addition or loss from the region is handled through the boundary conditions.

Boundary conditions for the part are specified using general heat transfer coefficient (convection-type) boundary conditions. For surfaces of the part other than that in contact with the roller or the bottom in contact with the base-plate, the following expression is adopted:

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

where the subscript i indicates that the variable may take on values appropriate for any of the three major coordinate directions. The value of the heat transfer coefficient selected should be appropriate for the air flow regime around the part being fabricated.

The region of the surface in contact with the roller is handled in much the same way. An expression of the following form is used:

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

An appropriately high value for this heat transfer coefficient is used. This has the effect of forcing the surface temperature to be close to that of the roller only in the region of contact. Movement of the roller across the surface is accomplished simply by moving the position of the "contact strip" or region with high heat transfer coefficient. The position of the contact strip is calculated as a function of time from the roller speed. The width of the contact strip can be calculated from the roller diameter and the amount of surface indentation that occurs on roller contact, or measured directly.

The bottom of the fabricated part is typically attached to the LOM base plate using a layer of double-sided adhesive foam tape. This boundary is also accommodated using a heat transfer coefficient boundary condition as follows:

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

The heat transfer coefficient for the tape is an effective value that can be estimated or experimentally measured. The base plate temperature was treated as a lumped parameter that could be held constant or computed as a function of the heat flux through the bottom of the laminated part.

The heat conduction equation (Eqn. 1) together with the boundary conditions described above were solved numerically using a 3-dimensional alternating direction implicit method. This technique involves discretizing the solution region, and then solving sets of simultaneous linear equations to compute the temperature distribution after a specified time increment. The nature of the LOM build process with its relatively short period for lamination followed by longer periods of "inactivity" required that the time increment used for numerical solution be varied depending on what part of the build cycle was being simulated. A very short time increment is required during the actual lamination process because rapid temperature transients occur in the part while in contact with the moving roller. During other periods of the build cycle which involve less activity, a much larger time increment was used.

Addition of a new layer of material is accomplished by expanding the solution region in the appropriate direction, i.e. adding additional nodes to the existing mesh structure. It is assumed that the new layer of material is at ambient temperature and that the temperature distribution of the old upper surface is as calculated by the model for that time of the build cycle. The temperature discontinuity at the instant of new layer application is handled by simply adjusting the temperature of the interfacial nodes to the average of the computed old surface temperature and the temperature of the new layer.

The model developed thus has the ability to simulate the entire build process including all phases of the build cycle. Rapid temperature transients during periods of roller activity are handled by decreasing the solution time increment, and periods of relative inactivity handled by increasing the time increment. This decreases the computation time required and also the amount of temperature data that has to be interpreted or graphically presented.

MODEL PREDICTIONS AND VERIFICATION

In order to perform a build simulation, a number of parameters must be specified and input to the mathematical model. These parameters relate to the physical and thermodynamic properties of the material being used to construct the part, the LOM machine parameters (roller temperature, speed, compression, cycle times), physical dimensions of the part, and estimates of heat transfer coefficients to the surrounding air and base plate. The parameters used for the simulation results presented are summarized in Table 1. All parameters were experimentally measured [10] except the roller-to-part heat transfer coefficient which was used as a tuning parameter.

TABLE 1. Data for LOM build simulation

Material	Silicon carbide ceramic tapes
Thermal Conductivity	1.25 $Wm^{-1}K^{-1}$
Density	1.98 g cm^{-3}
Heat Capacity	1.05 $Jg^{-1}K^{-1}$
Part dimensions	121.9 mm x 53.3 mm
Layer thickness	0.25 mm
Number of layers	20
Heat trans coeff (part to air)	18 $Wm^{-2}K^{-1}$
Heat trans coeff (part to base)	14 $Wm^{-2}K^{-1}$
Air temperature	22°C
Base plate temperature	22°C
Initial temperature of material	22°C
Roller velocity	25.4 mm sec^{-1}
Roller contact strip width	9 mm
Roller temperature	91°C
Heat trans coeff (roller to part)	3300 $Wm^{-2}K^{-1}$
Build cycle time	120 seconds

A simple experiment was conducted to verify the model performance. A twenty-layer rectangular parrt was built using a standard LOM-2030 machine and the ceramic LOM process [5]. A thermocouple was placed in the center of the top surface of every fourth layer beginning with layer 0 (the double-side tape layer). Temperature from each thermocouple was recorded every 0.5 seconds through the entire 40 minute build.

Figures 3 and 4 show the transient temperature behavior for thermocouples below the 1st, 5th, 9th, 13th, and 17th layers. Figure 3 depicts experimentally measured data, whereas Figure 4 represents model predictions for a simulation of an identical LOM part build. Before being embedded, the thermocouples were held in reserve at ambient temperature as indicated by the base lines. The random instances of noise in the base line might be explained by accidental bumping of the thermocouples during layer placement. Each temperature peak represents the cycle for one layer and is comprised of several events annotated in Figure 3. The first spike is the temperature rise upon the forward roller pass. The second spike, higher than the first, is for the reverse roller pass, where the temperature is expected to be higher. The third peak can be explained by local heating from the laser cutting. The fourth feature is the abrupt drop in temperature as a new layer is added.

From these figures it can be seen that the layer temperature varies widely when it is near the top of the stack. However, apart from short term transients of near-surface layers, the temperature of the part body through the thickness is fairly uniform with only minor gradients in the z-direction.

Also of interest is the "long term" temperature of the part (in this case fluctuating between 35 and 40°C) since it can be used as a good indicator of the overall part body temperature. It is this temperature that will determine the behavior of the part during lamination.

Figure 5 shows the transient temperature behavior for the thermocouple between the foam and 1st layer of the part. Both experimental results and model predictions are shown. As can be seen there is a excellent correspondence between simulation predictions and actual experimental measurements. As the part increases in size and more layers are added between the bottom of the part and the roller, the influence of roller passes on the temperature at that location decreases.

APPLICATION TO PROCESS CONTROL

As described above, the mathematical model has the ability to predict transient temperature distributions in a part being fabricated. Of interest is the temperature distribution in the z- or depth-direction. This information gives an indication of the overall average temperature of the part body. Experimental measurements and simulations have revealed the existence of only minor z-direction gradients for the ceramic material under investigation.

Excessive buildup of heat within the body of the part can result in a loss of structural rigidity, possible compression or shearing during application of pressure by the roller, and/or binder degradation. The part body temperature is determined by the roller temperature, the roller speed, heat transfer to and from the part, and time between roller passes. This last factor may vary widely from layer to layer as a direct function of the laser cutting time.

It is desirable to maintain the part body temperature within a certain range to ensure good lamination and also to prevent loss of structural rigidity. Helysis has suggested a method to control the surface temperature of the part during certain phases of the build cycle using the roller temperature and roller speed [9]. The mathematical model described here and the depth profiles calculated can be used to relate the surface temperature to the overall part body temperature. Model predictions could thus be used to indicate how well the surface temperature represents the part body temperature and could be used to investigate alternate control strategy.

If control of the process temperature is a critical issue for the fabrication of structurally sound laminated parts, then these modeling studies suggest an alternative method to control this parameter. Roller temperature and speed are the obvious variables to manipulate to control the part body temperature, but these may be constrained by other issues, e.g. good layer adhesion, low overall build time, etc. Simulations have been conducted where the base plate temperature was modified in order to examine the effect on the part body temperature. As can be seen in Figure 6, modifying the base plate temperature seems to provide a means to control the overall part body temperature without changing roller parameters. The efficiency of this control strategy will depend on the thermal conductivity of the double sided adhesive foam tape between the bottom of the laminated part and the base plate. In order for this strategy to be feasible, heat loss to the base plate needs to be at least of the same order of magnitude as convection heat loss to the surrounding air. This is the case with the current parameters although heat loss to the air is certainly higher than heat loss through the plate. This observation was made by noting the overall part temperature which rose only about 15°C although the roller temperature was incrased 40°C. Another method for controlling part temperature is through radiative heating via heat lamps. The model described here could be used to simulate this scenario by including radiative heating boundary conditions although no attempt has been made to do so at this time.

CONCLUSIONS

A mathematical model has been developed that describes the heat transfer occurring during building of LOM parts. The model is based on 3-dimensional transient heat conduction within the solid part body together with appropriate boundary conditions. It is capable of accurate predictions of both short term transient temperatures in the part as well as overall part body temperatures. The model also has direct applicability in the area of on-line process control and will be used as the basis for the future development of temperature control strategies for LOM processing.

NOMENCLATURE

C_p	heat capacity of build material (J/g K)
h_{air}	heat transfer coefficient, part to air (W/m^2 K)
h_{roll}	heat transfer coefficient, part to roller (W/m^2 K)
h_{tape}	heat transfer coefficient, part to base plate (W/m^2 K)
k	thermal conductivity of build material (W/ m K)
k_i	thermal conductivity in any of the 3 principal coordinate directions (W/ m K)
k_z	thermal conductivity in z-direction (W/ m K)
t	time (sec)
T	temperature (°C or K)
T_{air}	temperature of air surrounding part (°C or K)
T_{bottom}	temperature of part bottom surface (°C or K)
T_{roller}	temperature of heated roller (°C or K)
$T_{surface}$	temperature of part surface (°C or K)
x	spatial coordinate

x_i	any of the 3 principal spatial coordinates
y	spatial coordinate
z	spatial coordinate
ρ	density of build material (g/cm^3)

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ACKNOWLEDGMENTS

This work was made possible by a grant from the Ohio Board of Reagents, Research Challenge Program through the University of Dayton. Use of the LOM equipment was made possible through a grant from DARPA/ONR, N00014-95-1-0059.

ILLUSTRATIONS

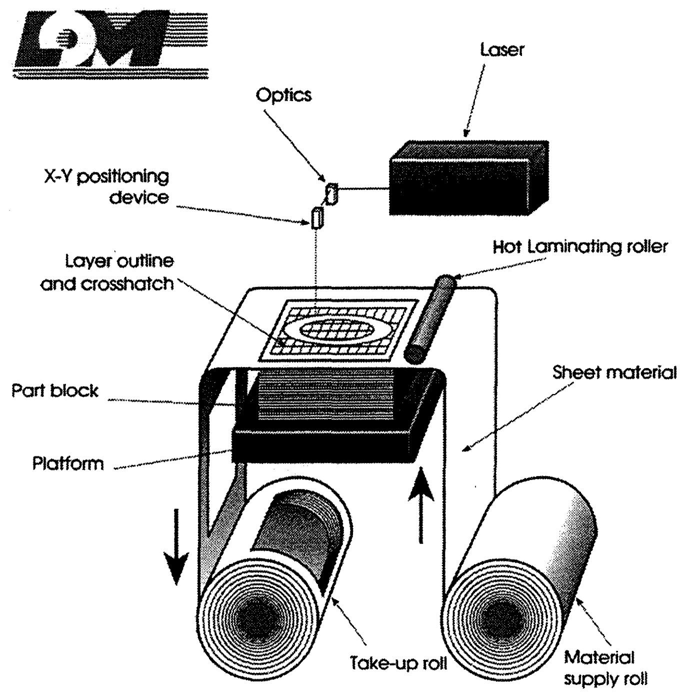

Figure 1 : schematic of the LOM process.

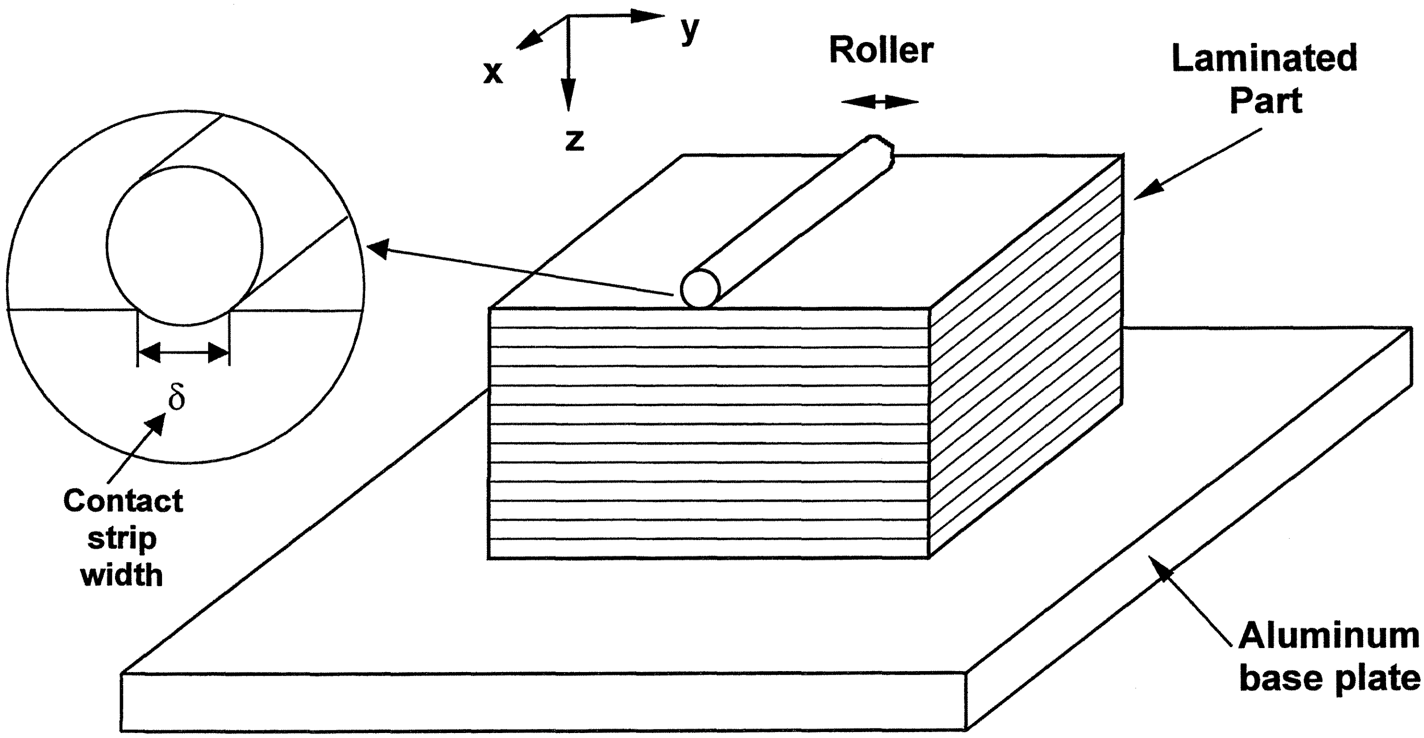

Figure 2 : geometry and coordinate system for model.

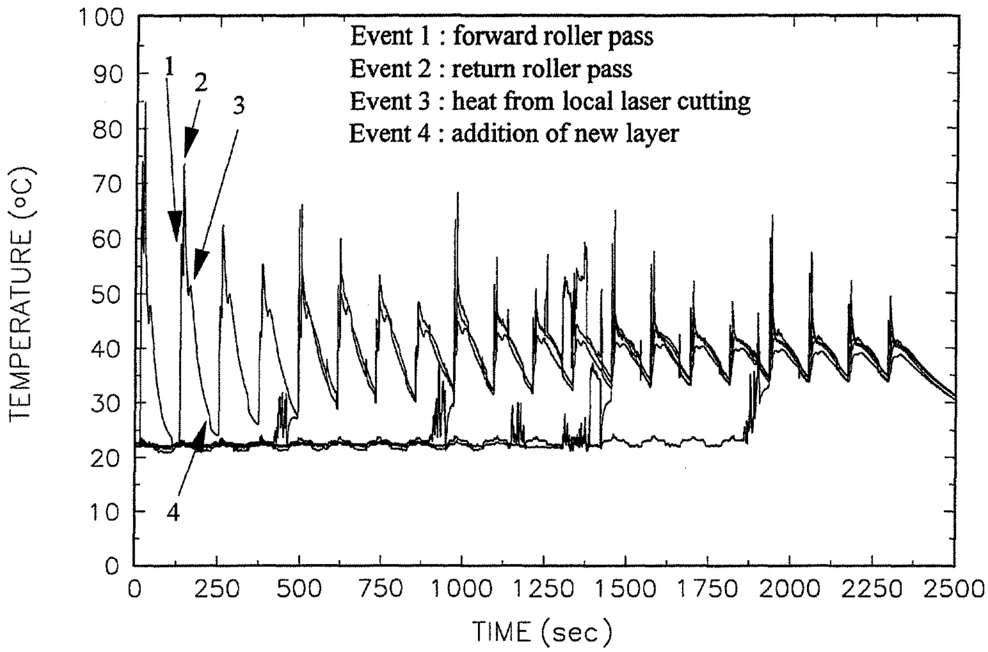

Figure 3 : measured temperature profiles from embedded thermocouples above the 0^{th}, 4^{th}, 8^{th}, 12^{th}, and 16^{th} layers in a 20 layer ceramic part built on a LOM2030.

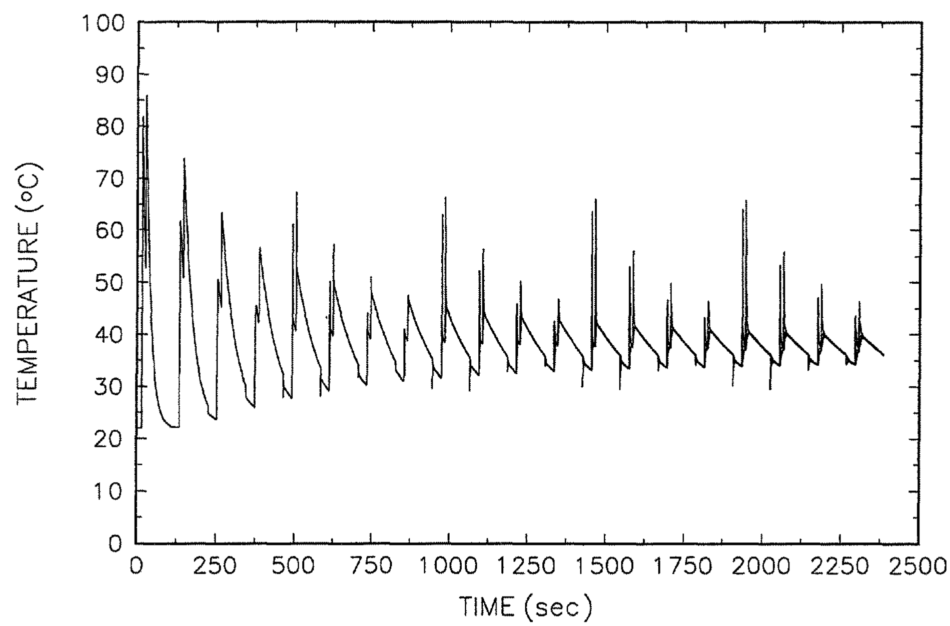

Figure 4 : predicted temperature profiles for nodes above the 0^{th}, 4^{th}, 8^{th}, 12^{th}, and 16^{th} layers in a 20 layer ceramic part.

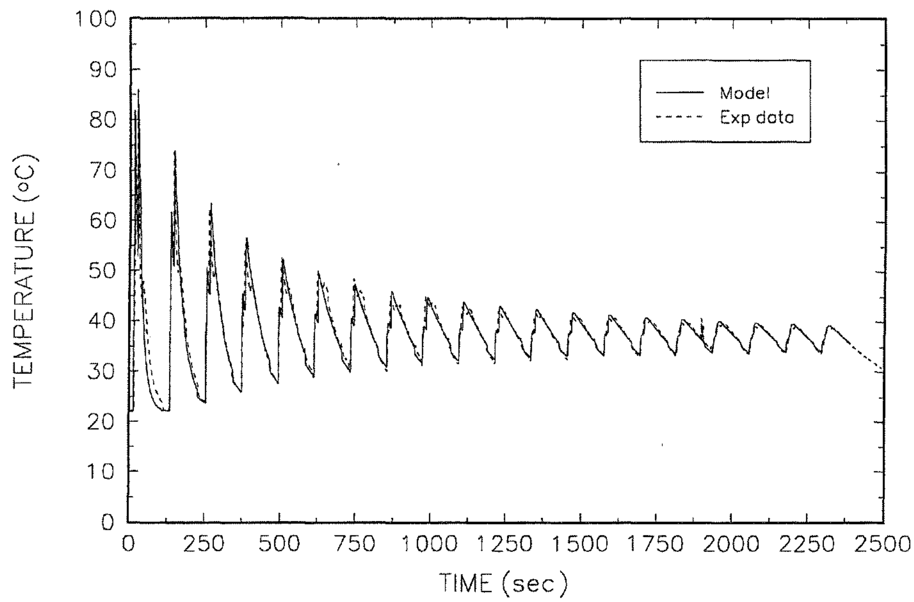

Figure 5 : measured and predicted temperature profile for thermocouple just above the 0^{th} layer (foam tape base).

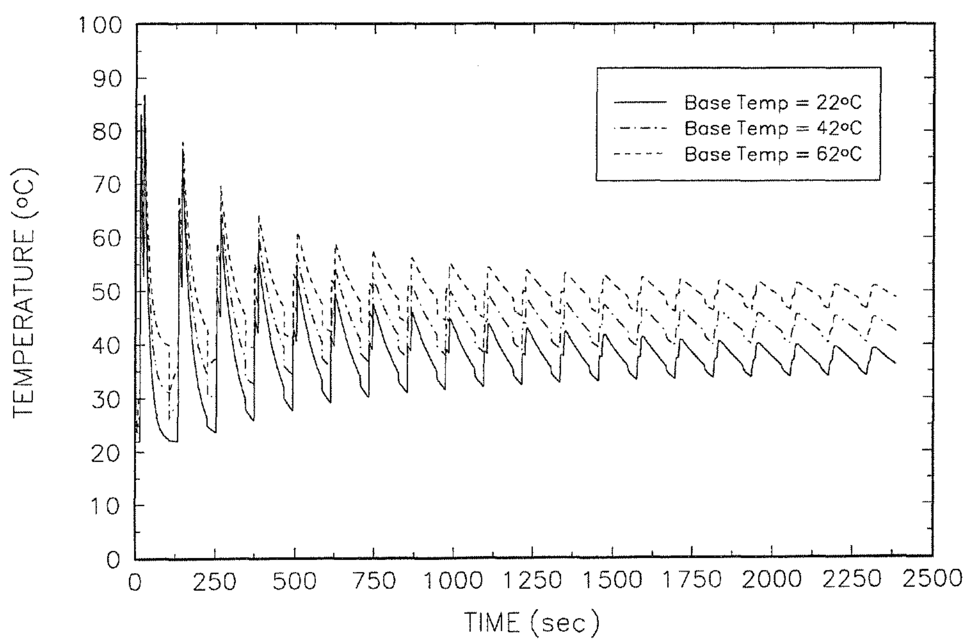

Figure 6 : predicted temperature profiles, analyzing effect of varying base plate temperature on overall part temperature.