MODEL-BASED CONTROL OF CURE DISTRIBUTION IN POLYMER COMPOSITE PARTS MADE BY LAMINATED OBJECT FABRICATION (LOF)

Donald Klosterman, Richard Chartoff, Lawrance Flach, and Eric Bryant

Rapid Prototype Development Laboratory, and
Department of Chemical and Materials Engineering
University of Dayton
300 College Park
Dayton, OH 45469-0131, USA

ABSTRACT

A mathematical heat transfer model was used to investigate process control strategies for making thermoset polymer composite materials by Laminated Object Fabrication (LOF). The temperature of the laminator was manipulated in order to control the uniformity and overall level of cure through the thickness of a 20-layer part. When the laminator temperature was held constant throughout the LOF build process, as is normally the case in practice, the model predicted that the resulting panel would have a steep cure gradient from top to bottom. This was considered to be undesirable. The model was then used in conjunction with an optimization algorithm to determine a temperature program for the laminator which would result in panels with a more desirable spatial cure profile (i.e. constant). Computer model simulations demonstrated that it should be feasible to control both the level *and* distribution of cure in thermoset composite panels layed-up with LOF by simply manipulating the laminator temperature with simple and realistic heating schedules.

INTRODUCTION

In recent years there has been a substantial R&D effort to develop materials and processing technology so that rapid prototyping (RP) can be used for the direct fabrication of functional advanced material parts. For example, it has been demonstrated that Laminated Object Manufacturing™ (LOM) [1] is suitable for the direct manufacture of prototypes made from a wide range of advanced materials, including fiber reinforced polymer matrix composites (PMC) [2], ceramic matrix composites (CMC) [3], monolithic ceramics [4, 5] including bioceramics [6, 7], and metals such as stainless steel and titanium [8]. Fully cured composites and fully dense ceramic articles could be produced in a matter of days, with minimal touch labor and no need for hard tooling.

The Laminated Object Manufacturing™ process falls within a more general category of RP techniques referred to as Laminated Object Fabrication (LOF) [9]. LOF techniques include those processes/machines developed by Kira Corp., CAM-LEM Inc., Schroff Development Corp., Javelin / Lone Peak Engineering, University of Utah / Shapemaker, Ennex Corp., Tsinghua University, and the University of Dayton (Curved LOM). The common characteristic of all these processes is the use of sheet based materials as building blocks for constructing geometrically complex objects by sequentially cutting and laminating, or laminating then cutting, layers of material. Often, a pressurized heating source is used to laminate layers.

The current study focuses on LOF process control when fabricating thermoset polymer composites (PMCs) from prepregs. Prepregs are sheets of alligned, continuous fibers (unidirectional or woven) which have been preimpregnated with an uncured resin, such as epoxy. The resin crosslinks, or “cures”, gradually with the application of heat. High performance PMCs normally require high cure temperatures (e.g. 175°C). One of the problems encountered in making PMCs with LOF is that the cure distribution in the fabricated parts (at the end of the build phase) is non-uniform. Modeling studies [10] have revealed that the lower layers of the part will be cured to a much higher degree than the upper layers of the part. This may result in problems during the subsequent processing (post-cure) of the part such as non uniform shrinkage, delamination, or microcracking.

The objective of this investigation was to determine whether control could be exerted over the cure distribution by any relatively simple means. In particular, it is desirable to have a uniform cure distribution in the part, as well as to have control over the level of cure. The investigation was conducted using a mathematical model for the LOF process and by performing a series of build simulations with optimal control strategies.

BACKGROUND - HEAT TRANSFER MODEL

Recently, a heat transfer model for LOF processes was developed (see [10] for full details). The model is based on one-dimensional heat transfer through the thickness of a stack of material while it is accumulating layers of constant thickness at regular time intervals. The model was derived from standard conductive and convective heat transfer theory and was implemented with a computer numerical solution technique.

A schematic of the LOF process is shown in Figure 1. As an example, we illustrate the construction of a twenty layer PMC panel using layers of “prepreg” comprised of continuous glass fibers in an epoxy matrix. As a case study, each prepreg layer was laminated with a weighted hot plate (pressure = 1 psi, T_{lam}=130°C) for 40 seconds, followed by a 40 second cooling cycle. The cooling cycle corresponds to the period during a normal LOF process when layer cutting is executed and/or the next layer is being transported to the stack. Thermocouples were embedded after every fourth layer (only three of these are shown in Figure 1). The prepreg stack rested on an insulating block atop a large aluminum plate. Other than the periodic application of the heating plate on the top surface of the prepreg stack, there were no heat sources.

The recorded and model-simulated time-temperature responses for various thermocouples are compared in another reference [10]. The agreement was very good. Using the model-simulated time-temperature profiles, the heat transfer model was used to predict the degree-of-cure distribution through the thickness of the stack (see Figure 2). It was found that the final cure distribution in the part was non-uniform with the lower layers being cured to a much higher

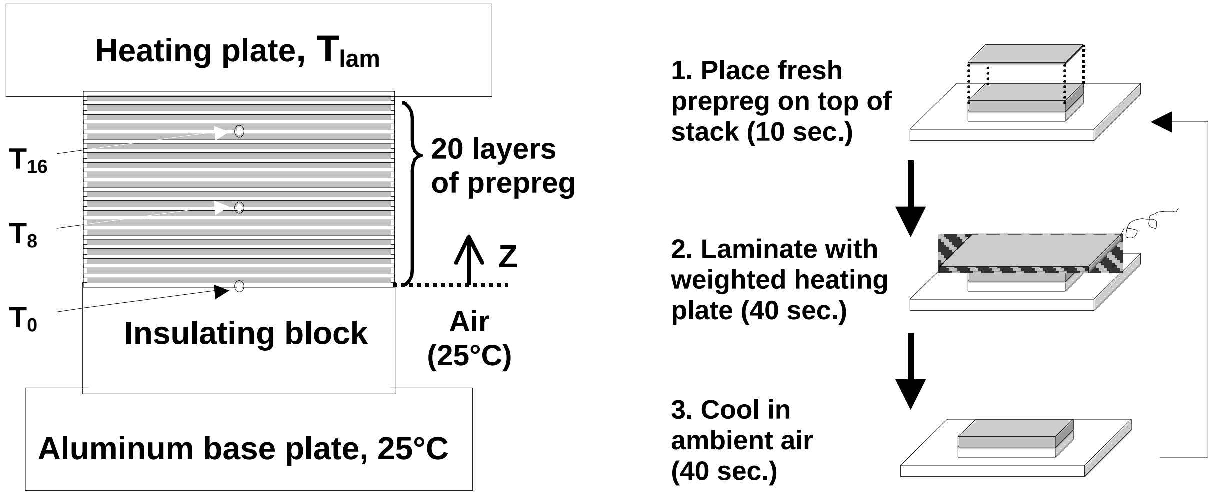


Figure 1: Manually operated, bench-top Laminated Object Fabrication process. (Left) Cross section of apparatus after all 20 layers of prepreg have been placed (**not to scale**). T_0, T_8, and T_{16} indicate placement of embedded thermocouples over indicated layer numbers. (Right) Layer-by-layer lamination sequence.

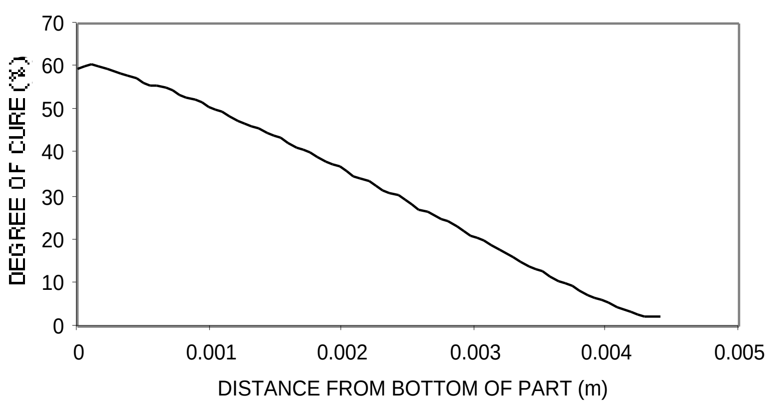


Figure 2: Model-predicted final cure distribution in a 20 layer glass fiber / epoxy part when the laminator temperature was held constant at 130^{o}C. The total thickness of the stack was 4.4 mm. Other LOF parameters are given in Figure 1.

degree than the upper layers. This result was expected due to the fact that the lower layers (those placed early during the build) were exposed to higher temperatures for a longer period of time and as a result reached more advanced levels of cure. The upper layers (those placed towards the end of the build) were only exposed to elevated temperatures for a short time and as a result were cured to a lesser degree.

THEORETICAL - OPTIMAL CONTROL STRATEGY

An optimal control strategy is one designed to manipulate a process in such a way so as to optimize some performance criterion [11]. In the present case where a specified final cure distribution is desired, the performance criterion would be related to what extent the actual final cure distribution deviates from the desired cure distribution. The optimal control objective would be to minimize this deviation by appropriate manipulation of the variables that affect the process.

Prior to development of the performance criterion for this specific situation, a suitable manipulated variable had to be selected. The manipulated variable is the process variable that is changed in order to achieve the optimal control objective. In this case the variable selected must have an impact on the final cure distribution in the part. The cure distribution in the part is most influenced by the temperature and also the time the material is exposed to elevated temperatures. Possible manipulated variables would include the temperature of the laminator, the time of contact between laminator and part, the time interval between laminations (during which cooling would occur), the temperature of the base-plate, and the temperature of the surrounding air. After consideration of these variables, it was decided that the most appropriate variable to use here would be the laminator temperature. Not only would control be easy to implement practically at some time in the future, but it also would have minimal impact on the build time.

The optimal control problem is two-fold: to manipulate the laminator temperature in order to achieve, as closely as possible, a uniform cure distribution; also to control the overall degree of cure. The degree of cure in the part is a function of position (depth only, since this has been reduced to a 1-dimensional problem) and time, and is thus represented as $\alpha(z, t)$. The final cure distribution is then $\alpha(z, t_{final})$. If the desired uniform final cure distribution is $\alpha_{desired}$, then a least squares performance criterion can be formulated as follows:

$$J = \int_0^{z_{\max}} (\alpha(z, t_{final}) - \alpha_{desired})^2 dz \quad (1)$$

The control objective would then be to minimize the performance index, *J*, by appropriate manipulation of the laminator temperature.

Since the control was based entirely on model predictions in this study (no feedback), a preprogrammed temperature schedule was used for the laminator. Four cases were investigated, as given in Table 1. In Cases #1-3, the laminator temperature is a continuous function of time. Functions of this type that are continuous and have continuous first derivatives are desirable for numerical optimization of the performance index *J*. In Case #4, the temperature was allowed to vary freely for each individual layer, although it was held constant throughout the lamination of that layer. No constraints were placed on these temperatures. In all cases, the optimal control problem thus reduces to finding the values of the parameters (e.g. *a*, *b*, and *c* in case 3) which would result in the performance index *J* being minimized.

Computer simulation allowed this problem to be solved numerically. Unconstrained optimization techniques were used to search for parameter values that minimize the performance index [12]. This task was computationally intensive, since for each set of parameter values attempted by the optimization program, a full LOF build simulation needed to be performed in order to evaluate the performance index.

Table 1: Laminator temperature profiles investigated.

Case #	Profile	Description
1	$T_{lam} = a$	Constant
2	$T_{lam} = a + bt$	Linear
3	$T_{lam} = a + bt + ct^2$	Parabolic
4	$T_{lam} = T(n)$	20-Variable Discrete

In Table 1, T_{lam} is the temperature of the laminator; t is the elapsed time since the beginning of the LOF building process (i.e. at the beginning of layer #1); a, b, and c are constants; and n is the layer number currently being laminated (n=1-20 in this study).

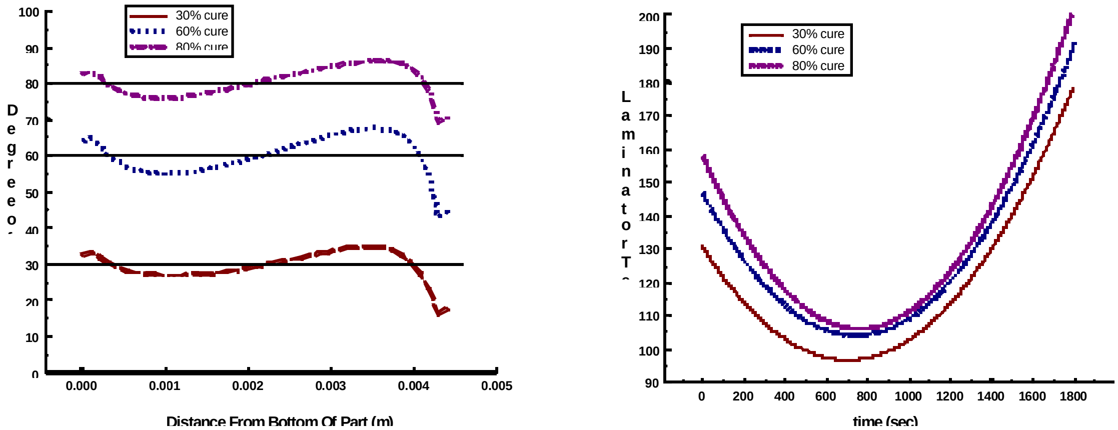
RESULTS AND DISCUSSION - OPTIMAL CONTROL OF LAMINATION

The LOF heat transfer simulation program developed by Bryant [10] was modified to allow the laminator temperature to vary as a function of time. This modified version was incorporated into an unconstrained optimization program, which was based on a quasi-Newton, gradient-based technique and developed from the algorithms of Dennis and Schnabel [12]. The result of an optimization calculation is the set of parameters (e.g., a, b, and c for case #3) that determine the best laminator temperature-time schedule for a desired cure distribution.

For the Case #1 temperature profile, the resulting cure profile for **a** = 130°C is given in Figure 2. No optimization was performed, since this case was given only as a reference point. For all the other cases given in Table 1, optimizations were performed for three different desired levels of cure: $\alpha_{desired}$ = 30%, 60%, and 80%. The results were analyzed qualitatively in two ways: how much the optimized cure profiles deviated from the desired cure levels, and whether the required laminator temperatures could realistically be achieved with normal equipment, such as an electric heating pad.

For the Case #2 temperature profile, the optimum degree of cure profiles deviated significantly from the desired levels. These results do not warrant further discussion, and are not presented herein. The results for the Case #3 temperature profile are given in Figure 5. As can be seen, the overall level of cure in the part at the end of the LOF build phase was controllable, and fairly uniform distributions were obtained. Furthermore, the optimal laminator temperature schedules are practical, with no extreme temperatures being required. As expected, higher overall levels of cure were achieved by maintaining higher temperatures in the part during the build and the corresponding use of higher laminator temperatures.

In Figure 5b, the fact that the schedules start at higher temperatures, pass through a minimum, and then terminate at high temperatures, also makes sense. Initially high temperatures are required to cure the lower layers because the part is thin, and looses energy rapidly to the base plate by conduction (even with the insulating block). During the intermediate period of the build phase, part thickness has increased, losses by conduction to the base plate are lower, and the layers remain at elevated temperature for moderately long periods; thus lower laminator temperatures can be used to achieve the desired levels of cure. Towards the end of the build, the



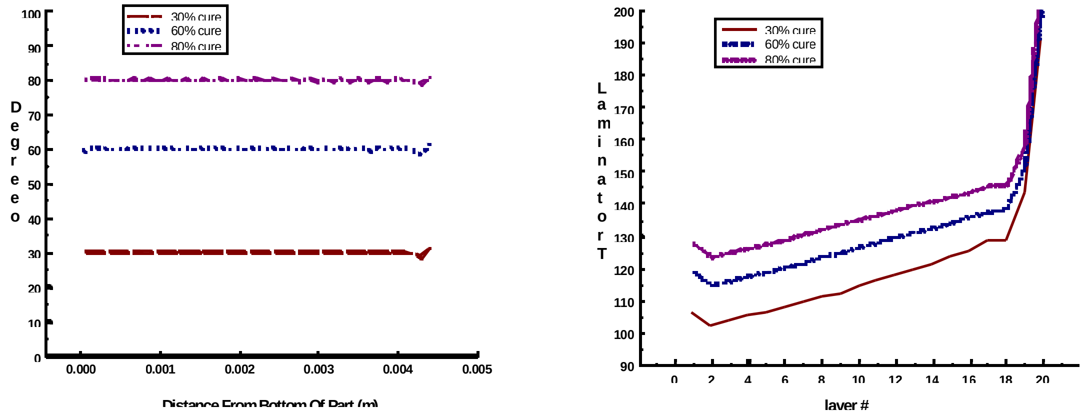
a **b**

Figure 5: optimal control of laminator for Case #3 temperature program and desired levels of cure 30%, 60%, and 80%: a) predicted final cure distributions and b) optimal laminator temperature-time schedules.

layers placed are subject to elevated temperature for a shorter period of time (it is assumed that the part is allowed to cool after completion of the build phase), and as a result higher laminator temperatures are required in order to achieve the desired level of cure for the upper layers.

The results for the Case #4 temperature profile are given in Figure 6. The optimized cure distributions deviate remarkably little from the desired levels of cure (30%, 60%, and 80%). Furthermore, the temperatures required to produce these cure profiles are feasible (Figure 6b), with the possible exception of the final few layers, in which the high temperature may scorch the material. It is interesting to note that the first layer requires a slightly higher lamination temperature due to the fact that it is cooled by contact with the base-plate, whereas the last few layers require considerably higher lamination temperatures due to the fact that these layers are maintained at elevated temperatures for a relatively short period of time (compared to the rest of the part) and are also directly cooled by convection from the surface of the part. For the rest of the part build, the laminator temperature variation with each layer is approximately linear. The small kinks towards the ends of the cure and temperature profiles may be a result of the approximate boundary conditions used and the size of the spatial discretization used for numerical solution of the model equations.

Should the laminator temperature be constrained in any way, e.g. temperatures above 200^{o}C scorch the build material, the resulting final cure profiles and values of the performance index, J, would then differ from those presented here. The value of J obtained from the constrained search would be higher and the final cure profiles less uniform. This is expected when comparing a constrained search to the equivalent free search. Another variation of control strategy that might be attempted is to vary the lamination time in addition to the laminator temperature, e.g. if the laminator temperature is constrained, then the lamination time for that layer could be varied. The introduction of constraints and additional variables (like lamination time) all add to the complexity of the optimization problem that needs to be solved.



a **b**

Figure 6: optimal control of laminator for Case #4 temperature program and desired levels of cure 30%, 60%, and 80%: a) predicted final cure distributions and b)optimal laminator temperature-time schedules.

For building parts larger than 20 layers, it is expected that the optimum temperature profile would be a simple extrapolation of the major linear region of Figure 6b. For example, for the 60% cure, the major linear region can be extrapolated to rise to approximately 170°C for a 40-layer part. However, it is likely that a sharp temperature rise will always be needed for the last few layers. As mentioned earlier, using lamination time as an additional variable may eliminate this problem by lowering the required temperature for the last few layers.

The quantitative accuracy of the results presented herein depends primarily on the accuracy of the heat transfer model, kinetic curing model, and boundary conditions. Previous experimental work [10] showed that the heat transfer model and boundary conditions are largely accurate over a wide temperature range, but the accuracy of the kinetic model for the specific polymer system under study was not as good. However, the kinetic model did produce reaction rates that are typical for autocatalytic epoxy materials in general. Thus, the optimum temperature and cure profiles developed in this study are being used only to demonstrate the possibilities in an approximately accurate manner. In any case, a more practical process control strategy would not involve predetermination of an entire cure schedule followed by its execution without feedback. It would be more beneficial to use an intelligent scheme coupling several elements: use of the current LOF model to predict temperature and degree of cure throughout the part in real time; a feed-back element consisting of simple process measurements, such as top surface temperature, which would be used to reduce LOF model deviations; and a feed-forward element in which the optimization techniques and LOF model predictions would be executed after every layer (if possible) to adjust the process conditions. This type of intelligent process control scheme has been demonstrated elsewhere with the curing of thick composite panels. [13]

SUMMARY AND CONCLUSIONS

The objective of this research was to use process simulations to investigate whether the cure distribution in polymer matrix composite parts fabricated by LOF could be controlled. The results for a glass fiber / epoxy composite indicated that use of an optimal control strategy can lead to uniform cure distributions in the parts, and that the overall degree of cure also can be controlled. These two results were accomplished by appropriate variation of the laminator temperature with time. The optimal laminator temperature-time schedules have been computed and seem to be reasonable. The methods developed and applied here are general in that they are applicable to any desired cure distribution within the part, e.g. it may be desirable to cure the interior layers of the part to a higher degree than the outer layers (a convex cure distribution). There is no reason why this could not be accomplished using a strategy similar to that described here. To achieve this, it is possible that a more complex function of time would be needed for the laminator temperature-time schedule.

ACKNOWLEDGMENTS

This work was supported by a Research Challenge Grant from the Ohio Board of Regents through the University of Dayton. The authors also wish to thank the Ohio Aerospace Institute (OAI) for Mr. Bryant's graduate research fellowship that he received as an OAI scholar.

REFERENCES

1. Laminated Object Manufacturing is a trademark of Helisys, Inc., 24015 Garnier St., Torrance, CA, 90505.
2. Klosterman, D., A. Popp, R. Chartoff, M. Agarwala, I. Fiscus, , E. Bryant, S. Cullen, M. Yeazell, "Direct Fabrication of Polymer Composite Structures with Curved LOM," *Solid Freeform Fabrication Symposium Proceedings*, University of Texas at Austin, Austin, TX, August, 1999, pp. 401-409.
3. Klosterman, D., R. Chartoff, N. Osborne, G. Graves, A. Lightman, G. Han, A. Bezeredi, S. Rodrigues, "Development of a Curved Layer LOM Process for Monolithic Ceramics and Ceramic Matrix Composites," *Rapid Prototyping Journal*, Vol. 5, Issue 2, 1999, pp.61-71.
4. Klosterman, D., R. Chartoff, N. Osborne, G. Graves, A. Lightman, G. Han, A. Bezeredi, S. Rodrigues, "Direct Fabrication of Ceramics and CMCs by Rapid Prototyping," *American Ceramic Society Bulletin*, Vol. 77, No.10, October, 1998, pp. 69-74.
5. Griffin, E.A., D.R. Mumm, and D.B. Marschall, "Rapid Prototyping of functional ceramic composites," *American Ceramic Society Bulletin*, Vol. 75, No. 7, July, 1996, pp. 65-8.
6. Steidle, C., *Automated Fabrication of Bioceramic Bone Implants Using Laminated Object Manufacturing (LOM)*, M.S. Thesis, University of Dayton, Dayton, OH, 1998.
7. Griffin, A., S. McMillin, C.Griffin, and K. Barton, "Bioceramic RP Materials for Medical Models," *Proceedings of the 7th International Conference on Rapid Prototyping*, University of Dayton and Standford University, San Francisco, March 31-April 3, 1997, pp. 355-9.
8. See Javelin Inc., 470 W. Lawndale Dr., Ste.G, Salt Lake City, Utah, 84115.
9. Lightman, A.J., D.A. Klosterman, "Laminated Object Fabrication," *Chapter 5, Handbook of Rapid Prototyping and Layered Manufacturing: Technologies, Fundamentals and Applications*, Series in Electrical and Electronic Engineering, Ed. M.C. Leu, Academic Press, *in press*.
10. Bryant, E., *Development and Verification of a Thermal Model for Curved-Layer Laminated Object Manufacturing of Polymer Matrix Composites*, M.S. Thesis, University of Dayton, Dayton, OH, 1999.
11. Sage, A.P. and C.C. White, "Optimum Systems Control", 2nd Edition, Prentice-Hall, 1977.
12. Dennis, J.E., and R.B. Schnabel, "Numerical Methods for Unconstrained Optimization and Nonlinear Equations", Prentice-Hall, 1983.
13. Buczek, M., D. Mason, C.W. Lee, A. Saunders, "Proactive Control of Curing Composites," *44th International SAMPE Symposium Proceedings*, Long Beach, CA, May 23-27, 1999.