Machine Design, Control and Performance of Automated Computer-Aided Manufacturing of Laminated Engineering Materials

Brian B. Mathewson*, Ravi Hebbar†, Sangeun Choi††,
Wyatt S. Newman†, James D. Cawley††† and Arthur H. Heuer†††

*CAM-LEM Inc., Cleveland, OH 44108.
†Dept. of Electrical, Systems, Computer Engineering and Science; ††Dept. of Mechanical and Aerospace Engineering; †††Dept. of Material Science and Engineering;
Case Western Reserve University, Cleveland, OH 44106.

Abstract

This paper describes machine design and control aspects of automating a viable CAM-LEM layered manufacturing process. The cut-then-stack sheet-based approach permits using sheet materials of different thicknesses, enabling optimization of build speed. Further, this cut-then-stack approach offers the possibility of assembling parts with multiple materials interleaved both layer-to-layer as well as within each layer. The key to realizing these prospective advantages is precise and reliable extraction and assembly of laser-cut regions from sheet feedstock. This paper presents our design approach and examples created on an automated CAM-LEM machine. It will be shown that the use of fugitive materials, automatically assembled interleaved with engineering materials, is feasible, allowing fabrication of laminated components with internal cusps and voids and improving the dimensional stability of components during post-processing. Results of this work are presented and applications of the technology are reviewed. Extensions to tangent-cut thick-sheet interleaved assemblies are described.

I. Introduction

The CAM-LEM (Computer-Aided Manufacturing of Laminated Engineering Materials) process fabricates components using layers of sheet material via a cut-then-stack approach. The CAM-LEM process was introduced in [3,12], and further developments have been presented in [1,2,4,5]. While the cut-then-stack approach involves significant material-handling challenges, a prospective advantage is that different types of materials may be interleaved both layer-to-layer as well as within each layer. Benefits of mixing multiple materials include: enabling support for overhanging structures during the build; providing support to prevent slumping of thin unsupported areas during fabrication and/or post-processing; and achieving even distribution of pressure throughout the component if pressure-aided lamination is used.

This paper describes a machine that has been optimized for fabrication of laminated components using multiple materials, including use of fugitive materials assembled among persistent materials within each build layer. It also describes how the CAM-LEM machine can take advantage of thick and thin feedstock options. Finally, we demonstrate a method for extending our cut-then-stack technique to handling thick, tangent-cut slabs.

II. The CAM-LEM Machine

CAM-LEM, Inc. has been developing a machine optimized for fabrication with multiple materials per layer. The current design supports up to five different in-feed options during automated fabrication. A picture of the machine is shown in Figure 1. At left is the feedstock carousel, which rotates one of six stacks of material into position for use in the machine. At the top center is a two-axis gripper, which performs most of the material handling in the system. The two-axis X-Y cutting table is just left of center, with the laser optics above. To the right is a waste chute, which collects waste materials cleared from the cutting table and directs them into a waste bin.

The gripper incorporates three independently controlled partitions: at left is a 100x100mm gripper for feeding sheet material from the carousel onto the cutting table. The center and right grippers are each capable of handling regions up to 150x150mm in size.

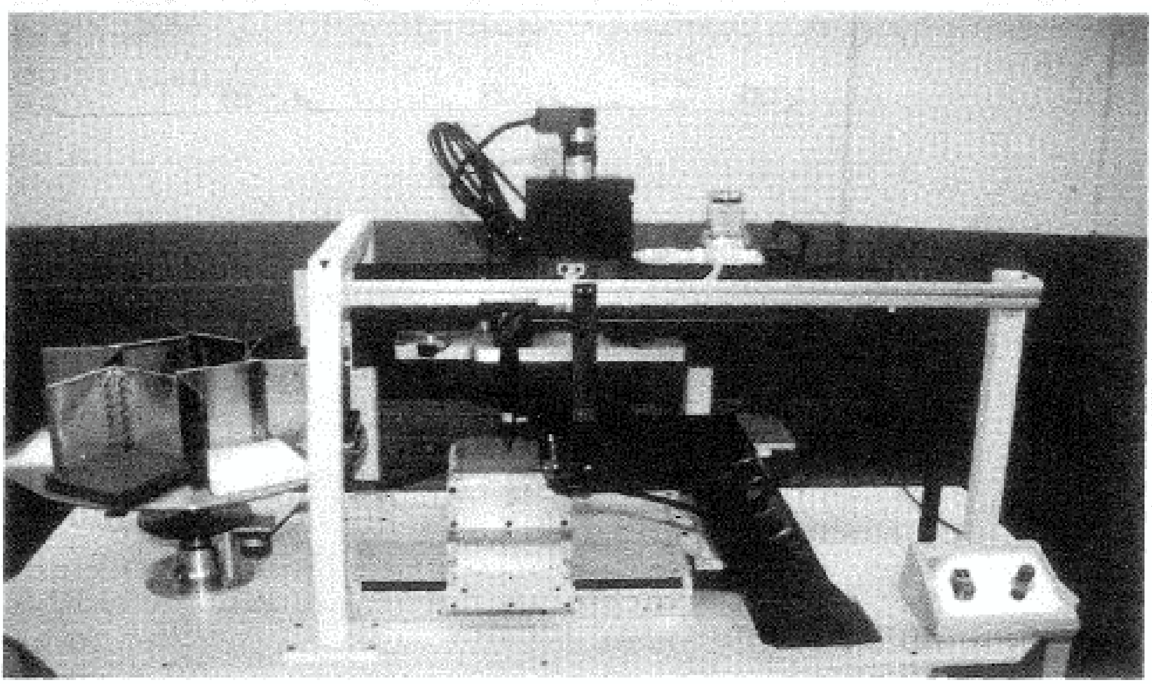

Fig 1: CAM-LEM machine

They are used to pick up and stack laser-cut materials, leaving the waste behind. This technique, described in [2], involves the use of a perforated mask through which vacuum pressure is drawn in selected areas. These areas are defined by the regions to be picked up, but may also be optimized to pick up multiple consecutive layers, depending upon the geometry of the layers.

Typically the left gripper handles the fugitive support material, and the right gripper handles the persistent component material. Because the masks required for the fugitive and persistent materials are complementary, a fugitive mask cannot be used for handling persistent material, and vice versa. The multiple-gripper design enables exploitation of multiple-use masks without the material-handling and space penalties associated with storing and retrieving masks.

The cutting table is mounted to a 200mm by 300mm X-Y positioning device. The active area of the cutting table is 150x150mm. The surface of the table has been designed to provide a high density of support, minimize reflection of the laser, collect fumes and debris due to laser-cutting, and provide vacuum to hold materials securely to the cutting table.

During multi-layer fabrication, the process must prevent any single error from compromising the entire build. One solution to this is to visually check each set of materials after it has been selectively removed from the laser-cut sheet, but before it is assembled onto the stack. We have incorporated a small CCD camera that can image either of the stacking grippers prior to assembly. At present, on operator views these images at run time to assure error-free handling prior to assembly. In the future, automated scene analysis will be performed, eliminating the need for human monitoring.

The most common errors encountered to date occur during cutting, gripping or waste clearing. During cutting, the material must be cut completely and cleanly, the material must not adhere to the cutting table (e.g., due to melting and resolidification of binder materials), and the material must be clamped to the table with sufficient vacuum suction to prevent displacement of cut regions by the laser-cutting air-jet assist. The first two issues are directly related to optimizing the cut quality by tuning laser power, cut speed, air-jet nozzle air pressure, and nozzle standoff. The last is simply a matter of replacing the cutting-table vacuum filter (which collects debris from the cutting operation) when the flow resistance becomes excessive.

During gripping, the most common errors are picking up excess material (the inclusion of waste material when picking up desired material), and leaving desired material on the cut table. The former is due to two factors: the geometry of the mask hole pattern and the porosity and mass density of the material. If mask holes are situated too close to the boundary of a part to be lifted, leakage may occur, resulting in undesired suction exerted on neighboring waste material. The second type of error, leaving behind materials meant to be picked up, is less common, and generally attributed to variations in the thickness of the mask and/or the flatness of the gripper and cutting table. The mask must make intimate contact with the desired material, or else sufficient vacuum force will not develop in order to lift and hold the piece. If the gripper and cut table surfaces are not flat or the mask material is thinner in some area, the material may not be picked up. Both these effects can vary based on the amount of vacuum and flow provided to the gripper plenums.

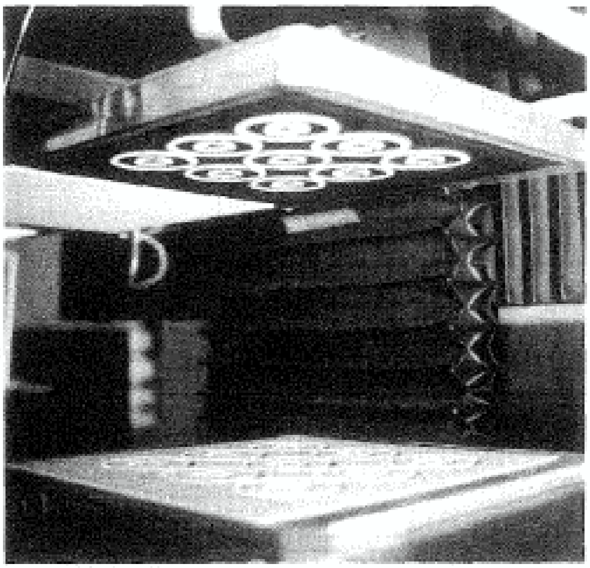

Fig 2. Fabrication of 9 parts in parallel.

Fig 2 illustrates correct operation of the gripper. In this photo, the gripper (above) has extracted a set of complex regions from the cutting table (below). The grasped parts are precisely located and ready for assembly onto the build stack.

Waste clearing from the cutting table is achieved by aiming a thin, 150mm wide region of compressed air generated using an air knife at the edge of the cutting table, then moving the table past the knife. The air lifts waste material up and into the waste chute, where it is directed down into a waste receptacle.

III. Automation of Fugitive Supports

Some means of fugitive support is present in all commercial SFF machines. The technique closest to our approach is that used in SDM [10,13], where fugitive materials are built up alternately with persistent material, producing flat surfaces at each build layer.

While there are similarities, the approach to utilizing temporary support structures in CAM-LEM is unique among SFF processes. In the CAM-LEM process, temporary supports are created from fugitive materials, laser-cut from sheet feedstock and assembled onto the build stack alternating with assembly of the desired (persistent) material. The fugitive material is later removed in a bulk post-processing operation (see [12]). Within each layer, persistent and fugitive materials are assembled interlocking, in the style of a jigsaw puzzle, resulting in a smooth, horizontal surface at each layer of the build. Based on a model's STL description, the shapes of fugitive materials are computed automatically, layer by layer, as the exclusive OR of a (default) square, continuous fugitive sheet and the computed regions of desired persistent material. Fugitive shapes thus computed are automatically cut and assembled. This operation eliminates the need for manual "weeding", employed in semi-automatic extensions of Laminated Object Manufacturing (LOM) to engineering materials [14].

An example of the fugitive build process is shown in Figures 3 through 5. In this example, 1.2mm thick paperboard was used to illustrate the process and to provide good contrast. Gray paperboard represents desired persistent material, and white paperboard emulates fugitive material.

Figure 3 shows the cut and stacked persistent material for the first build layer. Figure 4 shows the assembly after cutting and stacking the fugitive material for this layer.

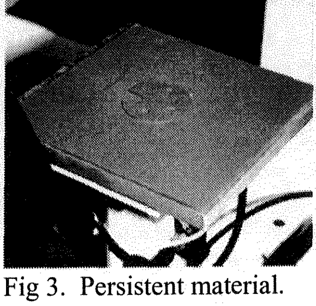

Fig 3. Persistent material.

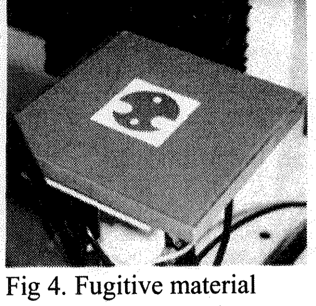

Fig 4. Fugitive material integrated with persistent.

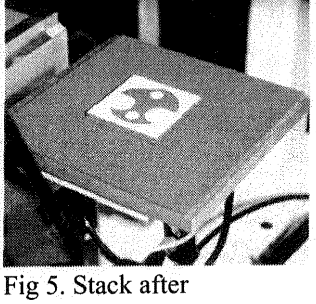

Fig 5. Stack after completion of fourth layer.

stack several layers later, with each completed layer constituting a horizontal surface of interlocking persistent and fugitive materials on which to build.

The sequence of operations to create such a stack is: 1) acquire a sheet of persistent material from the carousel and deposit it on the cutting table; 2) cut the contours of the desired persistent regions; 3) extract the desired persistent regions with the "part" gripper; 4) prepare the surface of the sub-assembly for lamination; 5) stack and laminate the persistent regions onto the build stack; 6) clear the waste material from the cutting table; 7) acquire a sheet of fugitive material from the carousel and deposit it on the cutting table; 8) cut the contours of the desired fugitive regions; 9) extract the desired fugitive regions from the cutting table using the "fugitive" gripper; 10) prepare the subassembly for bonding the next layer of fugitive to the build stack; 11) assemble and bond the fugitive regions (interlocked with the persistent regions for this layer) onto the build stack; 12) clear the waste material from the cutting table; 13) increment the z-height under consideration and repeat from step 1.

In the above sequence of operations, many of the steps can be executed in parallel. For example, assembly can be performed while waste is being cleared from the cutting table. Further, if new feedstock is provided to the cutting table before a grasped set of regions is assembled, then laser cutting can occur in parallel with preparation of the build stack for lamination to the next layer. By parallelizing operations, the build speed of the process is limited primarily by the laser cutting speed and not by the material handling requirements.

Steps 4 and 10 in the sequence above are required to provide at least temporary structure to the assembly. In previous work, we have described the importance of defect-free consolidation between layers. Our approach has been to dispense a fluid which acts as both a solvent (of the binder material) and an adhesive, then to stack the next layer and apply pressure rolling to assure intimate contact and express any surplus fluid or entrapped air. In our latest variation, we are exploring use of a heat-activated adhesive film pre-applied to the uncut feedstock. The top surface of the build stack is heated via a lamp, activating the adhesive just prior to assembly of the next layer. Early results are encouraging, indicating that this simpler lamination technique is also more robust than our previous fluid-based approch.

IV. Use of Multiple Materials

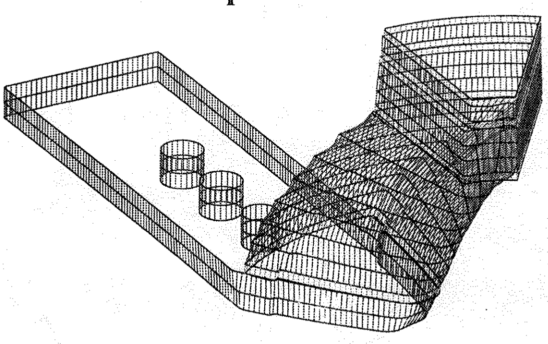

Fig 6. Model reconstructed with thick and thin layers

As shown in Fig 1, our CAM-LEM machine design is currently capable of drawing from 6 different stacks of sheet materials. As described, we allocate one stack each to gripper masks, fugitive materials, and persistent materials. The additional sites can be used for introducing additional materials. With the cut-then-stack process, CAM-LEM can vary the material constituency of an assembly layer-by-layer in the vertical direction, as well as within each layer, as we have demonstrated with fugitive materials. In addition, material variations can be more numerous if feed stacks are loaded pre-sorted, with the planned required sequence of materials made available in the order of the stack.

Another valuable option for the multiple feedstock sites is to make available multiple thicknesses of sheets. For fast build rates, it is desirable to use the maximum feasible thickness material. However, the maximum acceptable layer thickness typically varies as a function of build height. An example is shown in Fig 6. The model shown in this figure is adequately approximated with relatively thick, tangent-cut layers. However, there are crucial features, e.g. steps and flats, that must occur at specified elevations to within a tolerance smaller than the thickness of our default sheet material. By having thin sheets also available on demand, the system can build with thick layers when acceptable, yielding faster build rates, and can insert thin layers, as required, to satisfy tolerance demands. Use of thick and thin layers has been treated theoretically (see, e.g. [6,7,8,9]), but SFF processes have not been able to exploit this option to the degree achievable by the CAM-LEM system introduced here.

V. Extensions to Tangent-Cut Layers

In parallel with the CAM-LEM, Inc. machine design, researchers at Case Western Reserve University have been pursuing a CAM-LEM machine capable of building with tangent-cut thick slabs. A challenge of this extension is material handling after laser cutting. If a slab is cut with upward-facing surface normals about its edge, then the waste material can be extracted vertically without interfering with the cut part, whereas the cut part cannot be lifted without interfering with the waste. Conversely, if the cut part has all downward-facing edge normals, then it can be lifted without interfering with the waste. If, however, the part has both upward and downward-facing edge normals, then neither the waste nor the part can be extracted without interference. (A mathematically related problem is confronted by Shape Deposition Modelling in the process of depositing and machining persistent and fugitive materials to conform to the desired surface normals [13]).

To resolve this problem, we have proposed utilizing a second-pass, vertical cut through the waste material to enable extraction of part of the waste, followed by extraction of the desired cut piece. The process is illustrated in Fig 7. Figure 7a shows the top and bottom contours of a desired tangent-cut thick layer, where the bold line represents the bottom contour and the faint line represents the top contour. Figure 7b shows the result of subtracting the region enclosed by the top contour from the region enclosed by the bottom contour. The result represents the extent of the part's edge which has an upward-facing

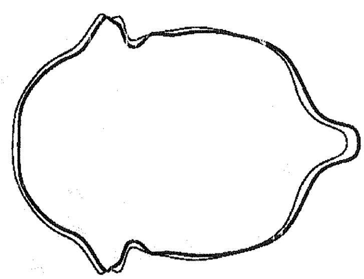

Figure 7a.

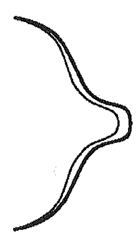

Figure 7b.

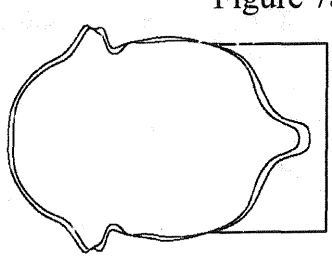

Figure 7c.

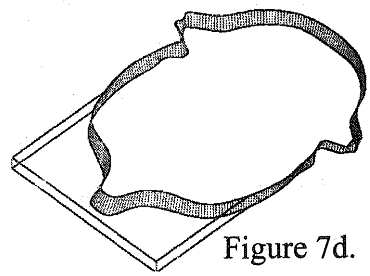

Figure 7d.

extractable by performing a second-pass cut with vertical orientation along the bold contour remaining in Fig 7b. However, in practice it was found that such a second-pass cut resulted in a chisel-point at the bottom of the waste material. For a finite-thickness kerf, this operation cut out the foundation of the waste "sliver", upon which the waste sliver would drop into the wedge-shaped kerf. Upon dropping into the kerf, the top surface of the waste was below the top surface of the rest of the sheet, and it was thus ungraspable by the vacuum gripper.

To keep the waste graspable, we have left more waste material connected to the region we wish to extract, as illustrated in Fig 7c. This additional waste material provides z-support to maintain correct elevation of the upper surface of the part, thereby enabling manipulation via our vacuum grippers.

Having segregated a part layer's edge into regions of upward and downward normals, manipulation without interference is possible, as illustrated in figures 8a through 8c. In Fig 8a, cutting a fugitive layer is illustrated. The desired part outline was laser cut, then the waste region (augmented with additional, connected waste material) was removed, the waste imitation of the desired part shape was removed, and the remaining waste material was transferred from the cutting table to the build platform. Figure 8b shows the result of operating on a sheet of the persistent material. The desired edge was cut, extra vertical cuts were added to the waste material occluding vertical extraction of the desired part, the resulting island of waste material was vertically extracted and discarded, and finally the desired tangent-cut part layer was vertically extracted and stacked within the "frame" of fugitive material originally positioned per Fig 8a.

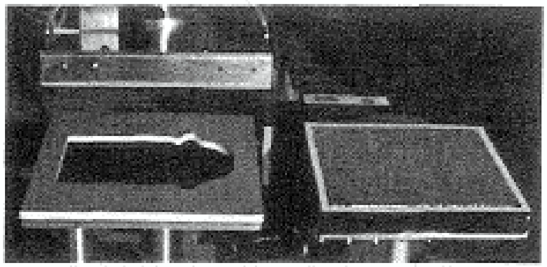

Fig 8a. Fugitive section transferred.

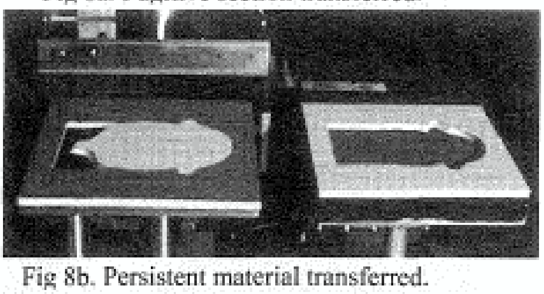

Fig 8b. Persistent material transferred.

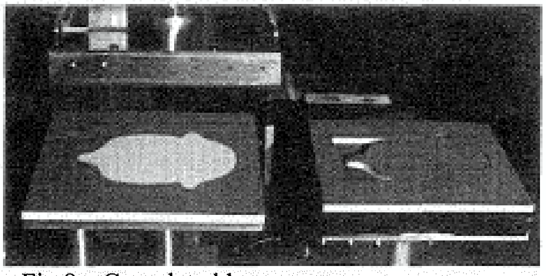

Fig 8c. Completed layer.

In Fig 8c, a sheet of fugitive material was cut, again conforming to the desired contour, augmented with the second-pass vertical cut in the waste material. The waste material lying above the upward-facing edge normal regions (and the connected additional mass of waste) was removed. This contribution to the fugitive was stacked on the assembly table by the robot, completing the construction of a fully-dense layer with embedded fugitive materials.

VI. Conclusions:

In this paper, we introduced the design of an automated process for CAM-LEM fabrication. Notable in the design is the availability of 6 feedstock options from an automatic carousel and the use of multiple grippers on a common gantry to improve material-handling efficiency. Exploitation of feedstock options enables the use of multiple sheet thickness alternatives, as well as use of fugitive support materials. The use of interleaved fugitive materials—introduced conceptually in the past—is reported here for the first time as being accomplished successfully in practice. Finally, an algorithm for extending the fugitive filler technique has been successfully demonstrated for tangent-cut part layers.

Acknowledgements:

This work was supported at CWRU in part by the National Science Foundation under grant number DMI94-20373 and in part by Sandia Laboratories, DOE, under contract AU4857. Work at CAM-LEM, Inc. was supported by an SBIR award from the Army Research Office, contract DAAL01-96-C-0061. This support is gratefully acknowledged.

References

1. Zheng, Y., and Newman, W.S., "Software Design Challenges for Computer-Aided Manufacturing of Laminated Engineering Materials", *The Sixth European Conference on Rapid Prototyping and Manufacturing*, Nottingham, UK, July 1997.
2. Newman, W.S., Mathewson, B.B., Zheng, Y., and Choi, S., "A Novel Selective-Area Gripper for Layered Assembly of Laminated Objects", *Robotics and Computer-Integrated Manufacturing*, Vol. 12, No. 4, pp. 293-302, 1996.
3. Newman, W.S., Zheng, Y., and Fong, C.C., "Trajectory Generation from CAD Models for Computer-Aided Manufacturing of Laminated Engineering Materials", *Proceedings of the 26th International Symposium on Industrial Robots*, Singapore, pp. 153-158, Oct 1995.
4. Choi, S., Hebbar, R., Zheng, Y., Newman, W.S., "CAD and Control Technologies for Computer-Aided Manufacturing of Laminated Engineering Materials", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, Texas, pp. 643-651, Aug 1997.
5. Zheng, Y., "Enabling Computational Techniques for Tangential-Building Solid Freeform Fabrication", Ph.D. Thesis, Aug 1997, Department of Electrical Engineering and Applied Physics, Case Western Reserve University.
6. Jager, P.J. de, Broek, J.J., and Vergeest, J.S.M., "Using Adaptive Ruled Layers for Rapid Prototyping: Principles and First Results", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, Texas, pp. 585-592, Aug 1997.
7. Kulkarni, P., and Dutta, D., "Adaptive Slicing of Parametrizable Algebraic Surfaces for Layered Manufacturing", *Proceedings DE-Vol. 82, Design Engineering Technical Conferences*, Volume 1, ASME, pp. 211-217, 1995.
8. Kulkarni, P., and Dutta, D., "An Accurate Slicing Procedure for Layered Manufacturing", *Computer Aided Design*, Vol. 28(9), pp. 683-697, 1996.
9. Suh, Y., and Wozny, M.J., "Adaptive Slicing of Solid Freeform Fabrication Processes", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, Texas, pp.404-411, 1994.
10. Merz, R., Prinz, F.B., Ramaswami, K., Terk, M., and Weiss, L.E., "Shape Deposition Manufacturing", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, Texas, pp. 1-8, Aug 1994.
11. Kumar., C., Jones, L., and Roscoe, L., "Support Generation for Fused Deposition Modeling", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, Texas, pp. 229-241, Aug. 1995.
12. Mathewson, B.B., Newman, W.S., Heuer, A.H., and Cawley, J.D., "Automated Fabrication of Ceramic Components from Tape-Cast Ceramic", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, Texas, pp.253-260, Aug. 1995.
13. Weiss, L., Prinz, F., Neplotnik, G., Padmanabhan, P., Schultz, L., and Merz, R., "Shape Deposition Manufacturing of Wearable Computers", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, Texas, pp. 31-38, Aug. 1996.
14. Griffin, C., Daufenbach, J., and McMillin, S., "Solid Freeform Fabrication of Functional Ceramic Components Using a Laminated Object Manufacturing Technique", *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, Texas, pp. 17-24, Aug. 1994.