

A System Approach in Extrusion-Based Multi-Material CAD

Cheng-Tiao Hsieh and Noshir A. Langrana

Department of Mechanical & Aerospace Engineering
Rutgers - The State University of New Jersey
98 Brett Road, Piscataway, NJ 08854

Abstract

For extrusion based multi-material Layered Manufacturing (LM) processes, a CAD system has been developed for the Fused Deposition of Multiple Ceramics (FDMC) hardware. This closed loop CAD system includes solid model design & multi-material slicing, multi-material toolpath generation and virtual simulation modules. Intelligent features and an adaptive roadwidth optimum toolpath generation algorithm compute void sizes & their location and generate a void free toolpath [1][2]. The present study focuses on a comprehensive approach, which includes a format that contains the information on the geometry of the multi-material components, the build materials and the necessary fabrication process information. Multi-CAD utilizes computer graphics techniques to visualize the fabricated part. The slicing algorithm is utilized to create multi-material contours, which then are integrated into our previously developed intelligent tool-path system.

Introduction

As we know, there are many advantages to introducing layered manufacturing systems into current manufacturing environments. These include the capability to fabricate parts with complicated geometry, shorter process time and the elimination of assembly of components. The above advantages dramatically reform the economics of current industry to satisfy the needs of the competitive market. Unfortunately, a big drawback of most LM systems is that constraints in handling multi-material products. A major reason is that their computer models do not contain material information. Without material information, LM systems are unable to distinguish the multi-material models and always treat them as single-material models. To overcome this drawback, developing a multi-CAD system to recognize multi-material models is needed. The developments in fabricating multi-material parts include two parts, the development of multi-material LM systems and the development of multi-material CAD system. Examples of the recent developments include the Shape Deposition Manufacturing (SDM) developed at Stanford University and Fused Deposition of Multiple Ceramics (FDMC) built at Rutgers University. Of multi-CAD systems, Vinod Kumar proposed an approach to modeling multi-material objects in 1997 [3]. Dan Qiu presented a multi-material tool path generation in 2000 [4][5].

1. The Configuration of Multi-CAD System

Figure 1 shows the configuration of our multi-material CAD system. This multi-CAD system is based on the Fused Deposition Method (FDM) - an extrusion based LM system. The FDM system includes a liquefier to heat up the filaments and a two-dimension table to drive the liquefier along the tool path to deposit the molten filaments layer by layer to build up the part.

The multi-CAD system requires component STL models from available CAD modelers such as I-DEAS, Pro/E and AutoDesk. The CAD systems allow us to position the STL models in the

desired locations. After all STLs are made, we use Multi-CAD to indicate the building material for each STL model separately and then assemble them into a new multi-material model [1][2]. This new multi-material model includes not only geometry information, but material information as well. The above information enables the multi-CAD system to display multi-material models on the screen and to proceed with LM multi-material fabrication processes (slicing process and tool path generation process). Because the LM fabrication processes applied in the Multi-CAD system all are based on a multi-material model, the model slicer and tool path generator must be able to recognize the multi-material model to accomplish their tasks. The model slicer slices a multi-material model into a slice model (a set of contours) and then the tool path generator executes its job according to the slice model. The tool path generator is designed to create void free FDM parts.

In previous studies at Rutgers, we had found numerous defects in fabricating multi-material FDM parts [1][2][4]. To eliminate the defects, we have introduced a material library into our Multi-CAD system [5]. The material library stores the control parameters for all of the building materials; the parameters guide the LM system to avoid the defects. Greater detail on the material library will be addressed later in this paper.

The multi-CAD system also provides fabrication simulation to make virtual FDM parts. It applies computer graphics technology to assist us in evaluating the FDM parts (especially the insides of the parts). This road shape simulator also links with the road shape library, which assists us in selecting the right shape of nozzle to fabricate void free parts.

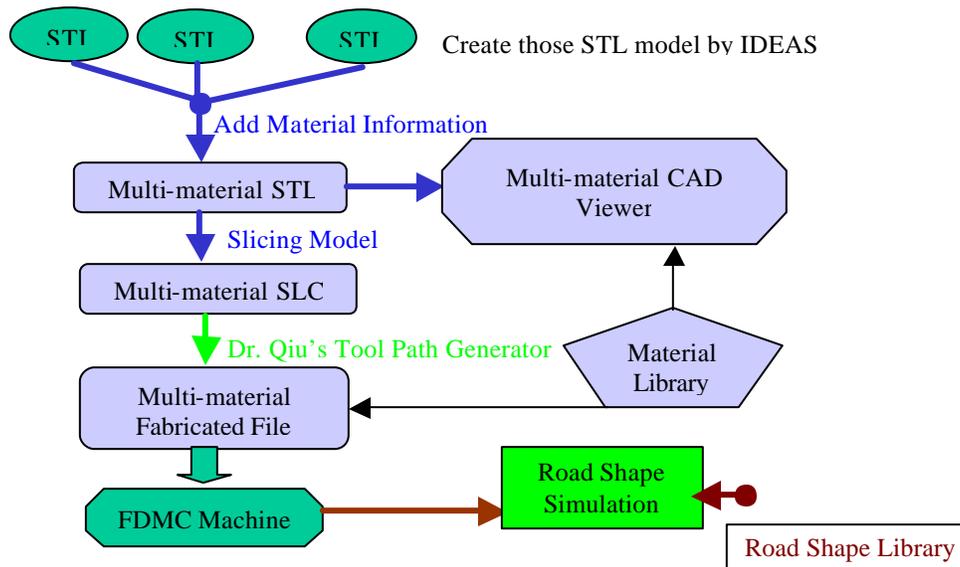


Figure 1 The Configuration of Multi-CAD System

2. Assembly STLs to Multi-material Model:

STL is the most common solid model format used in the LM industry. For this reason, we chose it for the components of the multi-material model. It describes its surface by a set of triangular facets; it is also known as a surface solid model. The format includes a file-name and a collection of triangular facets. Every facet is defined by a normal vector and three vertices. The normal

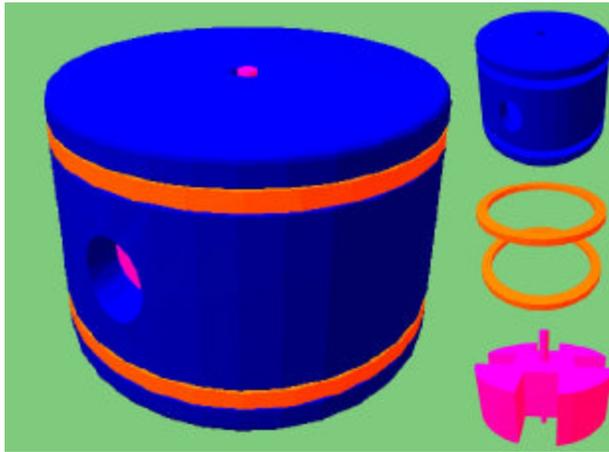
vector, a normalized vector, is used to indicate the outward direction of the surface. The most important task of this vector is to allow the computer to distinguish between the inside and outside of the solid model. In addition, it offers instant data for lighting effects in computer visualization. The vertex coordinates of the triangular facets play an important role in fabricating an accurate part by determining the shape and scale of the model.

2.1 Prepare STLs by Commercial Modelers:

STL contains only geometry information; this information is inadequate for supporting our multi-CAD system. The issues to be resolved in order to accomplish the preparation of STLs for a multi-material model are summarized as follows:

(1) Scale or Unit Issue:

Our goal is to fabricate an accurate multi-material part, so the scale and unit of the model is very important to us. Unfortunately, STL does not include information on its unit system. To handle this disadvantage of STL, it is necessary to know the type of unit system used in commercial modelers since they are the original sources of the STLs. In our investigation, we have found that STLs converted from IDEAS are based on the INCH system. This means that the scale of such STLs is 1:1 with the INCH system of IDEAS. Once the STL is generated, it can be treated as a standard and then scaled to other unit systems.



(a)

```

solid MATERIAL1
facet normal VX VY VZ
  outer loop
    vertex X Y Z
    vertex X Y Z
    vertex X Y Z
  endloop
endfacet
:
:
endsolid MATERIAL1
solid MATERIAL2
facet normal VX VY VZ
  outer loop
    vertex X Y Z
    vertex X Y Z
    vertex X Y Z
  endloop
endfacet
:
:
endsolid MATERIAL2
:
:

```

(b)

Figure 2 (a) Solid Multi-material Model (b) Multi-material STL Format

(2) Assembly Issue:

Since it is required that the componential STLs are created independently, we have to carefully create each component in its exact position to provide for perfect matches during the assembly process. Fortunately, most commercial modelers are good at translation and rotation. Using these functions, the STLs can be easily located to the desired positions and then assembled to the multi-material model. Our multi-CAD system does not have the

function to optimize the building orientation, so the building orientation should also be considered when componential STLs are created.

2.2 Multi-material Model Format:

Our multi-material model is a set of STLs, as shown on Figure 2(a). The title name of STL following the word “solid” is redundant data, so we replaced it with a material index (used to indicate the building material of the STL). The material index is a standard in our material library. Users continuously load the STLs and define their building materials by the multi-CAD system. Multi-CAD will automatically generate the multi-material model. The format of multi-material models is shown in Figure 2(b). It contains a material index, normal vectors of the facets, and the coordinates of the vertices.

For visualization, we treat the material index as a material color index because we would like to distinguish materials by color. In order to visualize multi-material models, it is necessary to store all OpenGL color parameters of the available FDM building materials in the material library. The material index in the multi-material format will guide the multi-CAD system to find its color parameters from the material library. The color parameters are then applied in OpenGL view functions to display the models appropriately.

2.3 Efficient Data Structure:

Many researchers have investigated the use of efficient data structures to speed up the slicing process [6][7][8]. Including topology information in data structures is one such method [9]. Based on this technique, the data structure shown in Figure 3 was developed to fulfill our need. Our data structure includes two sets of data: one set stores the coordinates of all vertices while the other set stores the instant data containing the topology (facet, the minimum points and maximum points in XYZ directions of componential models, normal vectors of facets, and the number of facets of componential models). The instant data were calculated from original STL data and stored in computer memory to await calling from our processes. The processes can immediately obtain them from computer memory without re-calculation, dramatically speeding up execution. The instant data offers good advantage, but unfortunately we cannot extend them without limit. Huge instant data will occupy enough computer memory to affect the ability of Multi-CAD systems to handle large models. In order to avoid this problem, we need to determine the optimal size of instant data.

Because the capability to handle large-sized models is one of our goals, we introduced the “INDEX” algorithm to reduce redundant instant data and save memory. The “INDEX” algorithm uses a 2-dimension integer variable type matrix to indicate the connection of facets and vertices, *facets[#facets][4]* storing three vertex indexes of the facet and one register for the slicing process. All of the vertex coordinates will be 2-dimension float variable matrix, *points[#points][3]* storing a point index and 3-D coordinates. As we know, the size of the variable *Integer* is 16 bits, and the size of variable *float* is 32 bits. The size of *integer* is just half that of *float*, so we can eliminate redundant instant data and shrink the size of instant data at same time.

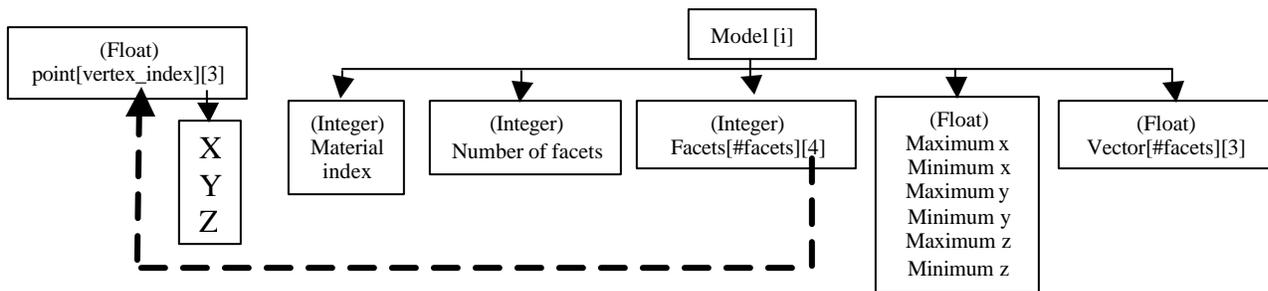


Figure 3 Data Structure Used in Multi-CAD System

3. A Slicing Process for Multi-material Model:

The slicing process includes three stages: search for appropriate edge to begin slicing, generating intersection points, and determining slicing direction [10]. The key to slicing multi-material models is to slice componential STLs independently and to indicate their building material on their contours at same time. In this study, the slice thickness is kept constant. The details of slicing a multi-material model are shown in the following chart, Figure 4.

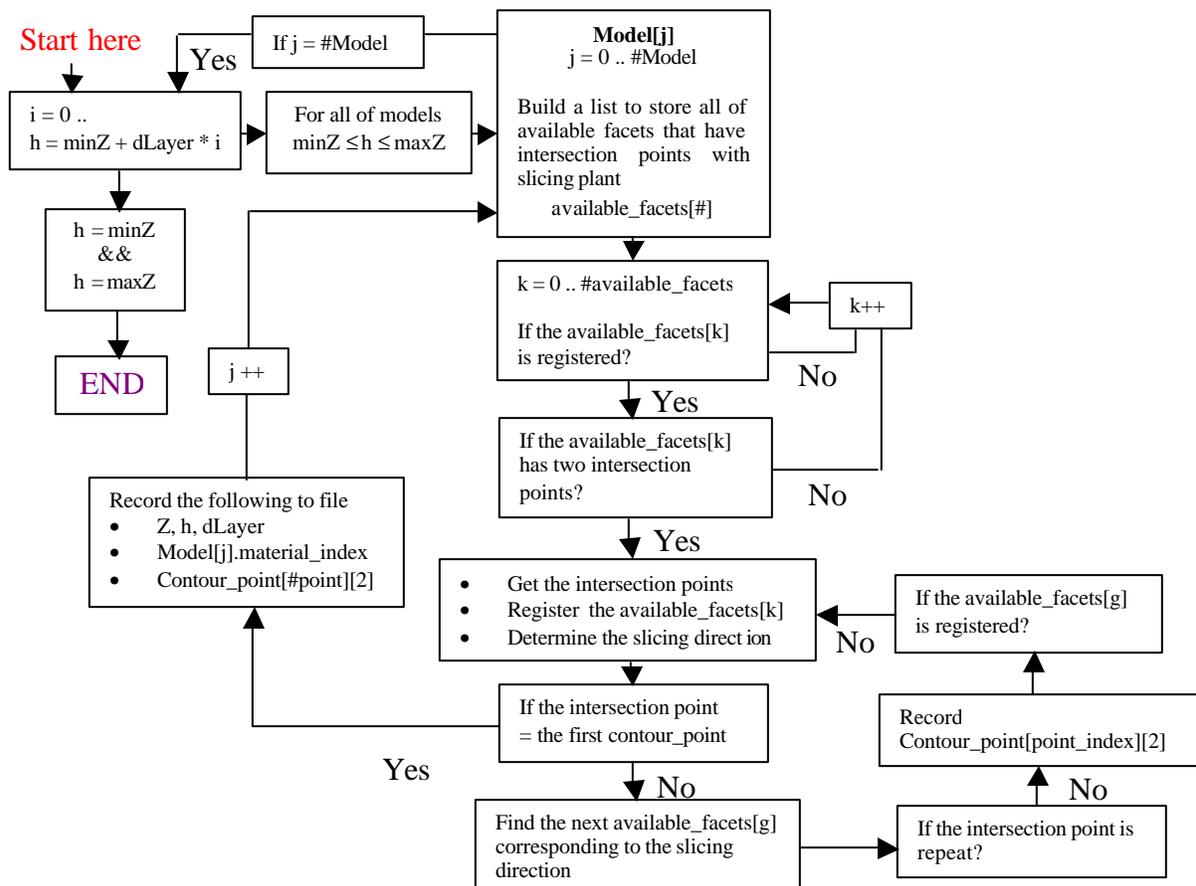


Figure 4 The Flow Chart of Multi-material Slicing Process

The sliced model visualization is the same as that of a solid model Figure 2, the material index guides the multi-CAD system to its OpenGL color parameters in material library and contours are displayed appropriately as shown in Figure 5(a). Since there is no standard format for slice files, the format of our multi-material slice file is similar to the Stratasys SSL file format shown in Figure 5 (b) [11].

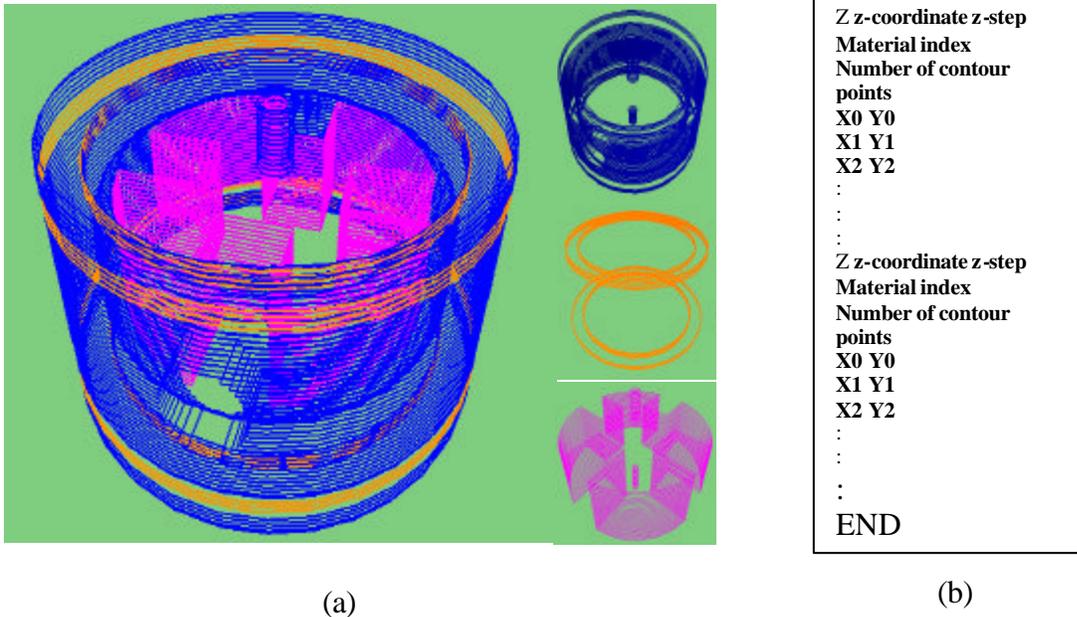


Figure 5 (a) Multi-material Contour Model (b) Multi-material Contour Format

4. Tool Path Generation:

Because our model is a multi-material model, it may include many contours with various materials at the same level. In addition, contours can also be classified as outside and inside contours. It is necessary to classify such contours group by group to allow the tool path generator to correctly process its task. Contour orientation is the way to distinguish between outside and inside contours. The orientation of outside contours is counterclockwise, and that of inside contours is clockwise. The multi-CAD slicer slices the multi-material model component by component, so contours with various materials can be easily classified. At this stage, the previously developed intelligent tool path generator [4] can be used to create defect free virtual parts.

5. The Generation of FDM Fabricated File:

The process to generate a FDM fabricated file is to put the tool path and hardware control parameters together. The hard control parameters include start flow, main flow, head speed, liquefier temperature, and the size and shape of nozzle. These control parameters are sensitive to the building material. In other words, the setups of control parameters will be different if the

building material is changed. To address this need, we introduced the material library into our multi-CAD system. It contains all of the control parameters for each building material. The multi-CAD system will choose the appropriate control parameters from the material library according to the material index of the multi-material model. Once the control parameters are defined, the multi-CAD follows the format of the fabricated file shown in Figure 6 to put them together with the tool path. The process is repeated for each building material in the multi-material model to complete the fabricated file for the multi-material model.

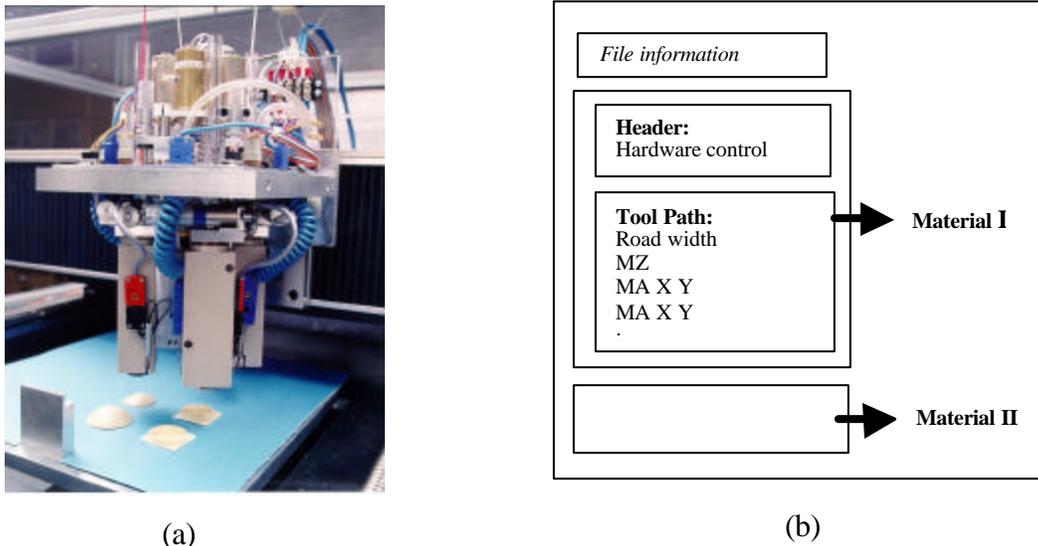


Figure 6 (a) Fused Deposition of Multiple Ceramics (FDMC)
 (b) The Format of Multi-material Fabricated File

6. Road Shape Simulation:

Based on our experimental study at Rutgers, we know that the size and the shape of the deposited roads are dependent on the material and the processing parameters. The purpose of building the road shape simulator shown on Figure 7 is to simulate the fabrication process of FDM (Fused Deposition Manufacturing). The simulation program using computer graphics technology allows us to detect errors and to remove the errors from the FDM fabrication process easily and quickly. Generating a virtual FDM part by the simulator requires little time; it is much faster than the time to generate a physical FDM part. This methodology reduces product cycle time and enhances the quality of products.

Conclusions

In this paper, we have demonstrated a systematic approach to fabricating multi-material products by a FDM system. The approach includes a new multi-material model, a multi-material slicing process, multi-material tool path generation, and multi-material fabricated file generation. In addition, we have also introduced a virtual manufacturing simulator to remove errors from the fabrication process. This system has demonstrated great benefit by shortening the product cycle and reducing cost.

Acknowledgement

The research reported here has been performed towards the partial fulfillment of requirements for PhD thesis of the first author. The authors would like to thanks the Office of Naval Research (ONR) Drs. R. Wachters, G. Spanos and K. Cooper for financial support under #N00014-96-1-1175 Multidisciplinary Research Program of Univ. Research Initiative (MURI).

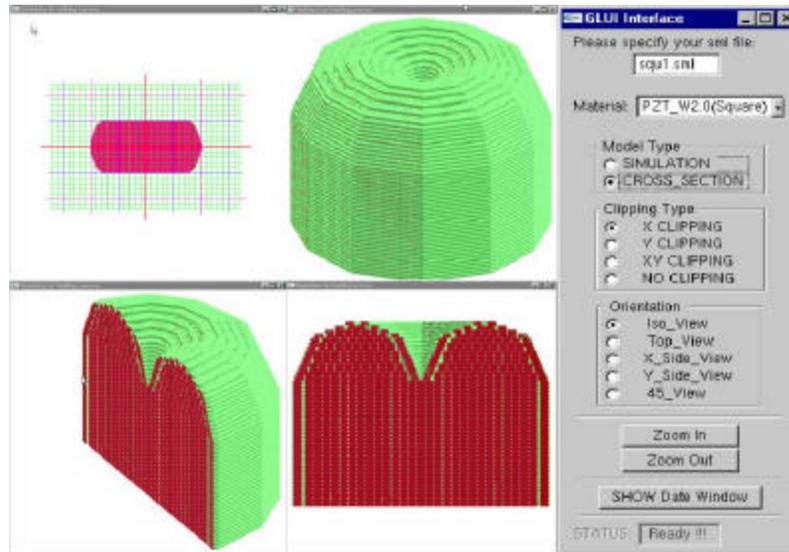


Figure 7 Road Shape

References

1. Langrana, N.A., Qiu, D. et al. (2000). "Virtual simulation and video microscopy for fused deposition method", *Journal of Materials & Design*, **21**: 75-82.
2. Langrana, N.A., Qiu, D. et al. (2000). "Design, Simulation and SFF Techniques for Functional Components", in the CD-ROM Proceedings of ASME 2000 Design Engineering Technical Conferences, DETCC00/MECH-14205, Baltimore, MD.
3. Kumar, V. and Dutta, D. (1997). "An Approach to Modeling Multi-Material Objects", pages 336-345, in the Proceedings of the 4th Symposium on Solid Modeling and Applications. Atlanta, GA.
4. Qiu, D. and Langrana, N.A., (2001), "Void elimination algorithm for extrusion based layered manufacturing", in the CD-ROM Proceedings of ASME 2001 Design Engineering Technical Conferences, DETC2001/DFM-21197, Pittsburgh, PA.
5. Langrana, N.A., Qiu, D. et al, (2000) "Design tools for Multi-material Layered Manufacturing System", in the Proceedings of 24th Annual Cocoa Beach Conference and Exposition, The American Ceramic Society.
6. Kulkarni, P. and Dutta, D. (1996). "An accurate slicing procedure for layered manufacturing." *Computer-Aided Design* **28**(9): 683-697.
7. Rock, S.J. and Wozny, M.J., (1991). "Utilizing topological information to increase scan vector generation efficiency", Proceedings of the Solid Freeform Fabrication Symposium, University of Texas at Austin.
8. Rock, S.J. and Wozny, M.J., (1992). "Generating Topological Information from a Bucket of Facets", Proceedings of the Solid Freeform Fabrication Symposium.

9. Tata, K., Fadel, M.G., et al. (1998). "Efficient slicing for layered manufacturing." *Rapid Prototyping Journal*, **4**(4): 151 - 167.
10. Sabourin, E., Houser, S.A., et al. (1996). "Adaptive slicing using stepwise uniform refinement." *Rapid Prototyping Journal*, **2**(4): 20 - 26.
11. <http://www.Stratasys.com> (personal communications)