

# Issues in Process Planning for Laser Chemical Vapor Deposition

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## ABSTRACT

Laser Chemical Vapor Deposition (LCVD) is a promising rapid prototyping and manufacturing process that deposits metals and ceramics by local heating of a substrate with a laser. Even though many LCVD process planning characteristics are shared with those of more common Solid Freeform Fabrication (SFF) technologies, LCVD process planning requires new efforts due to its unique characteristics. Unlike a conventional Layered Manufacturing (LM) technology that only builds a planar layer, LCVD can build conformal layers (conform to non-planar substrates), thin walls, and fibers (rod-shape). This paper explores process planning issues for LCVD in the context of its unique characteristics.

## 1. INTRODUCTION

The Laser Chemical Vapor Deposition (LCVD) is a promising rapid prototyping and manufacturing process. This technology has proven to deposit various materials such as C, B, Si, SiC, Si<sub>3</sub>N<sub>4</sub>, Al<sub>2</sub>O<sub>3</sub>, TiN, Mo, W, Co, TiSi<sub>2</sub>, Ni, W, Fe, and so on [1, 2, 3, 4]. During the process, the deposit is made one atom at a time so that the deposited material has high purity, low porosity, and a high degree of crystallinity, which leads to superior mechanical and thermal properties [5]. Additionally, LCVD can deposit multiple materials on the same part by just changing the reactive gases. Also, there is no difficulty to fabricate a complex geometry as like other common SFF technologies such as Selective Laser Sintering (SLS), 3D-Printing, Stereolithography (SLA), Fused Deposition Modeling (FDM), Multi-Jet Modeling (TJM), and so on. Unlike other conventional processes that only build a planar layer on the top of another planar layer, LCVD can make some unique deposits such as conformal layers (conform to non-planar substrates), thin walls, and fibers (rod-shape). Maxwell et al. even successfully fabricated helical micro-springs by using stage movements [6]. The unique deposit features can lead to a whole different direction in process planning. This paper starts by presenting unique deposit morphologies and explores related process planning issues.

## 2. UNIQUE DEPOSIT MORPHOLOGY IN LCVD

The LCVD system designed at Georgia Tech started operation in August 1999. Figure 1 shows the overall photo of Georgia Tech's LCVD system while Figure 2 shows the cross-section of build chamber. In the system, the laser defines the heated reaction zone and the gas-jet nozzle supplies the reagent gases at the spot to make desired deposits [5]. To date, the Georgia Tech's

LCVD system has showed the capability of fabricating four primitive shapes as shown in Figure 3: lines, curves, fibers, and inclined fibers. Real deposits will not be exactly rectangles or cylinders but for better illustration purpose, they are assumed to be like the shapes shown in Figure 3. Fibers and inclined fibers are unique primitives that only LCVD can fabricate amongst SFF technologies.

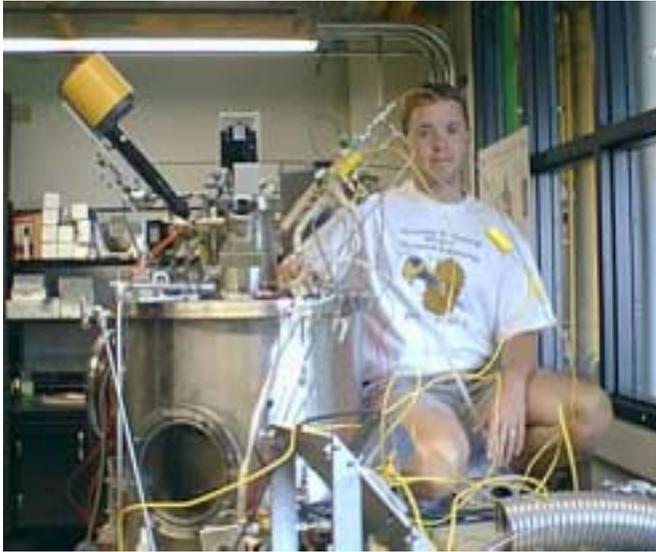


Figure 1. Georgia Tech's LCVD system

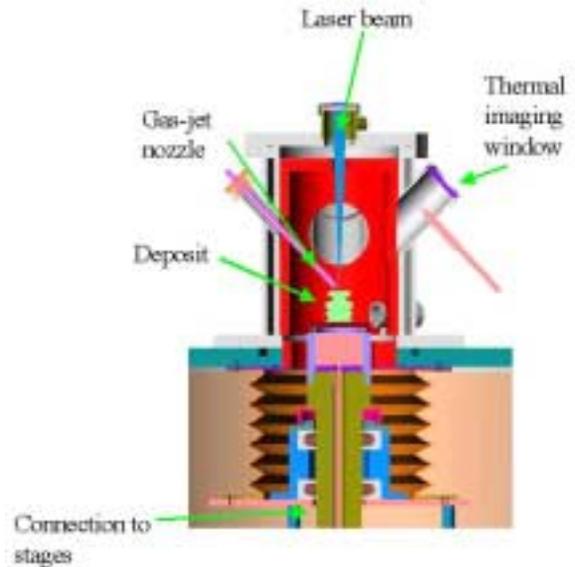


Figure 2. Cross-section of build chamber

Conventional SFF processes only build a horizontal planar layer using lines or curves. However, LCVD can generate not only horizontal planes but also vertical walls using available primitives. Those vertical walls can be either straight or curved, as shown in Figure 4, and can be composed of any of the primitives from Figure 3. In Figure 4, each one is considered to be a layer, where multiple layers make a final 3D part.

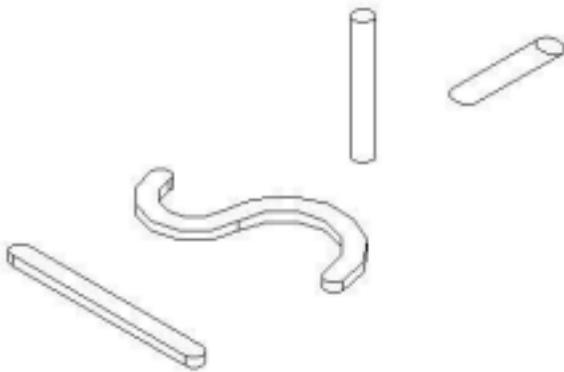


Figure 3. Four primitives generated by LCVD processes: line, curve, fiber, and inclined fiber (from the left)

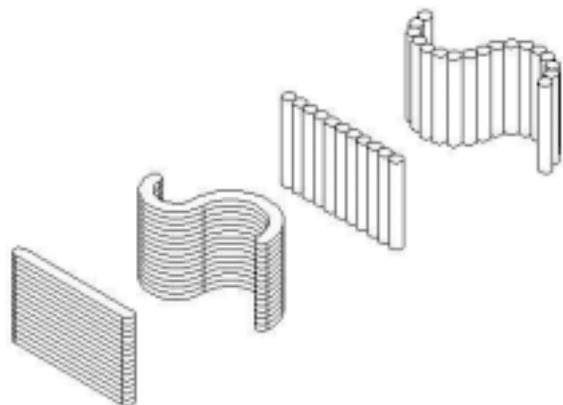


Figure 4. Four vertical layers using different primitives

Another unique deposit characteristic in LCVD is to make conformal deposits on concave or convex substrates, resulting in conformal layers that conform to non-planar substrates. This conformal layer idea is illustrated in Figure 5. While conventional SFF processes always generate planar layers, LCVD could generate conformal layers parallel to the non-planar substrate as shown in the figure. This characteristic is quite useful for building parts that have conformal shapes.



Figure 5. Comparison between conformal layers and planar layers

### 3. PROCESS PLANNING IN LCVD

As mentioned earlier, many LCVD process planning characteristics are shared with those of more common Solid Freeform Fabrication (SFF) technologies [7, 8, 9, 10, 11]. However, due to unique deposit morphology, LCVD process planning needs to address some newer issues that could be added to conventional process planning steps.

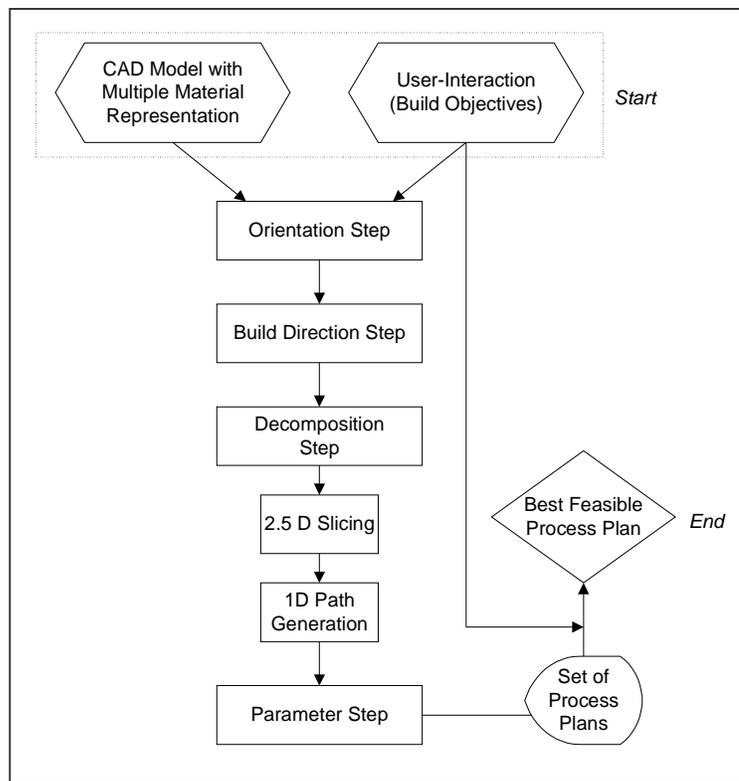


Figure 6. The overview schematic of LCVD process planning

The overview picture of the process planning steps in LCVD is shown in Figure 6. Most of these steps are common issues of SFF technologies [7, 8, 9, 10, 11]. In the figure, the 2.5D slicing refers to layer slicing and 1D path generation refers to generating scan patterns for each created layer. The parameter step refers to finding optimal values for process variables for the given build objectives. Throughout the paper, only new issues of process planning are addressed so that readers are assumed to have some basic knowledge in process planning issues of SFF technologies.

### 3.1. Build Direction

The build direction is the direction of stacking 2.5D slices, or namely layers. In most cases, if layers are not curved, the normal vector of layers is just the build direction. In most SFF technologies, only one direction, which is from the bottom to top, has been considered because the process is only possible for horizontally planar layers to be stacked up from the bottom. With LCVD, it is possible to fabricate not only horizontally planar layers, but also horizontally curved layers, vertically planar layers, and vertically curved layers. In other words, more than one build direction could be achieved. Three basic build directions were developed: the horizontal direction, vertical direction, and concentrically outward direction. The reason of concentrically outward instead of inward is that the gas-jet nozzle is not able to reach inside if the outside wall was built first. The basic three build directions are shown in Figure 7 with a simple cylinder example. Since the cylinder example is radially symmetrical, it generates no different results for the horizontal direction no matter where it starts from as long as it starts from the outer circular edge. However, for an arbitrary model with no symmetry, the starting point of the build direction must be considered because numerous horizontal directions and concentrically outward directions are possible depending on where it starts. Only one direction is possible for the vertical direction. Note that in general, it is possible to use a set of these three build directions for the same model similar to the approach taken in some multi-direction slicing research [8].



Figure 7. Three basic build directions with a cylinder example

### 3.2. Conformal Slicing

LCVD is capable of depositing curved layers onto non-planar substrates as explained earlier. This unique characteristic is extremely useful when fabricating a part like a thermionic emitter. The thermionic emitter is an electronic device responsible for emitting electrons such as in a cathode ray tube and is one of the challenging parts the Georgia Tech LCVD team is trying

to fabricate [12]. The emitter consists of a concave tungsten substrate on which alternating layers of insulators and metal grids are to be deposited.

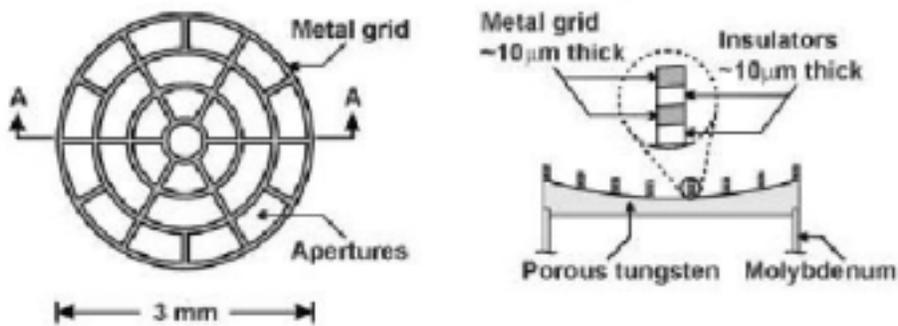


Figure 8. Thermionic emitter model (Source from [12])

When fabricating a part like the thermionic emitter, conformal layers obviously give more advantages compared with planar layers generated from conventional SFF processes. Figure 5 helps to understand how they are different for a non-planar part. Since conformal layers generate less layers and better surface finish as shown in the figure, better build time and accuracy can be achieved. For process planning, any given 3D model should be sliced for generating 2.5D slices. Conformal slicing could be performed if the part has a curved shape. This conformal slicing was implemented in our developed software. The algorithm is explained in the latter section of Software Development.

### 3.3. 1D Path Generation

In process planning, after 2.5D slices are generated, 1D paths should be planned. In LCVD, the 1D path refers to the way that the laser beam moves to make the deposit for filling each 2.5D slice. Since the deposit looks like a thin line, the terminology, 1D path, is used. Many researchers have studied about generating optimal paths for machining and SFF processes [13]. However, most of works have been concentrated on the basis of horizontal planes. Since LCVD can generate vertical layers as previously shown in Figure 4, the 1D path also should be examined for vertical layers. As shown in the figure, for a general vertical layer, two available schemes are considered. The first one is to use lines or curves stacking one on the top of another. The other scheme is to use rods arranging one rod next to another. Also, note that there might be some cases that using both schemes for the same layer results in better outcomes. For the line or curve stacking, it is straightforward because the build direction is always from the bottom to top. On the other hand, for fiber arranging, the build direction must be carefully chosen depending on the path of a jet-nozzle. In most cases, the concentric outward direction from the center of the horizontal cross-section of the part is chosen. For optimal path generation in general, it is desired to select paths that could minimize the number of line segments because it reduces build time and cost. At this development stage, due to the lack of experimental process data, it is hard to generalize ways to find optimal paths for any given model.

## 4. SOFTWARE IMPLEMENTATION

As a preliminary implementation, the software was developed using Microsoft™ Visual C++ V. 6.0, HOOPS™ 3D Application R. 6.0, and ACIS™ V. 6.3.1. Our developed software is capable of linear slicing and conformal slicing, which generate 2.5D slices for a given 3D CAD model. Since the conformal slicing is relatively new subject, only the algorithm for conformal slicing is introduced here.

### 4.1. Conformal Slicing Algorithm

The slicing is performed with any linear build direction and thickness, which are both specified by the user. After the slicing operation, sliced faces, the manufactured part made with sliced faces, and computational outputs are generated. The computational outputs include the original volume, manufactured volume, and volume difference calculations. Here, the volume difference is used to measure the accuracy between the original model (A) and the manufactured model (B) and it is calculated by the following equation:

$$\text{Volume\_difference} = \text{Volume\_of\_}(A-B) \cup \text{Volume\_of\_}(B-A) \quad (1)$$

The algorithm below shows steps of the conformal slicing method. The “curved face” input is the face of the 3D model that is to be used for conformal slicing. Only spherical surfaces have been tested to date.

**Given: 3D model, Thickness, Build direction, Curved face, and Output file name**

- 1) **Create a bounding box for the given 3D model:**  
`(Xm, Ym, Zm) = create_box(3D_model);`
- 2) **Create a bounding box for the hemisphere that contains a selected curved face:**  
`(Xcf, Ycf, Zcf) = create_box(curved_face);`
- 3) **Transform the selected build direction to the + Z direction**
- 4) **Create the generic slicer:**  
`radius = ((Xm,e - Xm,i) / 2)2 + ((Ym,e - Ym,i) / 2)2;`  
`center = ((Xm,i + Xm,e) / 2, (Ym,i + Ym,e) / 2, Zm,i);`  
`wire_body = make_circle(center_radius, radius);`  
`surface_equation = find_surface_equation(curved_face);`  
`generic_slicer = cover_wire_body(wire_body, surface_equation);`
- 5) **Create the actual slicing surface:**  
`hemisphere_box = make_box((Xm,i, Ym,i, Zcf,i), (Xm,e, Ym,e, Zcf,e));`  
`slicer = generic_slicer ∩ hemisphere_box;`
- 6) **Generate all slices and stop when the slicer no longer intersects the 3D model:**  
`i = 1;`  
`while(intersection_face != NULL)`  
`move_distance = thickness * (i-1);`  
`transformed_slicer = transform(slicer, move_distance);`  
`intersection_face = transformed_slicer ∩ 3D_model;`  
`output_file = keep_save(intersection_face);`  
`i = i + 1;`  
`end`
- 8) **Transform all intersection faces back to the original position**

Bounding boxes are created for the given 3D model and the selected curved face, where subscriptions m and cf denote 3D model and curved face respectively. Then, each bounding box of the model extracts two sets of coordinates. The first set,  $(X_i, Y_i, Z_i)$  is the low end of the leading diagonal of the box and the other set,  $(X_e, Y_e, Z_e)$  is the high end of the leading diagonal of the box. The detail algorithm for transformation of the selected build direction referenced to the positive Z direction does not show here but the software is capable of slicing for any linear build direction that is specified by the user. Since the selected build direction is transformed to the positive Z build direction, a radius is computed by  $((X_e - X_i) / 2)^2 + ((Y_e - Y_i) / 2)^2$  and the center of a circle is computed by  $((X_i + X_e) / 2, (Y_i + Y_e) / 2, Z_i)$ . Here, the slicer refers to the generated slicing face that is used as a slicing tool for the given model. The reason of using a circle for the slicer is that a circle made with  $((X_e - X_i) / 2)^2 + ((Y_e - Y_i) / 2)^2$  is larger than any of the XY cross-sections of the 3D model. After creating a wire body of the circle, the wire body is covered by a face that is generated by a form of equation through ACIS codes such as SURFACE::equation (). Using this surface equation, the curved slicer is finally created. One problem followed in this step was that the generated slicer by using the surface equation sometimes has redundant face part. For example, when starting with the lower hemisphere, the surface equation simply generates a general spherical equation, which includes both the lower and upper hemispheres. In order to keep only the desired face, a hemisphere box is generated with two diagonal coordinates of  $(X_{m,i}, Y_{m,i}, Z_{cf,i})$  and  $(X_{m,e}, Y_{m,e}, Z_{cf,e})$ . This box intersects with the generic face made by using the surface equation. This operation is expressed as “generic\_slicer  $\cap$  hemisphere\_box” in the algorithm. As a result, only the desired face remains. The remaining steps are straightforward as shown in the rest of algorithm steps. Figure 9 shows the graphical interpretation for steps of making the slicer to help better understanding.

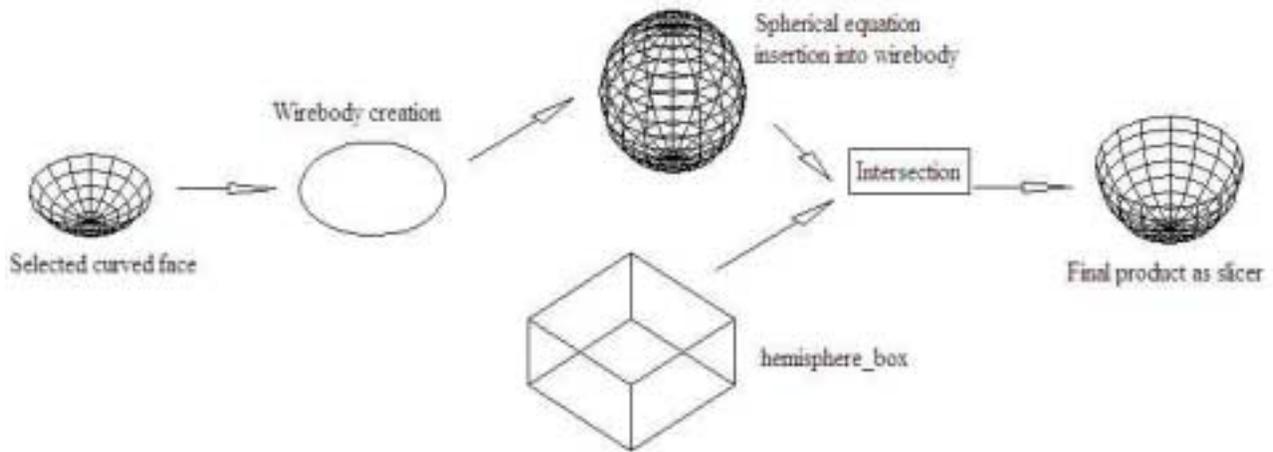


Figure 9. Graphical interpretation of creating the slicer

## 4.2. Example Of Thermionic Emitter

A thermionic emitter model of arbitrary size was used in order to test our developed software. The outer diameter of 30 and the grid thickness of 0.5 were used to create the model. For the positive Z build direction, both conformal and linear slicing was performed. Table 1 shows the comparison results, where V stands for volume. When linear slicing was applied, the

manufactured volume seems the same as the original volume. However, note that as shown in the % volume difference, the manufactured part by linear slicing is quite off the original model. In other words, the manufactured volume alone should not be used as a judgment of accuracy. The % volume difference is calculated by dividing the volume difference by the original volume.

Table 1. Comparison Results for Thermionic Emitter

Layer Thickness	Original V	Manufactured V		% Volume Difference		# of layers	
		Linear (L)	Conformal (C)	(L)	(C)	(L)	(C)
0.3	91	91	136	70.33 %	49.45 %	5	3
0.1		91	106	19.78 %	16.48 %	14	7
0.05		91	98	8.79 %	7.69 %	27	13

As expected, conformal slicing gives better build time and accuracy for the thicknesses tested. Here, the % volume difference serves as a measure of accuracy. Also, the number of generated layers could be interpreted as build time since fewer layers mean less time to build a part in general. Figure 10 and 11 show manufactured parts by linear slicing and conformal slicing respectively. As seen from the figures, the part made by using linear slicing has stair steps on top and bottom surfaces while the part made by using conformal slicing has smooth surfaces. Each figure has zoom-in shots for better illustration.

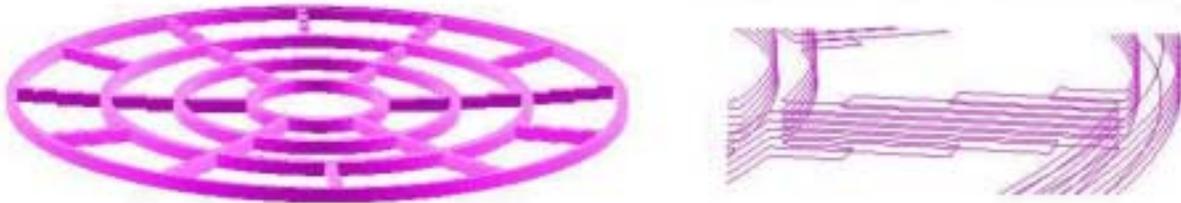


Figure 10. Part made by linear slicing

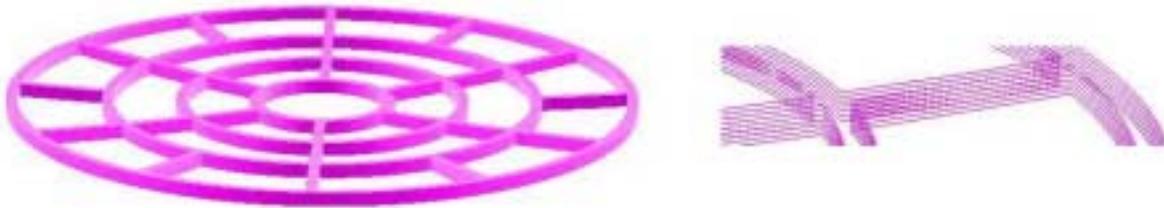


Figure 11. Part made by conformal slicing

## 5. CONCLUSION AND FUTURE WORK

Through studies of the LCVD process, the unique deposit characteristics were identified. With the LCVD process, lines, curves, fibers, and inclined fibers can be fabricated directly. Build directions can be horizontal or vertical. Layers can be planar or curved to conform to the shape of the surface on which the layer is being deposited. Given these unique characteristics, process planning for LCVD is much more challenging than for other SFF processes, since many more options are available for any given geometry. An initial LCVD process planning method

has been developed and implemented. Part orientation and either planar or conformal slicing can be performed.

Much more work remains to complete the process planning method. Methods must be developed for generating scan patterns of planar and conformal slices that are suitable for LCVD. Methods for evaluating part quality during process planning must be developed. This work depends upon the development of good process-structure-property relationships for our LCVD machine. These relationships will vary for different materials, compounding the complexity of developing a good process planning system.

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