"Curved-Layer" Laminated Object Manufacturing®

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Abstract

A process where a freeform solid object is built by bonding cut layers of material together is called a Laminated Object Manufacturing process. Until today, all of the LOM processes utilized straight forward planar cross-sections of the intended object for manufacturing. The "Curved-Layer" project's objective is to perform the LOM manufacturing process on a non-planar cross-section. Thus, the layers are going to be bonded together as non-planar surfaces providing additional strength to the built part as well as expedition of the built time for many objects. This project entails both software and hardware development for the implementation of the manufacturing process.

1. Introduction

Laminated Object Manufacturing (LOM™) is a process where a solid freeform object is manufactured with lamination of cut layers of sheet material. Until today all of the (LOM) processes have been implemented using straight forward lamination of material cut flatly based on planar cross-sections. The "Curved-Layer" project's objective is to perform the LOM manufacturing process on a "curved," non-planar, cross-section. This is especially useful for thin, non-flat parts. This project entails numerous approaches and techniques that are not currently available commercially. Consequently, an innovative effort is required to perform a build of an LOM part on a non-planar surface. A substantial modification of the conventional (planar) LOM process is necessary in both software and hardware.

2. Planar LOM Process

The planar process for laminated object manufacturing has been utilized by Helisys Inc. for rapid prototyping for some time. The most basic description of the process can be provided using a cutting and bonding cycle, see Figure 1. It is important to outline the main stages of the current process in order to better understand what needs to be done for the "Curved-Layer" project.

a) In the implementation of the current machine, the cutting is performed using a plotter system that transports a mirror and a focusing lens over the x-y envelope of a flat cross-section of the part corresponding to the [z = current height] plane. Everything, including the focusing lens, is fixed on the x-y plotting mechanism because the flat-layer is always parallel to the plotter's operational plane.

b) Once a layer is cut, a new, virgin layer is bonded on top by a heater-roller. Note, the material has heat sensitive adhesive on the bottom side. The heater roller is flat in the y direction and is designed to apply equal pressure and temperature to the part as it rolls over it.

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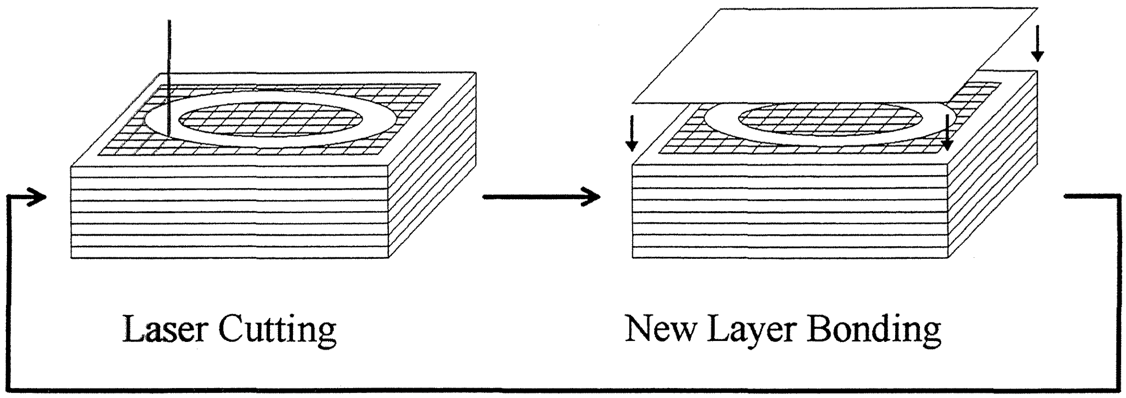

Figure 1 Planar LOM process

c) After bonding, the height of the part is measured and a new cross-section is computed by intersecting the part (.STL) file and the [z = current height] plane. After all the segments defined by the intersection of part facets with the height plane are identified, processing such as ordering, cross-hatching, beam-offset, among others are performed.

d) When the necessary calculations are completed, the new material is cut, thus returning to the beginning of the cycle, i.e., return to a).

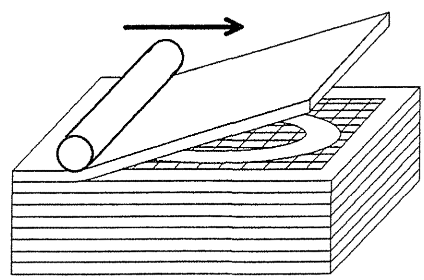

Figure 2 Roller bonding

The current planar LOM process is composed of components that in their design are inherently planar. The laser cutting, due to variable distance; the new layer bonding mechanism; the dependence on the part height measurement, because of reliance on part flatness; the planar cross-section, among all of the other 2D software components; and all the other LOM elements need to be rethought.

3. "Curved-Layer" LOM Process

The "Curved-Layer," non-planar LOM process in its concept is almost identical to the regular, planar LOM process, i.e., compare Figure 3 to Figure 1. However, the two processes have to be

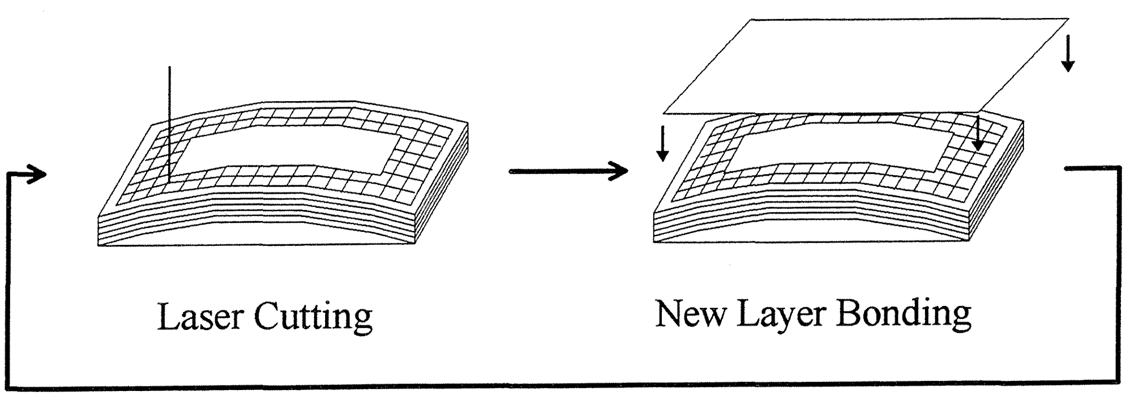

Figure 3 "Curved-Layer" LOM process

very different in their implementations. In this section, the relevant differences and their implications for both hardware and software are discussed.

3.1 Non-Planar Base

The planar LOM process uses a base constructed by adding flat layers of material to the metal platform. Afterwards, the part build cycle is begun on top of the base. The first major difference that the non-planar LOM process requires is the capability to form a base for the "Curved-Layer" build, see Figure 4. This is actually an intricate problem in itself. Many circumstances such as

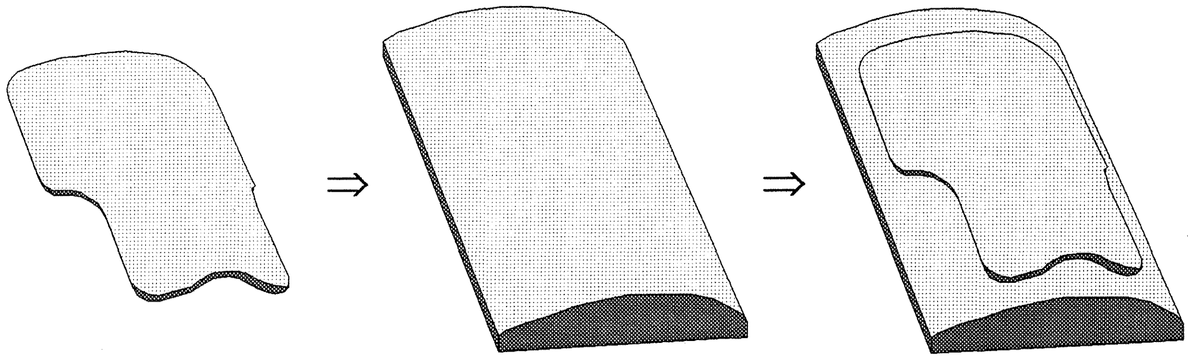

Figure 4 "Curved-Layer" base

holes in the original object, high slopes, and etc. may prevent the implementation of a non-planar part build because their presence in the base might interfere with the possibility of adding new layers of material. Therefore, such circumstances need to be eliminated in base creation itself. Thus, the software for such base generation needs to have intelligence to identify and address such features. Currently, the software developed uses some coarse heuristic approaches to remove the undesired extrusions, etc. However, this method is not foolproof, though we have been able to create satisfactory bases for most object files we tried.

Another new issue that exhibits itself is the base alignment issue. Right now, we create the base by having the software construct a .STL file for this base and consequently building the base from the .STL file using the conventional, planar, LOM process. Because the base is created separately, prior to the non-planar build of the part, the base needs to be placed in perfect alignment with where the computer's representation for the base perceives it to be. At this point, we do not think it to be practical to add new and very involved complexities of designing a closed loop system for automatic alignment. However, a manual procedure needs to be worked out for performing this task.

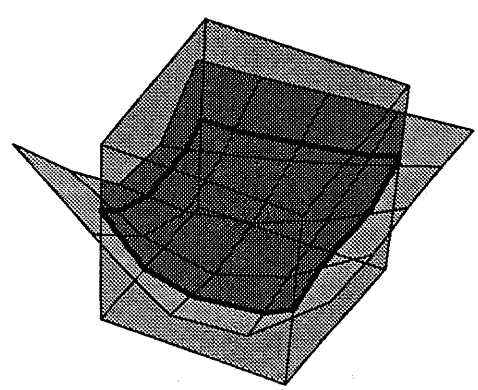

Figure 5 A "Curved-Layer" intersecting an object (cube)

3.2 Non-Planar Cross-Section

In order to identify the path required to cut on the recently bonded layer of material, we need to intersect the "Curved-Layer" with the object, i.e., identify the segments that constitute the intersection of the two, see Figure 5.

The mathematical "Curved-Layer" representation, in turn, needs to be a very accurate depiction of the actual top layer freeform. For planar layers the height measurement is taken after every new layer is laminated. Unfortunately, for non-planar layers there is a different height at every point. Thus, either a closed loop system is needed to measure a layer's profile at every layer, where we will gauge the height at every point on the layer, or this can be accomplished with a very accurate open loop system, where the height at every point will be approximated with a mathematical model as the part grows. Just as the case with alignment, because a measurement system would bring in considerable extra complexity and become a major detraction from the actual problem at hand and because if needed this feature it can be added later, we decided to proceed with an open loop approach at this time.

3.2.1 Height grid representation

We looked at a number of candidates for the model to represent the non-planar layer. After appreciable consideration we decided to use a height grid system. In this system, we divide the xy-plane into an evenly spaced grid and store the height (z) values as elements of this grid, see Figure 6. This approach has the advantage of being much more elementary than most of the other models. Also, by using this model, the update and initial values for the non-planar layer are more fundamental and can be obtained using more tangible methods.

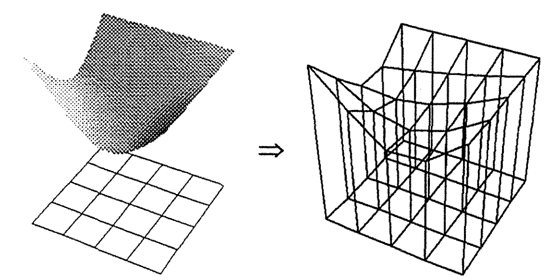

Figure 6 Height grid representation

3.2.2 Initial values

The initial values for the heights are first obtained by intersecting the triangles at the bottom of the object's .STL file with the vertical lines originating at the bottom of the grid, see Figure 6. Then, "foreign" values for the heights are filtered out using the same heuristic approaches that are used for the generation of the non-planar base generation. Note, this filter and the filter used for base generation are to have the same parameters in order to obtain an exact correspondence between the top layer of the base and the representation for the first layer.

3.2.3 Update

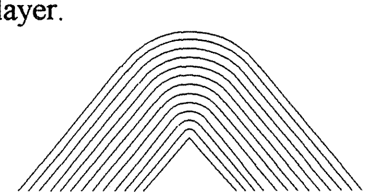

Figure 7 Part growth

After a new successive layer has been added above the previous one, a new "Curved-Layer" representation needs to be obtained. This new layer is not a perfect replica of the old layer. Though, it should be a "smoothened" version of the previous layer, see Figure 7. Because we have no way to measure these new heights, an open loop method was developed to approximate the new, updated grid heights for this new layer. The approach chosen for this case consists of taking a point form the previous grid along with four of the original surrounding points on that grid; constructing four triangles originating from our desired point; lifting each of the triangles by the material thickness in the direction of their respective normal vectors; fitting a curved surface tangent in desired places to the four offset triangles (a third degree polynomial is used); and finally taking the z-height value on that polynomial at the desired location in the xy-plane, see Figure 8.

This approach for updating the layer representation due to an addition of an extra layer has advantages over other methods we considered because, this method can model the smoothing that results after successive addition of layers. It also is superior to a 3D triangle based format of modeling curved layers, because this method does not grow in complexity. For this method, with each successive layer, the fineness of the grid remains exactly the same and thus the computational complexity is not increased, unlike most of the other methods we considered for which the complexity tends to grow by a factor with every layer. Moreover, in simple tests this method seems to perform very well in modeling the build growth even after a few hundred layers.

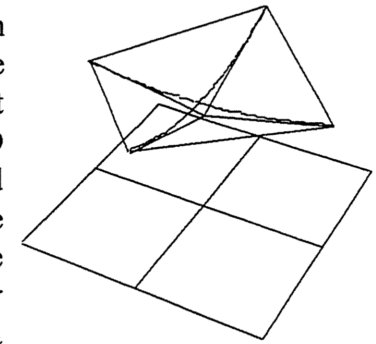

Figure 8 New layer model

3.2.4 A non-planar cross-sectional cut

An intersection between a non-planar layer and the object representation constitutes a non-planar cross-section, i.e., an object's periphery along which we would need to cut, see Figure 5. This intersection consists of segments that correspond to facet intersections, see Figure 9.

At times, the facet intersections lead to hard to handle, degenerate cases of triangle intersections, see Figure 9(c,d). These occurrences are numerically very unstable and lead to problems with extra and missing segments. Though for planar cross-sections, these cases are extremely rare and they can be avoided in a vast majority of occurrences, unfortunately for non-planar case, this is much more likely to occur and not as easy to avoid. This has a potential to be a major problem for certain parts.

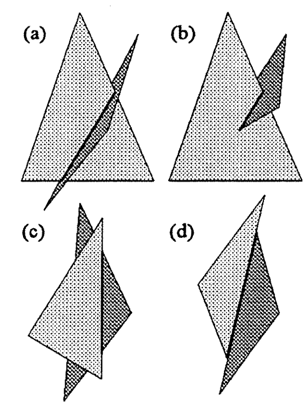

Figure 9 Facet intersections

3.2.5 Generalization of segment handling to 3D

The current LOM software for the planar process contains many routines for handling and utilizing the collections of segments in two dimensions, i.e., sorting, rearranging, beam offset, cross-hatching, etc. Most of these routines are just as much an absolute necessity for curved slicing as they are for planar slicing, e.g., arrangement of segments into continuous loops. Others, such as crosshatching are also very important. And finally, features such as the beam offset (to account for the thickness of the beam) are desirable and come with very little cost, assuming the other components are incorporated.

We have extended the segment handling capability of the planar LOM software to 3D almost entirely, see Figure 10.

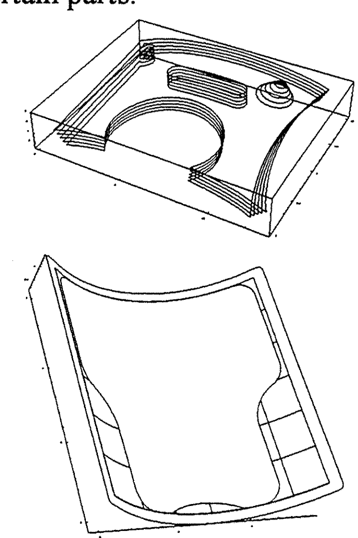

Figure 10 Segment handling

3.3 Non-Planar Cutting (Focusing)

As mentioned earlier, the distance from the focusing lens to the cutting surface varies for "curved layer" cutting. Because the plotter transporting the focusing lens is a 2D device and the surface is no longer flat, the cutting surface will be out of focus if the cutting is done in the conventional, planar manner. This is another major difference between the two processes that need to be addressed.

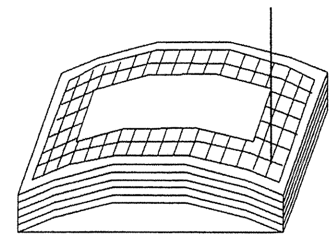

Figure 11 Non-planar cutting

3.3.1 Platform compensation

One approach to keep the laser constantly in focus is to move the platform supporting the part to compensate for the variability in height. This approach, in concept, does not require any hardware changes. Unfortunately, in practicality, this is not true because the currently used motion control boards, as well as most motion control boards on the market, do not support circular arc motion in 3D. However, it is possible to implement the current motion using the current hardware if we stop the cutting motion every once in a while in order to adjust the height, see Figure 12. Nonetheless, this method is not the most practical because the motions of the platform are slow and are not always smooth. Moreover, the jitters resulting from platform motion can interfere with cutting. Redesign of the platform system is costly, time consuming, and does not guarantee a satisfactory result.

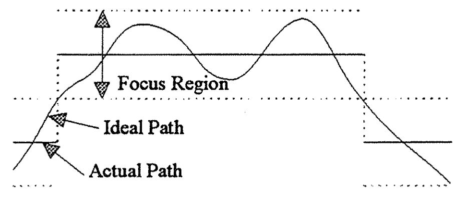

Figure 12 Platform compensation

3.3.2 Large focal distance lens

Another method, to compensate for the variable part height, we are considering is to increase the focal distance of the lens, i.e., the focus region is extended by using a lens that focuses the beam further from itself, see Figure 13. The drawback of this approach is that the width of the beam at the focus spot is not as tight as it is with the original lens. As a result, it is not certain that we will be able to cut the material with this new lens. At this time, we are making the necessary hardware changes (to the lens housing, etc.) in order to try to cut with it at real time speeds.

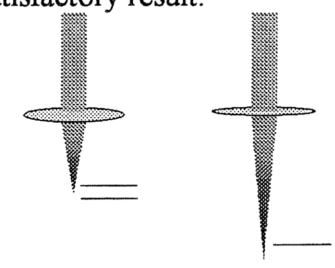

Figure 13 Large focal distance lens

3.3.3 Controlled focal distance

Finally, the last method we are exploiting for this problem is the possibility of moving the focusing lens up and down so that the laser is kept in focus on the cutting surface. If the other methods are found not satisfactory then this method will be developed fully. The only drawback of this method is that the added weight of the focusing system will effect the balance of the plotter. Thus, the plotter might have to be modified.

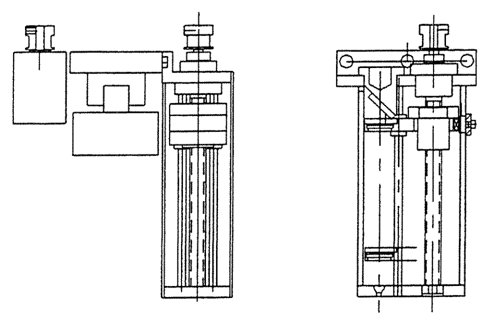

Figure 14 Controlled focal distance

Of the three, this method is the most general with the fewest drawbacks, though it is the hardest to implement because it requires a mechanical, an electronic, and a software redesign effort.

3.4 Non-Planar Bonding

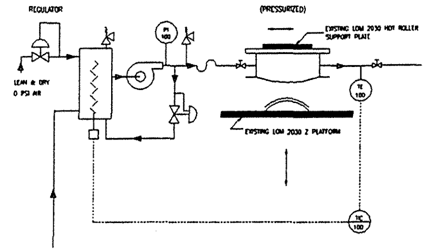

Figure 15 Bladder bonding

The bonding issue is of most concern to us and is the issue that seems to be the least open to workable solutions. It is not completely apparent how one is to deliver both heat and pressure uniformly to a loose sheet of material on a surface of a non-flat object so as to achieve smooth bonding with no ripples. Many approaches have been considered and rejected due to one drawback or another. We are still considering a few approaches, but are in the design stages for only one, though it too has many drawbacks.

We are building a hot rubber bladder bonding mechanism. The bladder is to be filled and pressurized with circulating hot air. The rubber surface (siliconized rubber, so it can withstand high temperatures) comes in contact with the part by raising the part on the platform into the bladder. A previous non-pressurized prototype has produced some favorable results.

3.5 Sheet Feeding

Because often it is much more accommodating to produce many materials in sheets as opposed to rolls, especially the materials we are considering for "Curved-Layer" building, the idea of a sheet feeder for the material is being considered. (Thus far the LOM process has only been implemented with rolls of LOM material.) However, the mechanical design of such a mechanism would require an almost exact knowledge of many characteristics of the material in question. Thus far, the materials to be utilized are only being developed. Such characteristics as stiffness, texture, lamination to the stack, and etc. are still not known. Moreover, if the material is too brittle, not stiff enough, or sticks to the stack too much, it might not be possible to implement a sheet feeding mechanism at all.

4. Summary

The "Curved-Layer" project to modify the LOM process from planar to non-planar build necessitates a substantial design effort. Many issues such as mechanical, electrical and software need to be addressed. In this paper we discussed our progress on many of these issues and what our concerns at this point in time are. Major components of the software effort have either been implemented or are in the implementation stages. Though, some new software components will be necessary when certain hardware designs are finalized. Also, the hardware components still necessitate a substantial effort in their design and implementation. We are going into uninvestigated territory and experimentation is needed before a final satisfactory product can be formed.