ADAPTIVE LAMINATED MACHINING FOR PROTOTYPING OF DIES AND MOLDS

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ABSTRACT

Adaptive laminated machining is the fusion of slicing a solid model into layers and producing parts by CNC milling machines. Unlike other solid freeform fabrication processes which create the part by addition of material, adaptive laminated machining can create solid parts by selectively removing in layers. The research issues and practical limitations on shape and manufacturability are thus different from other processes. However, the biggest advantage is the ability to obtain a solid metal part such as a die or a mold directly. In this paper, the concept of this technique, and initial results and parts produced in Clemson will be presented. In addition, future research needs and issues will be discussed.

INTRODUCTION

The main problem in manufacturing prototypes lies in the control of the delay between design and production. Until recently, a prototype of a new part required weeks or months merely to see if the shape or features would be acceptable or not. With the newer technologies developed in the past four years, a prototype can be created within hours. These new processes are grouped under the generic term free form fabrication (FFF).

FFF techniques can produce parts without any shape restriction because: (i) no tooling is required and (ii) parts are built layer by layer. 3D Systems' StereoLithography, DTM's Solid Laser Sintering, Cubital's Solider, Stratasys' Fused Deposition Molding are some of the commercially available prototyping units. If the slices are thin, texture quality and dimensional accuracy are competitive with more traditional manufacturing processes like milling and turning. However, the materials used by the FFF techniques are limited to polymers (liquid and powder) and ceramic powders, and cannot reach the mechanical properties required for many practical uses, such as dies and molds. Therefore, these processes are limited to the production of smaller parts and those to represent shapes and sizes only.[1]

A recent study presented at an MIT conference on Leadership for Manufacturing in 1991 (Table 1) shows that computer numerical controlled (CNC) machining matches stereolithography in many points. The greatest advantage of FFF over CNC machining is its capacity to produce any intricate shape. However, most, if not all, FFF processes are limited to non-metallic materials or metals with a relatively large void fraction. In addition, due to size limitations, dimensions of parts producible on these FFF units are limited to 20 inch cubed. CNC machining is limited by its programming time needed to convert a three dimension solid model to a machined part. If the programming time for CNC machining can be reduced without affecting other parameters, new applications can be developed for this conventional manufacturing process for both prototyping and limited batch production.

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1 Several other processes are being developed using paper, metal and ceramic powders and other materials as of this writing. However, these processes are not commercially available and were not included here.

In this paper, a concept on product realization from a CAD solid model is developed by fusing FFF processes and conventional machining. This concept, called adaptive laminated machining, is based on the integration of slice generation as in FFF technologies and 2½ dimension CNC machining. The overall idea is to decompose a solid model of the part into layers and then to automatically machine each layer to create the finished shape. The final aim is the automation of prototyping of dies and molds from a computer aided design (CAD) model. The approach taken to develop adaptive laminated machining and some results is the subject of this paper.

BACKGROUND

Introduction to FFF

Several techniques can be used to produce prototypes, like stereolithography, solid base curing, selective laser sintering, fused deposition modeling and three dimensional printing [1-6]. All of these techniques decompose the CAD model into a number of layers, called slices. The slices generated by the slicing algorithm comprise of basic entities, such as arcs, circles and straight lines, which are used to reconstruct a solid object. Therefore the first step for all FFF processes is slicing based on the graphical representation of the part. An overall scheme presented in Figure 1 describes the process flow.

The advantages in using an FFF process are:

1. texture quality and dimensional accuracy can compete with conventional machining;
2. no shape constraint comes from the process itself, the only limitation is associated with CAD;
3. the manufacturing process is fully automated, and can be run untended overnight;
4. no tooling or special fixturing is required;
5. the production of several parts at the same time with different geometries is possible;

and

6. the building speed is a function of both process characteristics and dimensions of the part, and it is not affected by the geometrical complexity.

The main drawback of these processes is that because of the materials used to date, the mechanical properties of the parts are insufficient. Hence the applications of the processes are limited to look-alike parts rather than true prototypes with the same strength, stiffness and toughness. Secondly, the initial cost of hardware, software and training is very high when compared with conventional manufacturing techniques. These technologies utilize novel materials and concepts, and thus require the acquisition of knowledge of the materials and familiarization with the concepts (e.g., slicing) and machines (e.g., stereolithography apparatus).

Table 2 compares the characteristics of different FFF processes based on the data obtained from the references. It should be recognized that since all these processes are new, the values are based on few experimental measures, some on theoretical calculations, while those for some others are not available at this time. With time the characteristics of these processes should be better understood and evaluated.

Slicing Algorithms

Slices are 2 dimensional geometrical entities (or cross-sections) assembled sequentially to create a solid object. Since all rapid prototyping technologies fabricate objects out of slices, they are the basic geometrical entities [7]. The general procedure to produce the slices from the CAD representation of the object is shown in Figure 2. Because surface texture, and form and dimensional accuracy are important to the prototype, it is essential to keep the best CAD representation possible to minimize geometrical error.

The first step in Figure 2 shows the transfer of the original CAD file into an STL format, which has become the de facto standard for FFF processes. This new representation approximates the surface of the object by triangles, the vertices of which belong to the original surface. The accuracy of the tessellated file can be improved by increasing the number of facets, requiring greater storage space and computation time. The slicing algorithm then utilizes this STL file and computes the intersection between the object and horizontal planes. The boundaries obtained through such an intersection, represented by polygons, is the cross-section of the object at that layer. The information on the cross-section of the object is utilized to create the part one layer at a time.

At present the concept of slicing is well established. Many commercial CAD packages provide capabilities for slice generation from a solid model to generate the software manually. In addition, researchers at University of Dayton, Carnegie Mellon University and Clemson University [8] have been working independently to automatically convert solid models to slices. The key issue in developing such indigenous software is to provide faster computation, better control over the process and minimize errors due to slicing.

ADAPTIVE LAMINATED MACHINING

Given that it is not possible to produce metal parts with FFF processes, classical techniques like machining need to be developed to reduce the time between design and production. Although computer aided manufacturing systems (CAM) have considerably simplified process planning, they are not adapted to the complex shapes encountered in parts like dies and molds. Such tasks require the knowledge of an experienced operator. The combination of CNC machining and production of parts layer by layer can give a satisfactory answer to this specific problem.

The objective of this research is to develop an integrated design for manufacturing system to prototype dies and molds using adaptive laminated machining as presented in Figure 3. Similar to slicing and cross hatching in stereolithography, tool path planning is of paramount interest in adaptive laminated machining. The core of the study will focus on issues related to tool path generation shown in the highlighted boxes in Figure 3.

Slice controlled machining is based on the decomposition of the solid object into layers, and a contour describing the cross-section of the object at each layer. A complex die or mold can thus be rapidly manufactured for prototyping purposes by breaking it up into simpler three dimensional segments (if necessary), decomposing each of these segments into layers, machining the contour for each layer, and thus creating the die layer by layer. This process thus requires an efficient slicing process for the original solid model and a tool path generation algorithm for both rough machining as well as finish machining.

The objective will be met by addressing three research issues: (i) developing the interface between a CAD system and CNC machining through a slicing algorithm (to be developed for adaptive laminated machining) (ii) developing an integral tool path generator to work with the slicing process and a wide variety of milling machines by using standard commands; and (iii) characterizing the quality of parts obtained by slice controlled machining to produce dies and molds whose quality will be comparable to those obtained using existing manufacturing processes (such as casting and machining).

CONCEPT AND VALIDATION

By selecting machining to fabricate dies and molds, most of the process parameters are already pre-established by the working environment. Examples in point include shape complexity, presence of cooling and/or heating circuits, fixturing constraints, strength and stiffness at critical locations in the die or mold, surface quality obtainable using CNC machining.

In adaptive laminated machining, the process planning and execution of CNC machining will be completely modified. This approach leads to the creation of computer numerical controlled (CNC) machine codes for each slice generated, proceeding one slice at a time from top to bottom. This will permit the handling of any shape of a die surface with the desired texture, and dimensional and form accuracy. Alternatively, in conventional methods, the special features would need to be identified and generated individually utilizing machining rules in an expert system which is being investigated by other researchers [9, 10].

The overall concept of adaptive laminated machining is presented in Figure 4. The sliced boundaries are directly obtained from the original CAD model. Therefore an intermediate file like the STL format, which is a faceted representation of the geometry and used by many other commercially viable rapid prototyping systems, can be avoided. Due to this difference with other rapid prototyping systems' approach, existing slicing algorithms are not applicable any more. However, slicing becomes easier because only the intersecting boundaries of the solid model with the slicing planes are needed, and no post processing of data to obtain any hatching inside the contour is needed. Therefore, a built-in macro in any CAD package to intersect a plane with a solid model can be used. This implementation inside the CAD environment can benefit from flexibility and diversity of CAD commands. Thus, the algorithms can focus on quality issues instead of trying to solve entity manipulation, intersection, and graphic representation problems.

The object is drawn using AutoCAD AME extension as a solid model. Using the standard AutoCAD plane intersection algorithm the object is divided into different layers. Thus, the slicing is done within AutoCAD using its C libraries. The resultant is a slice containing the boundary of the object due to intersection of the layer with the object. The object is thus broken down into a number of layers, separated by the slice thickness specified by the planner. Each layer boundary is stored in a file, sequentially, utilizing the AutoCAD data exchange format (DXF). This file thus contains line and arc segments corresponding to each layer. Each line or arc segment is then defined in terms of its radius of curvature (if appropriate) and the coordinates of its end points. This data is used in a C program to generate the process plan from layer to layer and subsequently the numerical part program to drive the machine.

The example in Figure 5 illustrates the feasibility of the method with a manually varied z increment. It is possible also to develop the slices with variable z increments to better represent the surfaces [11]. The finished part produced on a desktop 3 axis milling machine using a flat end mill is shown in Figure 6. The work to date clearly shows the feasibility of the process and the ability to produce a large die or mold cavity from a metal block using adaptive laminated machining.

DISCUSSION

Several geometrical limitations are expected using this approach. In addition to machining constraints imposed by the milling machine itself, the slicing process adds new shape restrictions. Feature like threads, grooves or convex shapes are to be machined using a more conventional technique or after refixturing. Figure 7 provides some examples of geometrical constraints in adaptive laminated machining.

Once the undesired features are removed from the CAD model and the pockets are extracted, the minimum number of fixturing has to be determined as a function of the degrees of freedom of the machine tool. If a single fixturing is desired, the solid model can be used directly by slicing program, with no further modification. Parts such as dies and molds have geometrical properties where the positive shape is extractable and these parts do not have any undercut. If the parts need refixturing, only a minimum number of fixturing needs to be used. This is an area of ongoing research and will be discussed in depth in a future paper.

The direction of the slicing and identification of dominant features are two other domains of research in adaptive laminated machining. The choice of the direction of slicing will relate to the minimum number of fixturing needed and thus ultimately to producibility of shapes by machining. Another issue of concern is tool path generation and tool offset necessary for different geometries. These too will be discussed in a future paper.

ACKNOWLEDGEMENT

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Table 1: Comparison of Four Prototyping Techniques for Part Representation and Realization

	Computer Aided Design (CAD)	Stereolithography	CNC Machining	Reaction Injection Molding (RIM)
Strength to stiffness ratio[1]	0	0.38	0.80	0.85
Form accuracy[1]	0.83	0.85	0.85	0.95
Appearance[1]	0.50	0.80	0.90	1.0
Shape and texture perception[1]	0.20	0.52	0.98	1.0
Cost to produce a prototype[1]	0.95	0.22	0.5	0
Speed of producing a prototype	Very fast	Fast	Medium	Slow
Overall rank[2]	4	3	2	1

[1] Rated on a scale from 0 to 1, with 1 being the highest possible and 0 the lowest

[2] Ranked between the four techniques considered here

Table 2: Comparison of some of Free Form Fabrication Processes [5, 6].

	Materials	Accuracy	Speed	Remarks
Stereolithography	liquid photopolymer resin	Slice thickness 0.125 – 0.75 mm x/y +/–0.46 mm[1] x/y +/–0.12 mm[2]	Variable with size From 20 s to 3 min/layer	uses toxic polymers needs post curing
Selective Laser Sintering	investment casting wax, polycarbonate, PVC, ABS plastic and nylon.	+/–0.12 – 0.05 mm	Scanning speed .76 to 1. m/s building rate: 12 to 25 mm/h	powdered metals and ceramics are under development
Three Dimensional Printing	alumina powder and colloidal silica binder	+/– 0.05 mm for slow axis	above 30 mm/h with 100 jets (under development)	Used for ceramic shells and cores for metal casting
Ballistic Particle Manufacturing	wax, plastics	+/– 0.1 mm in x/y plane		Under development
Fused Deposition Modeling	nylon like material, investment casting wax	+/–0.12 mm	Scanning speed: 381 mm/s	Capable of a 1 min material changeover
Laminated Object Manufacturing	material in sheets: paper, metal	x/y/z +/– 0.1 mm	Cutting speed: .4 m/s	
Solid Base Curing	photopolymers + wax as support	+/– 0.05 mm	90 s/layer	
Mask (Cubital)	liquid photopolymers	0.1% in all dimensions	110 s/layer	
Desktop Machining	Polymers, Light alloys, steels ...	+/– 0.012 mm	0.7 m/min	uses tooling and fixturing

(1) Based on a study from E.I. Du pont de Nemours and Company Wilmington

(2) Claimed by most manufacturers

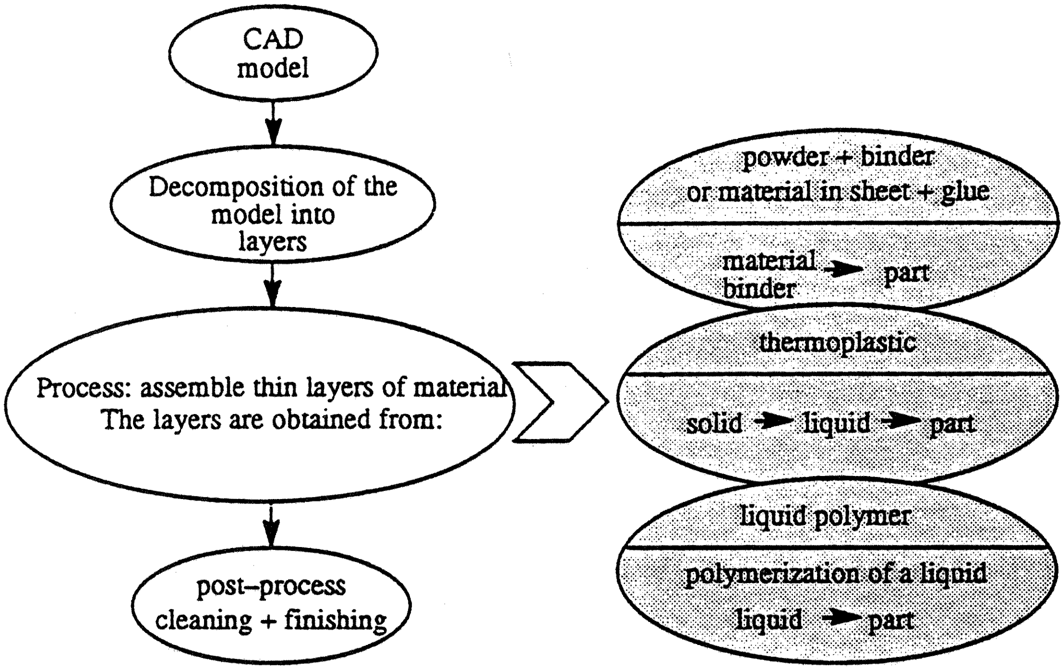

Figure 1: Overview of Free Form Fabrication

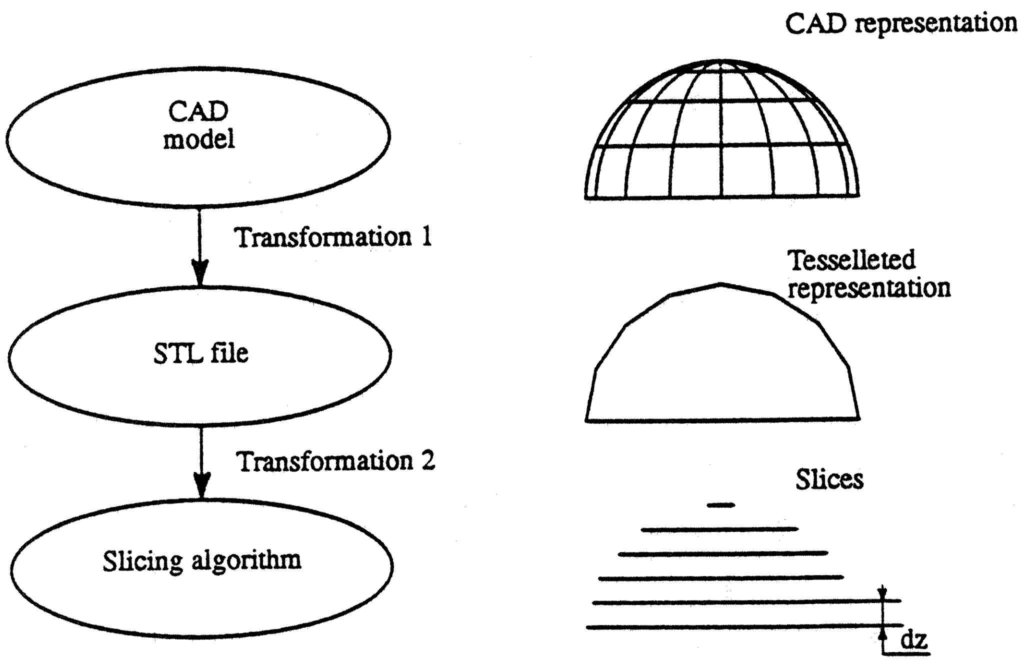

Figure 2: Slicing Procedure

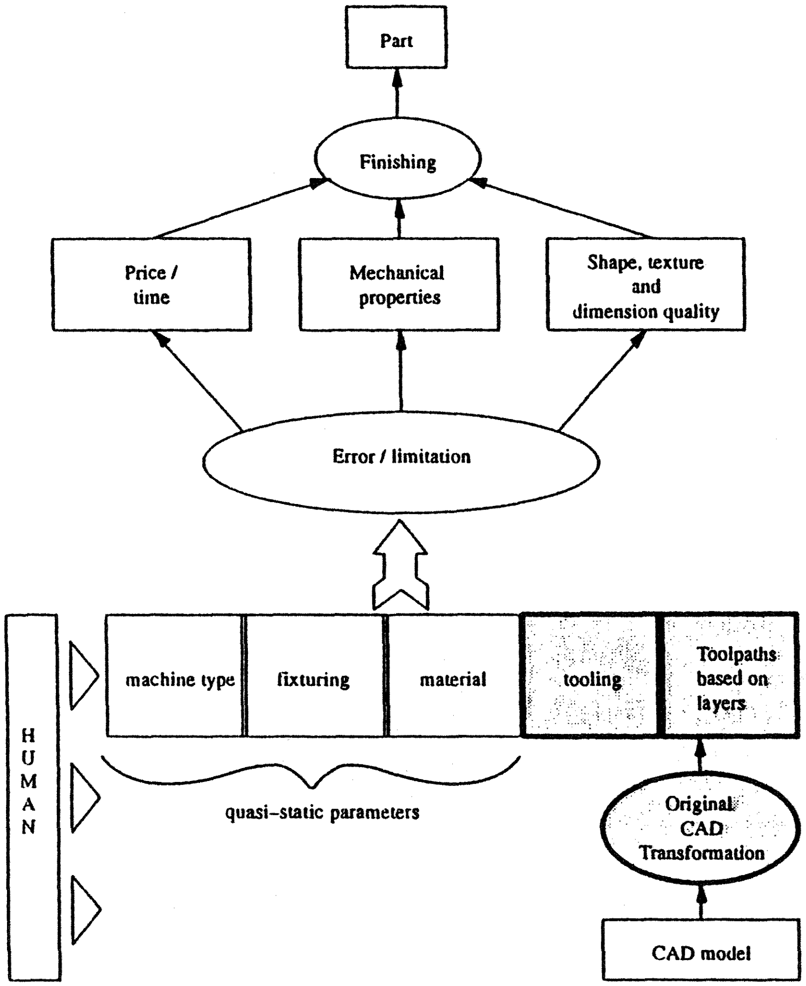

Figure 3: Adaptive Laminated Machining: Environment and Goals

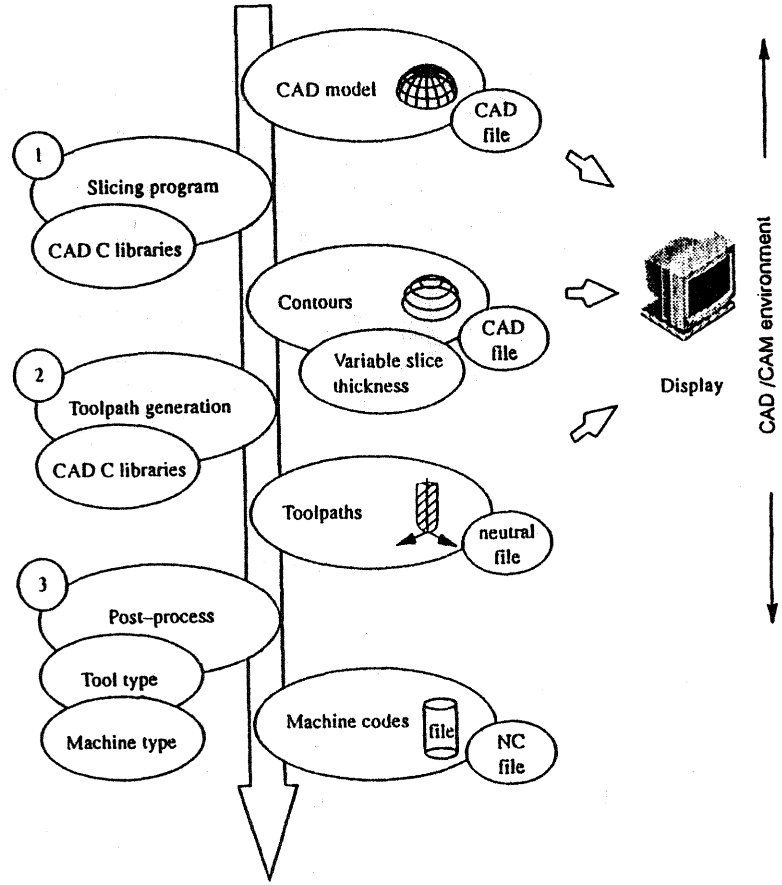

Figure 4: Details of process planning issues necessary in adaptive laminated machining (shown in the highlighted boxes in Figure 3).

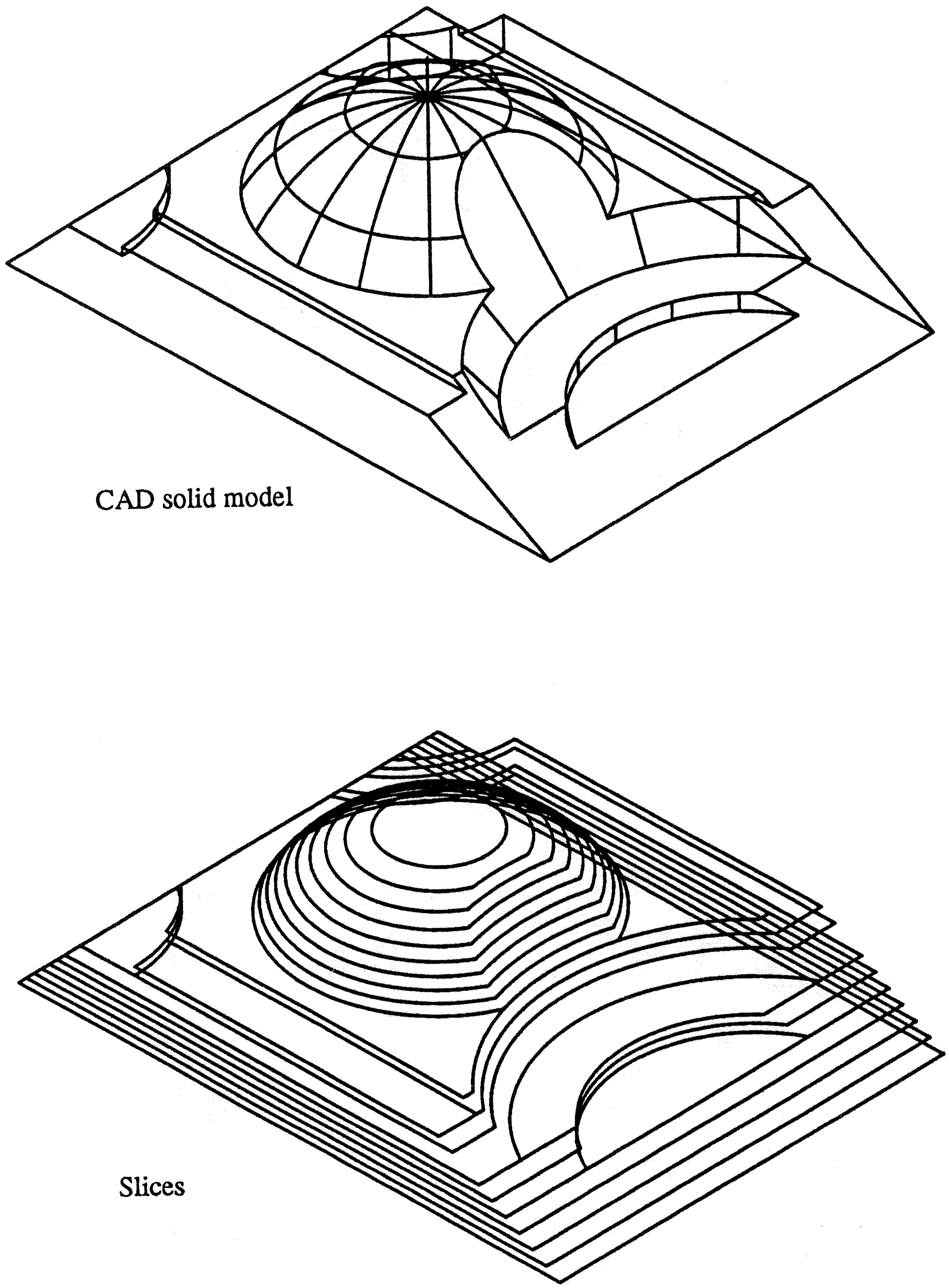

Figure 5: Transformation of a solid model into slices using AutoCAD

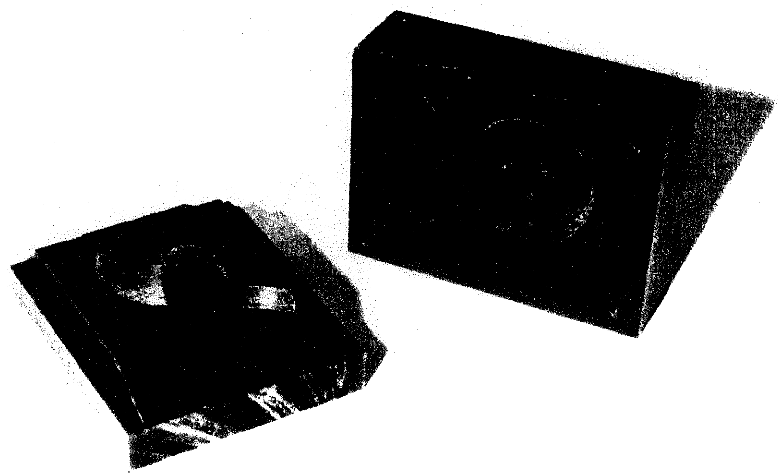

Figure 6: The finished part produced by adaptive laminated machining on a 3 axis milling machine and a flat end milling cutter.

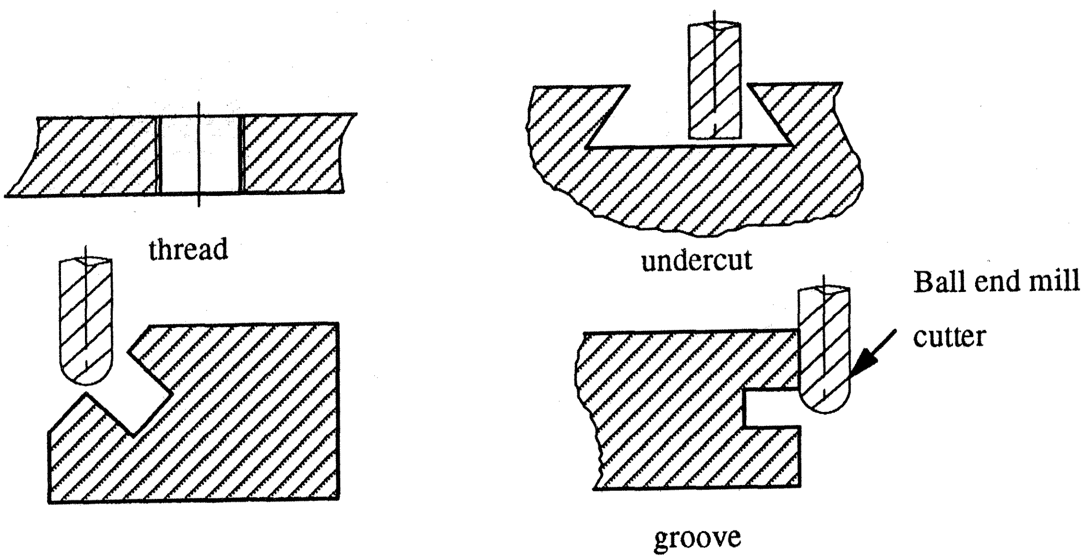

Figure 7: Examples of geometrical constraints in adaptive laminated machining