Features in Layered Manufacturing of Heterogeneous Objects

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ABSTRACT

The usage of features in computer aided design and manufacturing has increased significantly over the last decade. By and large, all such features are geometric (form features).

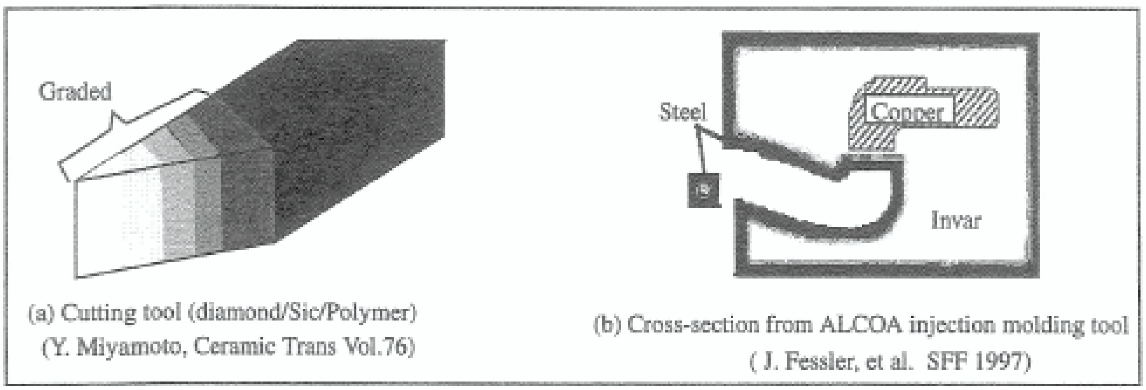
In this paper, we shall discuss the need to go beyond current geometric features and consider material -- composition, and gradation -- within the object. This need has been brought about by layered manufacturing technologies which build up parts, layer by layer, under computer control. While industrial use of this new technology has been for making prototypes, functional metallic parts can/are being made by layered manufacturing. Furthermore, a variety of materials can be deposited to create multi-material and functionally graded components.

We consider features in this new domain (of layered manufacturing) and identify research topics and present an overview of our current focus on "material features" in the context of heterogeneous solid models.

1.0 Introduction

Layered manufacturing(LM) refers to the host of manufacturing technologies that deposit material, layer by layer, under computer control. It is also referred to as solid freeform fabrication (SFF) and in industry as rapid prototyping. Layered manufacturing methods can be used to make functional parts which have good surface quality and good material property. One distinguishing characteristic of LM is that it is capable of depositing multiple materials in a layer as well as varying the material composition. Harnessing this characteristic is the focus of our research.

In this paper, we consider heterogeneous objects i.e., objects made of different constituent materials and having continuously varying material composition and/or microstructure (See Fig. 1). The state-of-the-art design and analysis research indicates that heterogeneous objects naturally arise in the context of thermal expansion coefficients, mechanical strength, creep, thermal and electrical conductivity, etc. Applications of heterogeneous objects include automotive engineering, aerospace, and biomaterials, etc.



(a) Cutting tool (diamond/Sic/Polymer)
(Y. Miyamoto, Ceramic Trans Vol.76)

(b) Cross-section from ALCOA injection molding tool
(J. Fessler, et al. SFF 1997)

FIGURE 1. Heterogeneous objects

A key requirement for the fabrication of heterogeneous objects is their accurate representation in CAD systems. Solid modeling techniques for heterogeneous objects are just beginning to emerge [1][2]. However, there is a need for tools that can facilitate the fabrication process planning of such objects. Process planning for layered manufacturing can be a complicated task, involving the determination of orientation, slicing, deposition path planning, etc. In addition, fabrication of heterogeneous objects demands very delicate control of deposition to achieve desired material composition and gradient.

In our research, we explore the use of features to facilitate the high level conceptualizing of material composition and gradation and its downstream transforming to layered manufacturing instructions. Features were initially proposed to automate the link between design and NC path generation [3]. Since then, features have been widely and successfully used in CAD/CAM. Feature based design expedites the design process and feature recognition facilitates the fabrication process planning. A feature based product model also simplifies the assembly and inspection planning, etc. [4].

In this paper, we report on our ongoing work. We propose a feature based architecture for design and process planning for layered manufacturing. In this context, we present several feature related issues. We then describe how we propose to address these issues and conclude with a summary.

2.0 Feature-based design and process planning for LM

Our proposed feature based design and fabrication integration approach is illustrated in Fig. 2. In this scheme, design can be carried out either by a feature based design method (explicit design whereby material composition is explicitly imposed over the geometry) or by an implicit design method (whereby material information is derived such as in homogenization design method). In feature based design method, the design features are mapped to fabrication feature. In implicit design method, a heterogeneous CAD model is employed to represent the design and a feature recognition module is adopted to extract the fabrication feature from this heterogeneous CAD model.

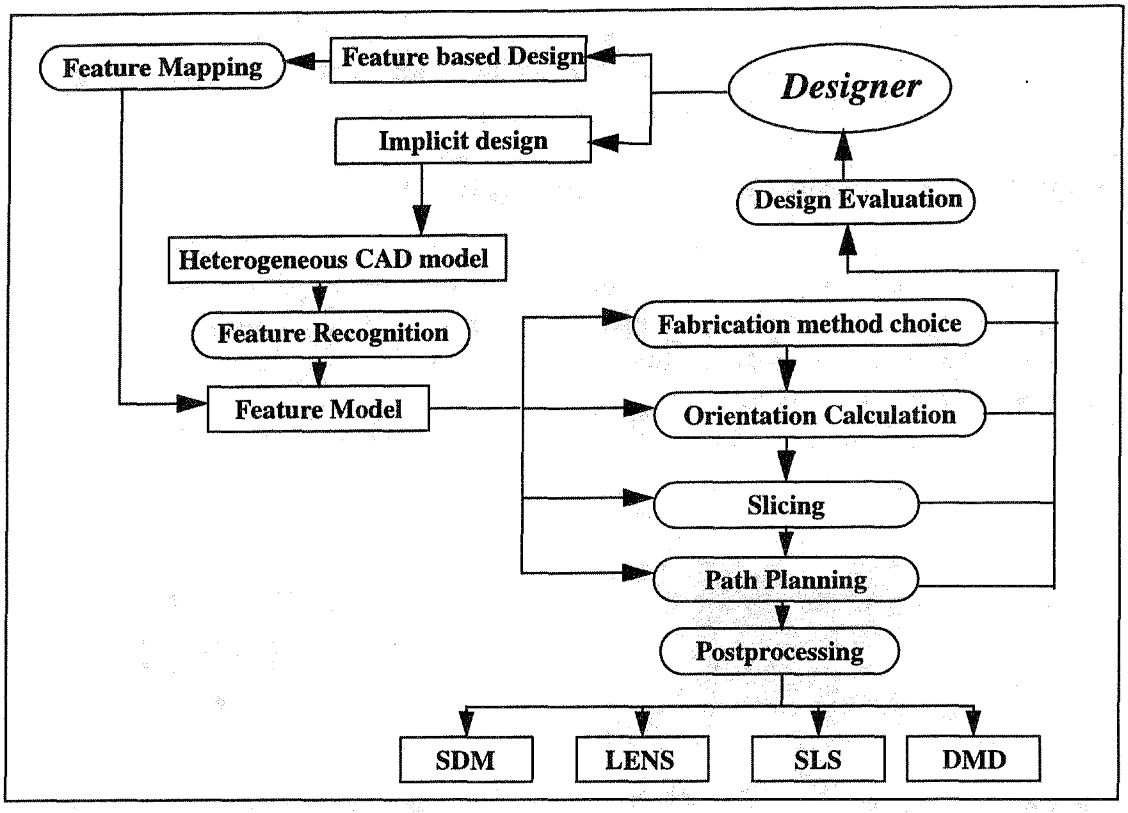


FIGURE 2. Feature based design and process planning for layered manufacturing

Understanding and characterizing the layered manufacturing processes is essential to generate the correct fabrication strategy. Feature based process planning is carried out on the basis of these characterization as well as the identified fabrication features. A set of mapping rules enable the identification of fabrication strategies, including orientation, slicing, road width, deposition path, etc., from the fabrication feature model. A final step might be post processing to generate the machine-specific data.

3.0 Features related issues in the LM domain

3.1 Design feature and fabrication feature

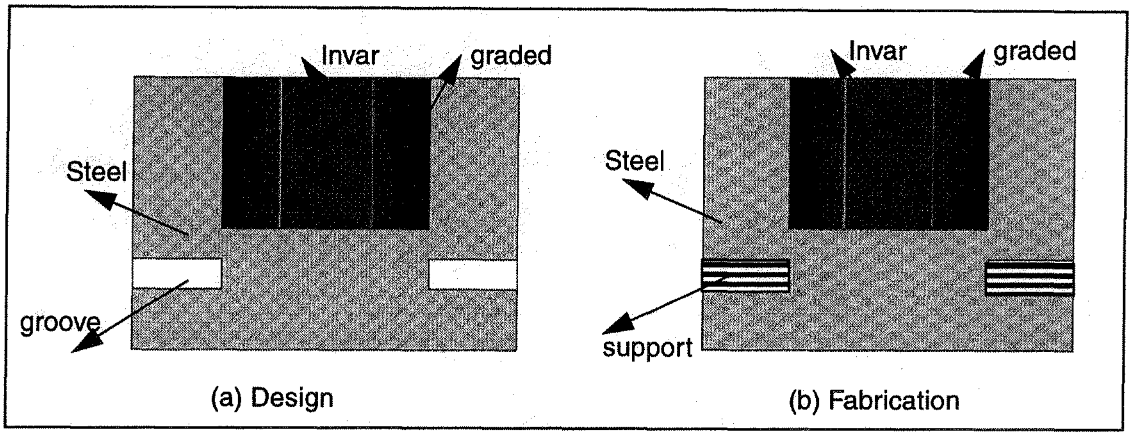
Developing the concept of design feature in the context of heterogeneous object is of importance in the feature based design approach. In this context, a closer look at how heterogeneous object design is done will be helpful. Furthermore, methods representing the design feature is also an important issue. In addition, the interactions among features of different material compositions demand specific feature operators beyond the conventional boolean operators. Finally, a library of design features can be developed to support the feature based design approach.

Similarly, understanding and identifying fabrication features in the context of layered manufacturing processes is necessary for the automation of process planning. This fabrication feature identification will be at the core of the fabrication strategy generation. Also an efficient representation of the fabrication feature is important.

Implicit design schemes such as the homogenization design method yield heterogeneous objects[5]. Creating heterogeneous solid models from such density data is a topic of ongoing research. For processing such designs, feature recognition algorithms will be necessary to extract the fabrication features from the heterogeneous solid model.

3.2 Mapping from design feature to fabrication feature

Consider the heterogeneous object shown in Fig. 3. During its design (Fig. 3a), the groove would be a design feature. However, for layered manufacturing, the same groove, becomes a fabrication feature made of (sacrificial) support material (Fig. 3b). As illustrated by this simple example, there is a need to identify situations requiring design-to-fabrication feature mapping and develop efficient mapping methods.



(a) Design

(b) Fabrication

FIGURE 3. Mapping from design feature to fabrication feature

3.3 Co-existence of NC feature and LM feature

It is increasingly becoming evident that in the future, manufacturing will include both NC machining and layered manufacturing. Hence, it is important to develop methods that exploit the symbiotic relationship between NC and LM -- material removal and material deposition. Consequently, feature extraction should be looked at within an enlarged context -- the synthesis of NC machining and layered manufacturing. Based on the extracted NC features and LM features, the optimal balance between NC machining and layered manufacturing has to be determined.

4.0 Our current research

4.1 Characterization of material variation

Heterogeneous materials arises in shape and materially optimized structures. They can provide a smooth transition between materials which are otherwise incompatible because of their mechanical or chemical properties. They can also be used as a coating to modify the electrical, thermal, chemical or optical properties of a substrate [6]. The material variation is usually along some specific direction, based on the functionality and design intent and can be explicitly captured by a swept volume representation (See Fig. 4).

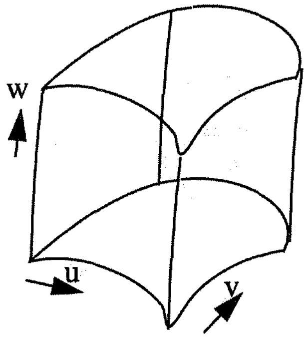


FIGURE 4. Swept Material Volume

Swept Material Volume [Working Definition]: *Swept Material Volume is composed of a cross-section and a path. The material could vary along the cross-section and/or along the path.*

Conventionally, a swept volume S (Fig. 4) is defined by sweeping a surface r(u,v) along path p(w). If '*' denotes sweep, the swept material primitive (Fig. 4) could be written as

$$\mathbf{SM(S, M) = (r(u,v) * p(w), m(u,v,w))}$$

where S represents the geometric volume, M represents the material composition, and material variation function m(u,v,w) represents the material changes along the cross section r(u,v) and path p(w). The material variation function could be any user defined function (e.g., constant, linear, step function, parabolic, exponential, etc.).

In practice, material variation typically would happen only along one of the u, v, w directions, denoted as m(u), m(v) and m(w). The function m(u,v,w) would enable full three dimensional material variation.

This characterization of material variation provides a simple way to impose and manipulate material composition over geometry. The actual part could be composed of a combination of these *swept material volumes*. Similar to a CSG object in current solid modeling, material survival rules in the synthesis of such volumes is an issue of ongoing research.

4.2 Design feature

The design feature volume is composed of a *swept material volume*. The following (working) definition extends the conventional feature by adding the material dimension:

Heterogeneous Design Feature

= (Conventional) Form Feature + Material Composition/Variation

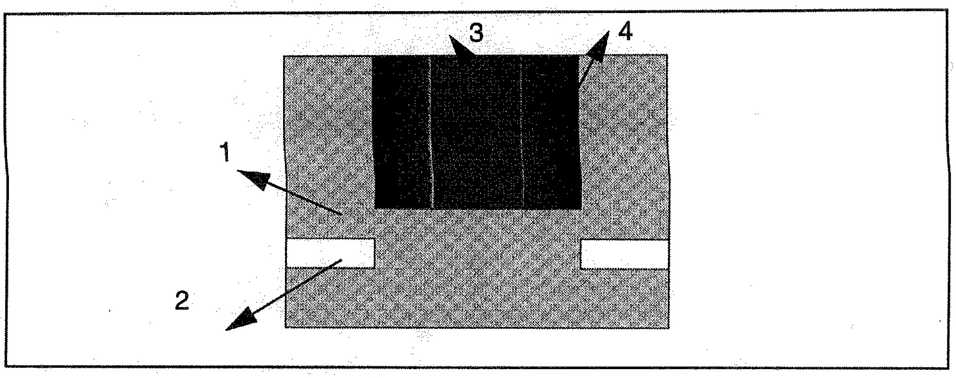


FIGURE 5. Design Features for Heterogeneous Object

In the sample part shown in Fig. 5, there are four design features (numbered 1 through 4). Each feature has a geometry and its own material composition (and fulfills a design function). Feature 1 is the base of the part and made of homogeneous material. Depression feature 2 is a groove. Feature 3 is made of another homogeneous material that is different from the base part material. Feature 4 provides the transition between 1 and 3 and makes the material property (e.g. coefficient of thermal expansion) transit smoothly from feature 3 to feature 1. In this way, feature based design can provide the designer an efficient way to synthesize heterogeneous objects.

4.3 Fabrication feature

Layered manufacturing parameters for heterogeneous objects would consist of layer thickness, road width, material composition and its gradation. Based on this characterization, *fabrication feature* can be thought as a subvolume that can be produced by LM in the same deposition configuration (i.e., material composition and gradation, road width, and layer thickness, are kept "constant"). We have the following (working) definition:

LM Fabrication Feature

= Subvolume + Deposition Configuration

The fabrication feature is a subvolume of a part that is distinguished either by the material type, material gradation, or the fabrication method. Each fabrication feature element shares the same material composition or shares the same material gradient and is part of the same *swept material volume.*

4.4 Feature based slicing

We envision fabrication features will facilitate the process planning for layered manufacturing. Here, we specifically look at how slicing information can be determined from the fabrication features under the assumption of simple geometry and compatibility of process resolution.

Denote the material composition at the height z as f(x,y,z). Then the maximum allowable layer thickness (d) could be derived from the maximum vertical gradient (Fig. 6) as:

$$d = \min\left[\frac{\delta}{(\partial f)/(\partial z)}\right]$$ where δ is the allowable material composition tolerance

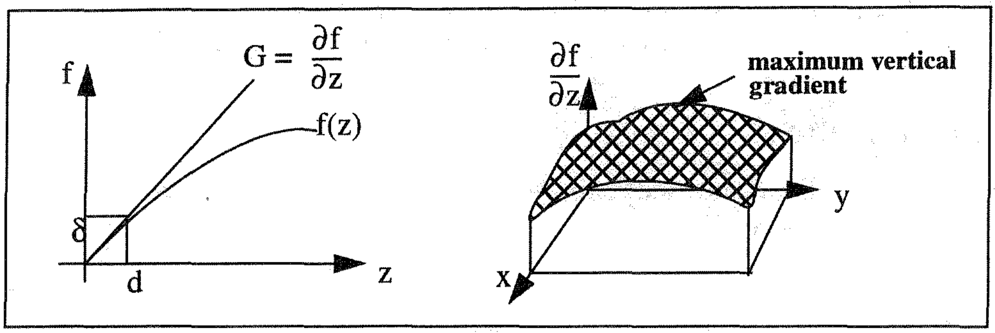


FIGURE 6. The vertical component of material gradient in one slice

Fig. 7 illustrates how material composition affects the slice thickness and road width.

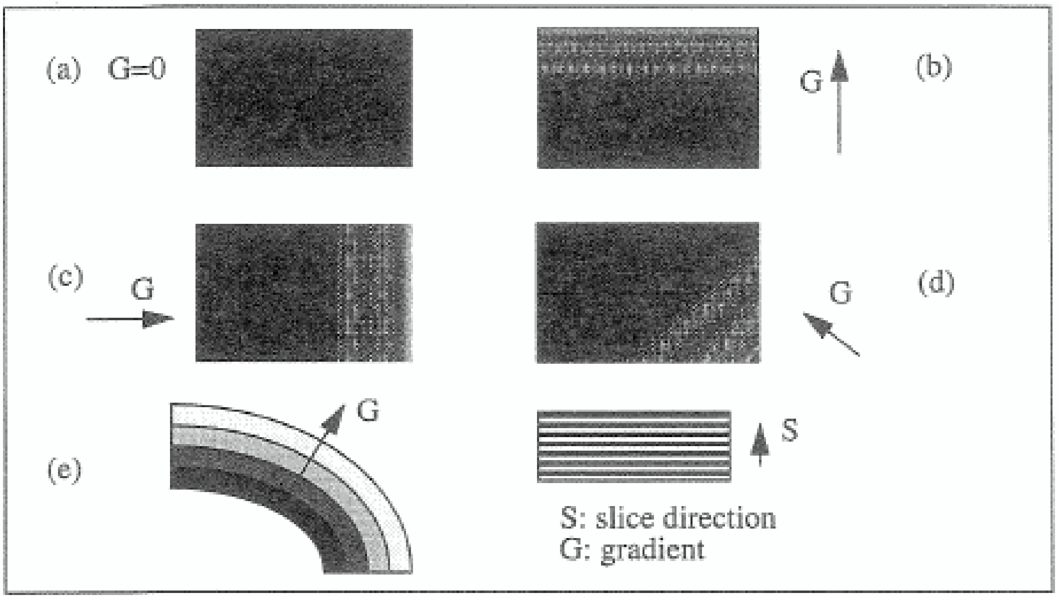


FIGURE 7. Material Gradation Direction versus Slice Direction

Denote the slice direction as S, the gradient as G, θ is the angle between S and G, δ is the allowed material composition tolerance. Then, the following rules can be used.

- If G=0 (Fig. 7a), it is a homogeneous object and the material composition can be ignored.
- If G || S (Fig. 7b), the slice thickness can be δ/G, and the road width can be maximum.
- If $G \perp S$ (Fig. 7c), the slice thickness can be maximum, the road width can be δ/G.

- If θ is the angle between S and G (Fig. 7d, e), the slice thickness can be $\delta/G\cos\theta$, and the road width can be $\delta/G\sin\theta$.

5.0 Summary

In this paper, we described feature related issues in the layered manufacturing of heterogeneous objects. An architecture for a feature based CAD/CAM system for layered manufacturing was presented. We proposed working definitions of *swept material volume, design feature* and *fabrication feature*. We also provided an overview of our ongoing work.

6.0 Acknowledgment

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7.0 References

1. Kumar, V. and Dutta, D., "An Approach to Modeling and Representation of Heterogeneous Objects", accepted for publication in *ASME Journal of Mechanical Design*, available as technical report, 1998.
2. Marsan A. and Dutta D., "On the Application of Tensor Product Solids in Heterogeneous Solid Modeling", *1998 ASME Design Automation Conference*, Atlanta, GA, Sep. 1998.
3. Grayer, A., "A Computer Link between Design and Manufacture", Ph.D. Dissertation, University of Cambridge, UK, Sep. 1976.
4. Shah, J. J., Mantyla, M., and Nau, D. S., edited, *Advances in Feature Based Manufacturing*, Elsevier, 1994.
5. Bendsoe, M. P. and Kikuchi, N., "Generating Optimal Topologies in Structural Design Using a Homogenization Method", *Computer Methods in Applied Mechanics and Engineering*, Vol. 71, pp. 197-224, 1988.
6. Rabin, B. H., and Shiota, I., "Functionally Gradient Materials", *MRS Bulletin*, Jan. 1995.