CAD MODELING AND RAPID MANUFACTURING OF HETEROGENEOUS OBJECTS: A REVIEW

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Abstract - Rapid manufacturing is emerging as a technology that enables the fabrication of three-dimensional heterogeneous objects. Compared to homogeneous objects, the fabrication of heterogeneous objects is very complicated for the processing of material information especially Functionally Graded Materials (FGMs). To take full advantage of rapid manufacturing, some methods to design and fabricate heterogeneous components have been developed. This manuscript presents the review of available CAD modeling systems for heterogeneous objects which need to accommodate the specification of geometry as well as material properties within the entire object. The use of heterogeneous CAD models in the process planning enables the automatic generation of valid and useful RP manufacturing data. The review of rapid manufacturing techniques that can take advantage of the discussed process planning method for the fabrication of heterogeneous objects are also described in detail.

Keywords: CAD model for heterogeneous objects, Rapid manufacturing, Process planning.

I. INTRODUCTION

Traditional CAD systems, used for conventional design method, can only represent the geometry and topology of an object. No material information is available within the representation which is required for heterogeneous objects. With the capability to fabricate heterogeneous objects, functionally efficient and cost reducing designs can be realized. The heterogeneous object design process involves three steps (i) one, designing the configuration of an object, (ii) two, determining the required material properties for each region of the object, and (iii) three, selecting material microstructures and/or constituent composition for each region according to the desired material properties. Rapid prototyping (RP) techniques allow heterogeneous material objects to be produced using 3D CAD models by varying material composition region-wise, layer-wise, or point-wise. The required 3D CAD model should have not only the geometric information but also the information of material, property, etc. at each point inside an object. Recent studies show that an effective heterogeneous CAD modeling system should at least meet the following specifications [6]: (a) Intuitive in representing geometry, topology and material information simultaneously; (b) Capable of representing complex solids: the solids to be modeled may be complex in geometry as well as in material variations; (c) Compact and exact: the representation should be compact, and both the geometry and material information can be retrieved accurately and efficiently; and (d) The representation of material properties must be compatible with current or proposed standards for geometric modeling representations as described in ISO 10033. This is essential to exchange data among design, analysis and manufacturing process plan domains.

In this paper, first, the heterogeneous objects are classified in Section 2. Then, the available procedure to fabricate heterogeneous objects is discussed in Section 3. Several existing CAD models for heterogeneous objects, suggested by various researchers, are presented in Section 4. Section 5 includes process planning tasks required for fabrication of heterogeneous objects. Available rapid prototyping processes for fabrication of heterogeneous objects are discussed in Section 6 and summary in Section 7.

II. HETEROGENEOUS OBJECTS

The term ‘heterogeneous object’ is defined such that it can have different material composition within an object. There are three subclasses of heterogeneous object [15]: (i) Multiple materials object; (ii) Object with sub-objects embedded; and (iii) Object without clear material boundary (Functionally graded materials, FGM) as shown in Fig. 1(a), Fig. 1(b), and Fig. 1(c).

![Fig. 1(a) Multiple materials objects](image)

![Fig. 1(b) Objects with sub-objects embedded](image)

![Fig. 1(c) Functionally graded materials](image)

III. STAGES IN FABRICATION OF HETEROGENEOUS MATERIALS

The deposition of material in RP processes can be explicitly controlled by providing unique opportunities to selectively deposit material. The material deposited can be varied from the region to region to create a multi-
material object or, varied continuously to yield a heterogeneous object. Fig. 2. shows a schematic of various stages involved in the design and manufacturing of heterogeneous objects.

IV. HETEROGENEOUS SOLID MODELS FOR RAPID MANUFACTURING

Methods for Heterogeneous Object Modeling (HOM) have been extensively studied in recent years. Some authors introduced the \( r_m \)-set and \( r_m \)-object model for the representation of heterogeneous solids which is defined as a set of points, whose material distribution can be represented by the same material mapping function \( F \), such that \( M = F(P) \) holds true for every point within the set [7]. In order to model these \( r_m \)-sets \( r_m \)-objects, modified Boolean operations have also introduced. Some proposed new operators such as heterogeneous insertion, merge and immersion in FGM modeling [14]. A complex-union operator is proposed in modeling multi-material objects [16]. The reasoning Boolean operation algorithm is currently limited to manipulate heterogeneous objects with two distinctive volumes and is not applicable to model functional degradable objects. A multiple material object \( A(M) \) is built up using the materials stipulated in the material vector \( M \). It is made up of a number of homogeneous material regions \( R^3_{Hi} (M_i) \), which can be written as:

\[
A(M) = [R^3_{H1} (M_1), R^3_{H2} (M_2), \ldots, R^3_{Hn} (M_n)]
\]

Complex solids are divided with tetrahedron decomposition methods and applied control points (for geometry) and control compositions (for material) in HOM [3]. In each decomposed sub-region, the material composition is obtained in terms of a set of control points and control compositions blended with barycentric Bernstein polynomials.

A level-set based variation decomposition method for the design of heterogeneous objects is proposed [18]. Level set model for two material classes is defined, in which the design objective is a regular and continuously differentiable function related to the material functions and a set of quantities representing physical behavior of the object such as stresses and strains.

Theory of \( R \) -functions is employed to construct smooth approximations to distance functions for closed semi-analytic features [10]. The geometry \( G \) is described as a set of points constrained by an implicit \( R \)-function. Using this approach, the inverse distance weighting interpolations can be generated and applied in smooth material gradation. Some authors model the heterogeneous objects as ‘multidimensional point sets with multiple attributes’ based on a function representation (FRep) which is used as CAD representation for point set geometry, and the attributes (material compositions in the context of FGM object modeling are represented independently using real-valued scalar functions) [8].

These decomposition-based methods need to decompose the interior into several simpler sub-regions. These methods possibly generate redundant entities (e.g. vertices, edges and faces) at the interfaces. This may challenge the material continuity at the interfaces. In addition, in some methods, the shape and material composition are represented by 3-D parameterization (e.g. NURBS or Bezier formulation). However, the general parameterization of an arbitrary 3-D solid is almost impossible.

To overcome the difficulties of decomposition-based methods, a new representation, namely constructive representation, was proposed [12]. Based on the variant design method, this scheme focuses on the construction of complicated heterogeneous parts, guaranteeing desired material continuities at all the interfaces. A heterogeneous object \( O \) is defined as a finite collection of heterogeneous leaf primitives \( P_a \) and heterogeneous Boolean objects \( B_i \), each of which is a Boolean construction of two lower-level heterogeneous objects. That is:

\[
O = \{ P_1, \ldots, P_a, B_1, \ldots, B_b \}
\]

where and \( a \) and \( b \) are finite

\[
= \{ (G_1, M_1), \ldots, (G_a, M_a), (Q_1, C_1), \ldots, (Q_b, C_b) \}
\]

The resulting material continuity depends on the designer’s intent and can be either no continuity (for homogeneous lumps of dissimilar materials) or higher order continuity for graded materials.

An enhanced model which allows structural variation in the dimensions and orientation is described [15] and a new concept of grading source is proposed. Using this concept, the effect of grading can be easily modified since the material data is independent of the primitives. Instead, they depend on the reference (e.g. point, line or plane) of the ‘grading source’. Some other information such as material distribution functions and composition arrays are also stored in the grading sources. Material grading take place between two material compositions arrays \( M_i \) and \( M_j \), which are defined to store the two end fractions of the grading process.

\[
\sum M_{ij} = 1 \text{ and } \sum M_{ij} = 1, \quad 1 \leq j \leq n
\]

where,

\[
M_{ij} = j^{th} \text{ element of material composition array } M_i
\]

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\]

\( n \) = number of primary materials

The volume fraction for the \( j^{th} \) primary material is:
\[
\begin{align*}
    v_j &= f(d) \times (M_{ij} - M_{ij}) + M_{ij}, \quad 0 \leq f(d) \leq 1 \text{ and,} \\
    \sum_{j} v_j &= \sum [f(d) \times (M_{ij} - M_{ij}) + M_{ij}] = 1, \quad 1 \leq j \leq n \quad (4)
\end{align*}
\]

For any chosen grading source, a distance function \( f(d) \) is used to evaluate the material composition of the object by considering the distance \( d \) of a point from the reference. The \( f(d) \) can be either linear or non-linear mathematical function according to which three regions are defined for each grading source \( G \) inside a heterogeneous object i.e. (i) effective grading region, (ii) – ve complementary region, and (iii) + ve complementary region. Hence, each of the grading regions is paired up with corresponding material composition array \( B \). The derived mathematical model has the capability to incorporate structural information, such as volume fraction, aspect ratio and orientation, of fiber reinforcement within the heterogeneous object.

Representing the microstructure in the heterogeneous model also needs to be studied that requires huge number of data to be stored. Even with the help of high-speed modern computers, the processing of the model is extremely difficult and needs extreme care. Few researchers developed a modeling method, which divides a component into many material regions \( (M_{ij}) \); based on two region sets \( (C \) and \( S) \), each has a specified material composition and microstructure [1-2]. For each region, integrated CAD model consists of three sub-models: geometric model, material composition model, and material microstructure model can be written as:

\[
 Q = \{ \text{Material constituent composition model:} \}
 C = \{ C_i, \ i = 1, 2, \ldots, n \}
 S = \{ S_j, \ j = 1, 2, \ldots, m ; m = (u + v + w), \}
 S_j \in (R + P + O) \}
 C \in \{ \text{Composi} \text{tive model:} \}
 R = \{ R_a, \ a = 1, 2, \ldots, u \}
 P = \{ P_b, \ b = 1, 2, \ldots, v \}
 O = \{ O_0 = "nil", \ d = 1, 2, \ldots, w \}
 M = \{ \text{Material region:} \}
 M = C \times S = \{ M_{ij}; \ i \in (1, 2, \ldots, n), \ j \in (1, 2, \ldots, m) \}
\]

Most of the heterogeneous objects modeling methods involve a sequential approach: first on 3D geometric modeling, followed by addition of material properties to models (material modeling) after the 3D geometry is fully defined. Although the material distribution can be modeled at 3D level, however the material is undefined or assumed homogenous at the lower 1D/2D level. With this assumption, the reference entities are generally homogenous in feature based schemes, and only 1D dependent material gradation can be modeled. Also, this sequence of modeling leads to unnecessary operations and over segmented 3D regions during heterogeneous object modeling processes. Some authors proposed a novel method, direct face neighborhood operation which combines the geometry and material decisions into a common computational framework as opposed to separate and sequential operations in existing modeling systems [9].

Some authors proposed a feature based method which retains the geometry-material relationship inside the complex geometry heterogeneous object [11]. It represents heterogeneous objects by a group of four characteristic sets, namely, a set of features (\( F \)) and a set of relations (\( R \)), the material composition (\( M \)) and composition variation (\( C \)). The point-set constituting a heterogeneous object made of \( n \) primary materials \( M_1, M_2, \ldots, M_n \) is denoted by \( O \) as follows:

\[
 O = \{F, R, M, C\}; \quad F = \{\{FF\}_{a=0, \ldots, A} \cdot \{GF_b\}_{b=0, \ldots, B}\} \in E_3
 R = \{R_{a,b} \}_{a=0, \ldots, A, a \neq a, b=0, \ldots, A, a \neq a}
 M = \{\{M_{ik}\}_{i=0, \ldots, A, k=1, \ldots, n}\} \in E_a
 C = \{C_b\}_{b=0, \ldots, B}
\]

To represent the continuous spatial distribution of material compositions, B-spline functions are used which can represent any shape of material variation.

In the feature-based design approach, an object model is designed using its form features which are constrained by means of various parameters specifying their relationships with other features. The main advantage of the model is that the features of an existing relationships can be changed to obtain a new model, called a variant, and the process is called variational design. In the variant model, all the constraints of the parent model are maintained. To exploit this advantage, the relationships are developed between material attributes and geometric features which are formalized and established as object-material constraints.

Few researchers developed a system prototype for modeling the components made of multi heterogeneous materials under the guidance of axiomatic design theory [2]. It consists of three main functional modules, that is, heterogeneous component modeling module, models integrating module, and object demonstrating module. The first main module contains all the information needed for modeling, including geometric model and different schemas holding the material information.

The second main module can combine all the schemas into an integrated model and describe it using a unified data structure. The last main module is used to slice the component at a certain position selected by users to obtain the contour of cross-section, and to display the cross-section with the contours of different material areas and show the detailed microstructures if needed. Since the system was designed under the guidance of Axiomatic Design, it has good modularity.

A novel approach of representation and process planning for rapid prototyping of 3D complex shaped FGM objects, termed as equal distance offset (EDO), has been developed [20]. The two key components of the EDO approach are (i) the association of the material composition with the 2D layers rather than the 3D object directly, and (ii) the generation of the material composition in each 2D layer through the application of the equal distance offset algorithm. As per this approach the distance from the internal boundary to the external...
boundary in g-direction is 1, and (m - 1) contours are generated from the internal to the external boundary.

Fig. 3 EDO approach of representation of sub-regional FGM: (a) determination of gradient direction and (b) relationship between contours and sub-regions [20]

As shown in Fig. 3., C_2, C_3,……….and C_r represent the contours to divide the 2D sliced region into a number of the sub-regions. In this case, the distance from the internal boundary C_r (i.e. C_r) to the jth (j = 1, 2,……, m + 1) contour (or boundary) can be expressed as: d_j = (j - 1) / m, j = 1, 2, ………,m + 1. Thus the gradient material distribution function f(d_j) can be defined as:

\[ f(d_j) = \begin{cases} 0, & \text{for } d_j = 0 \\ f(d_j) \in (0, 1), & \text{for } d_j \in (0, 1), \text{ discrete } 1, \\ f(d_j) = 1 & \text{for } d_j = 1 \end{cases} \]  

(7)

Most of the available heterogeneous CAD models for FGM have 1D dependent material variation which limits its applications and do not assure smooth material distributions in all directions. Therefore FGM with multiple materials interfaces and complex material variations can be obtained by considering 2D/3D dependent material properties. In nature, objects with compound material distributions are also common. Examples of this type of objects are animal tissues (e.g., human bone and cartilage), plant structures (e.g., wood.) and geological materials (e.g., rocks, soil). The material information should be accessible at all the 1D, 2D and 3D levels. In this context, the hierarchical representation is developed that integrates material information at these levels and the Heterogeneous Feature Tree (HFT) structure is proposed to model the material variation dependency relationships [6]. One-dimensional heterogeneous features are first defined; 2D and 3D complex features are subsequently built hierarchically from the lower level 1D/2D heterogeneous features.

V. PROCESSING OF HETEROGENEOUS SOLID MODELING FOR RM

The RM processes are dependent on a CAD model of the heterogeneous object which generates the required information for driving the RP machine. The necessary tasks to generate this information are termed as process planning tasks. Current process planning tasks for homogeneous objects are orientation (build direction selection), support generation, slicing (uniform or adaptive) and tool path generation (fill pattern generation) for each layer. Process planning of heterogeneous objects, as shown in Fig. 4., requires the determination of a near-optimal orientation for the part, the generation of a support structure and subsequent decomposition of the part into simpler entities that are conducive to automated fabrication.

However, this mode of operation does not allow for easy and early communication of process-planning concerns to designers who are not already process experts. One method of early communication is to provide designers with pre-processed library components, and rules for transforming and merging them into designs. Another approach is to convert continuous material variation into stepwise variation by employing a pre-processing step called discretization. In fact, by employing this pre-processing step, material information inside an object is converted into material features (internal surfaces) like geometric features (external surfaces). After discretization, each discretized lump can thus be processed by the conventional process planning tasks. Procedures for generating the database hierarchy and the storage of the heterogeneous model, and derivations for developing the processing algorithm for fabrication of heterogeneous structure are evolved.

The available algorithm is applied to a heterogeneous structure consisting of two discrete material volumes, and the detailed processing path is described [19]. The algorithm begins with the generation of material volume regions by assigning material attributes (identification) into the STL files that were exported from the heterogeneous solid assembly. The material volume regions serve as the interface between the heterogeneous structure CAD modeling and heterogeneous fabrication structural modeling. After the generation of geometrical profiles for each of the material volume regions assembled in the heterogeneous model, the process for slicing can be defined. Slicing can be uniform, with a constant layer thickness, or adaptive, with...
variable layer thickness according to the curvature of the bounding surfaces in the model. Each material volume region will generate cross section contours and will form faces during the slicing process. Using parallel scan lines to scan these polygons at each layer, the fabrication path can then be generated. The processing program is the assembly of the fabrication path after all layers of heterogeneous fabrication structure model is processed.

In processing a heterogeneous solid model, the continuous material distribution is discretized in 2D space rather than in 3D space and only material distribution functions are saved in slice files. The slicing process goes along with the manufacturing process of heterogeneous objects concurrently. Therefore, much memory can be saved. In this approach, the slicing process of heterogeneous objects is divided into two steps. First, the geometry of the 3D model is directly sliced into many thin 2.5D layers with a constant layer thickness to determine the contour of each layer. The determination of layer thickness should consider not only geometry tolerance but also material tolerance. The minimum layer thickness that meets the requirement of both geometry and material tolerance should be selected to slice the model. Second, material compositions information of the model is decomposed (sliced) to determine the material distribution in each layer. This is a process of discretizing the continuous material distribution that includes tessellating the contour into many cells and evaluating the material compositions in each cell. First, the contour of each layer is tessellated into many small cell meshes. Each cell is small enough to be considered as a homogeneous lump. Second, the distance from the center of each cell to the reference feature is evaluated so that the material compositions in each cell can be evaluated by material distribution function, which uses the distance as its parameter.

VI. RM PROCESSES FOR FABRICATION OF HETEROGENEOUS OBJECTS

RM involves some RP processes which can fabricate heterogeneous objects by selectively depositing various materials in a point-wise fashion using 3D-CAD data representation without special tooling. In these processes, a uniform layer of powder is spread over the build area and the different layers are joined together by different methods to form the prototype.

Selective laser sintering (SLS) of powder materials seemed to have the potential to produce functional prototypes, even for direct tooling fabrication [13]. Shrinkage, porosity, and low density of parts are the limitations of SLS that prevent it from competing against machining. Laser cladding (LC)-based freeform fabrication technology has emerged as a promising approach to remedy the deficiencies in SLS. LC offers several advantages including flexibility in processing materials, fine grain structure, low dilution, minimal thermal degradation, formation of non-equilibrium crystalline and amorphous structures, and extension of solid solubility of alloying elements [17]. Despite such significant development, the LC-based RP processes suffer from drawbacks including unsatisfactory surface finish, residual stresses, low dimensional accuracy, porosity, and crack formation.

To produce high-performance functional components, such as molds and dies that are free of the defects as mentioned above, a novel LC-based RP technique, namely, laser-based flexible fabrication (LBFF), has been developed [4]. LBFF uses a quasi-coaxial nozzle for powder delivery to fabricate objects with functionally graded composition and microstructure with desired surface finish and dimensional tolerance, and reduced residual stresses and dilution in the functional layers. Since LBFF involves direct interactions between moving heat source and powder materials, the phenomena of mass transport, heat transfer, and fluid flow makes it rather complex.

Another RP process, 3D Printing is particularly well-suited to the fabrication of parts with local composition control (LCC). 3D Printing creates parts in layers by spreading powder, and then ink-jet printing materials into the powder-bed. Shape deposition manufacturing (SDM) is a RP process that integrates material deposition and material removal processes. Another type of RP process - ballistic particle manufacturing (BPM) builds prototypes by solidification of molten material. Besides the BPM process, a similar RP process - fused deposition modeling (FDM) can be employed to build multiple material objects.

VII. CONCLUSION

The present work identifies various types of heterogeneous objects and presents the available CAD modeling systems for heterogeneous objects with simple geometry and complex material variations. It also tries to assess the suitability of various CAD models for modeling heterogeneous objects especially FGMs. Further research is still required to be conducted to develop CAD model for complex geometry heterogeneous objects with 3D material variation. The heterogeneous CAD models are processed to generate the required information for driving the RP machine for rapid manufacturing. Process planning of heterogeneous objects requires the determination of a near-optimal orientation for the part, the generation of a support structure and subsequent decomposition of the part into simpler entities that are conducive to automated fabrication. The heterogeneous CAD models for the process planning are still needed to be modified to enable the automatic generation of valid and useful RP data. Compared to homogeneous objects, the fabrication of heterogeneous objects is complicated due to inclusion of material information especially in the case of FGMs. The deposition of material in RM needs to be explicitly controlled to provide unique opportunities to selectively deposit material. RP processes to fabricate heterogeneous objects with 3D material variation and to produce high-performance functional components that are free of the defects are still required to be developed.

REFERENCES

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