# Converting a CAD model into a manufacturing model for the components made of a multiphase perfect material

Feng Zhu[a], Ke-Zhang Chen[a], Xin-An Feng[b]
[a]Department of Mechanical Engineering, The University of Hong Kong, Hong Kong
[b]Faculty of Mechanical Engineering, Dalian University of Technology, China
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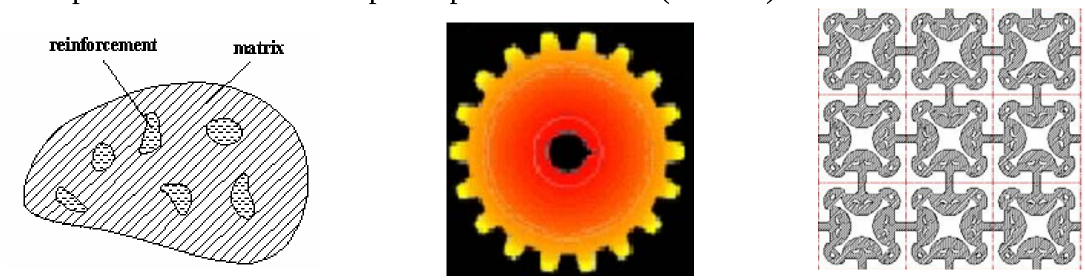
## Abstract

To manufacture the component made of a multiphase perfect material (including homogeneous and multi heterogeneous materials), it CAD model should be processed and converted into layered manufacturing model for further transformation of numerical control (NC) coding. This paper develops its detailed approaches and corresponding software. The process planning is made first and includes: (1) determining the build orientation of the component; and (2) slicing the component into layers adaptively according to different material regions since different materials have different optimal layer thickness for manufacturing. After the process planning, the layered manufacturing models with necessary information, including fabrication sequence and material information of each layer, are fully generated.

## 1. Introduction

With the rapid development of high technology in various fields, there appear more special functions of the mechanical components or products, which may require component materials to possess some special properties. Since conventional homogeneous materials cannot satisfy these requirements, attention has been paid to heterogeneous materials, which may include composite materials, functionally graded materials (FGMs) and heterogeneous materials with a periodic microstructure (HMPMs), which are shown in Figure 1. However, different portions of a component may have different special requirements and the component made of a single heterogeneous material cannot meet all special requirements in its different portions, but only some. To satisfy all requirements, it would be necessary to use components made of different materials, including homogenous materials and the three types of heterogeneous materials, thus meeting all special requirements in different portions and also making the best use of different materials, just like nature's organisms (e.g. bamboo, tooth, bone etc.) which have perfect combination between materials and functions after a long time of evolution. A component, which has a perfect combination of different materials (including homogeneous materials and different types of heterogeneous materials) in its different portions for a specific application, is considered as the component made of a multiphase perfect material (CMPM).




(a) (c)

(b)

Fig. 1 Three types of heterogeneous materials

To design and represent such components according to the requirements from high-tech applications, a corresponding computer-aided design method [1] (including both geometric and material design) and a corresponding CAD modeling method [2, 3] (containing both geometric and material information) have been successfully developed and can be implemented by applying the functions of current CAD/CAE software.

## 2. Review of the fabrication approach for the CMPMs

To produce the CMPM, the fabrication technique should satisfy the following requirements [4]: (1) Adding materials that may have different constituents with their required volume fractions for each pixel (needed for all these heterogeneous materials) and inclusions with the required distribution and quantity (needed for composite materials); (2) Obtaining the material layer (probably very thin) with precise thickness (needed for periodic microstructures) and boundary(needed for all these heterogeneous materials); (3) Removing materials from the layer to create very small and precise voids for periodic microstructures (needed for the materials with a periodic microstructure).

It is obvious that the CMPM cannot be fabricated using traditional material subtractive processes (e.g. machining) or material additive processes (e.g. layered manufacturing (LM)). A hybrid manufacturing technique incorporating with traditional machining, LM and micro-fabrication techniques was proposed [4]. The workflow of this hybrid LM technique is as follows:

(1) If there is adjoining material regions which are higher than the layer to be spread, remove the superfluous material from the layer by an end mill to obtain precise boundary of the layer, since the spraying area of a jet is much larger than a pixel so that the practical area of obtained layer is larger than the required area, and, at the same time, suck out the formed chips by vacuum;
(2) Spread a material layer with the required thickness (layer thickness must plus a rough grinding allowance and a finish grinding allowance for the material region of periodic microstructures) and constituent composition (for all material regions) and, at the mean time, spray the inclusion with the require distribution and quantity to stick in the layer (only for composite material region) for every pixel;
(3) Grind the top surface of added material layer by the annular end face of a cup grinding wheel to obtain a required thickness of material layer (layer thickness must plus a finish grinding allowance for the material region of periodic microstructures), since metal cladding is not flat enough and the thickness of the added layer is not accurate enough, and, at the mean time, suck out the formed chips or sludge by vacuum; If the layer being fabricated is not the material region of periodic microstructures go to step (1).
(4) Engrave or sculpt the layer to create the necessary voids for periodic microstructures with a required depth (layer thickness plus a finish grinding allowance), and, at the mean time, suck out the formed chips or sludge by vacuum.
(5) Fill the void with a material with lower strength and high melting point to avoid the refilling of the material spray for next layer;
(6) Grind the top surface of the material layer again to remove superfluous lower strength material and the burrs formed (3). This will ensure that the required thickness and flatness of the material layer is produced;

(7) Repeat step (1) to spread material for next layer until the component is completely fabricated. The component so formed will have the required constituent composition, inclusions and their distribution, and/or periodic microstructures with lower-strength materials in the voids. The lower-strength metal in the voids will not affect the function of the component and can protect the component from erosion.

In the second step, plasma spraying [5] has been selected for the spreading and Laser micromachining [6] is used for the engraving in the fifth step.

## 3. Process planning for the CMPMs

Based on the hybrid fabrication technique, the process planning (PP) for the CMPMs can be further developed. The PP acts as a bridge between the 3D CAD model domain and 2.5D layered manufacturing model domain. Although the CMPMs cannot be produced by applying the current LM machines, they are still fabricated layer by layer in the hybrid manufacturing process. Therefore, the PP for the CMPMs can be developed based on that of the traditional LM. The PP for the traditional LM goes through: (1) determining the build orientation of an object; (2) slicing the object; (3) generating the support structure for the object; and (4) generating the tool paths. After the first two steps, the 3D model has been converted into 2.5D layers, and the necessary information has been generated. Since the last two steps can be performed based on the generated layers and usually implemented by commercial software packages, the last two steps are not discussed in this paper.

Many algorithms for the PP in LM have been reported in some literatures [7, 8]. However, these methods are mainly based on an object's geometry and do not consider the material variations, inclusions and microstructures in the heterogeneous objects. Some researchers [9] proposed a new approach for objects with FGM by taking into account the material resolutions and the varying direction of material volume fractions. But the machinability and the effective properties of microstructures still have not been considered. Thus, a new approach for CMPMs should be developed, in which the first priority should be to ensure its functional properties, i.e. material effective properties, and the geometric accuracy can be regarded as the second priority.

### 3.1 Determining the build orientation of an object

The purpose of the first step is to select a suitable direction in which the object is to be fabricated. During determining this direction, many related factors need to be considered, such as the total build time, surface quality and finish, component mechanical properties etc [8]. The orientation of the objects made of FGM in some powder-based LM processes is determined mainly based on reducing build time and material constituent composition error. In these processes, a heterogeneous object is discretized into a lot of small homogeneous layers, each of which has a specified mixed material without gradation. All of the layers are deposited one by one and the powder for the specified mixed material of each layer is fed manually. Therefore, the goal is met by selecting a suitable direction that can minimize the variation of material constituent composition in each layer [9], which is also the best way to ensure the effective properties of the finished FGM [10]. But, using the plasma spraying in the hybrid manufacturing system, the material powders are mixed automatically according to the requirements and deposited pixel by pixel. Therefore, the objects' quality and build time are not effected by the varying direction of material constituent composition.

In the case of CMPMs, the machinability and the effective properties of periodic microstructures have to be considered further. This requirement can be satisfied by minimizing following summation ($\sum\int A_i\alpha_i$), where $A_i$ is the area of the main surfaces in base cell, and $\alpha_i$ is the angle between surface $A_i$ and the normal of the worktable of LM machine. The approach can increase layer's thickness in LM machine, thus can improve the fabrication efficiency.

### 3.2 Adaptive slicing

After the build direction has been determined, the orientated model is sliced to yield the slices. To slice the objects with homogeneous materials, only geometric surface finish of the object and build time are considered. The contradiction between these two factors led to the development of different slicing algorithms [12]. However, these algorithms cannot be directly applicable to heterogeneous objects, and have to be modified to take into account the material information [13]. Kumar et al. [13] proposed an approach to address the issues of slicing heterogeneous objects by considering both the geometric profiles and material variations. But, for object with multi heterogeneous materials, the reasonable layer thickness for periodic microstructures and composites should also be considered, respectively, because different heterogeneous materials have different optimal layer thicknesses for manufacturing. Figure 2 illustrates different layer thickness for different material regions (denoted with different colors and symbols). It should be emphasized that a "layer" in this paper refers a material slice for one type of material region, not for the whole component. Therefore, a new slicing algorithm needs to be developed. Before the slicing operation, the component should first be divided into blocks using parallel planes perpendicular to the build orientation to ensure that each block only has the (part of) material regions whose height equal the height of block. Since the slicing operation is associated with fabrication sequence determination, its detail will be discussed in the next section.

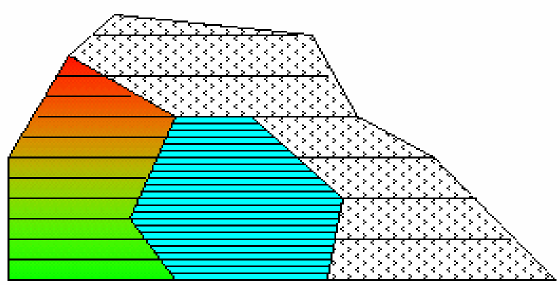


Fig.2 Different layer thickness for different material region

## 4. Establishing the layered manufacturing model

Although the CAD model for CMPMs include all the necessary information, it cannot be applied for layered manufacturing directly. The 2.5D layers with geometric and material information should be integrated as a layered manufacturing model, so that the numerical control codes can be programmed. The layered manufacturing model has three types of data: (1) Fabrication sequence; (2) Spraying information; and (3) Periodic microstructures information. The approaches for generating these data are introduced as follows:

### 4.1 Fabrication sequence

As mentioned previously, for the object with multiphase perfect materials, the reasonable layer thickness for different material regions may be different. In other words, the spraying surface of different material regions are usually not identical. The spraying thickness of periodic microstructures regions should be determined by the size and complexity of their base cells. The base cells with smaller size and more complicated shapes have smaller thickness. This thickness can be assigned as 1/10 ~ 1/20 of the base cell dimension, and usually less than 0.1 mm. The spraying thickness of composite materials and FGM regions should be determined based on the variations of material constituent compositions, and typically 0.5 ~ 2mm. The region with larger gradient of material constituent compositions has smaller thickness. Since the top surface of added material will be grinded by an annular face of a cup grinding wheel after the spray operation, the material surface to be grinded should be higher than others. Therefore, a reasonable fabrication sequence planning is imperative. The procedure goes through (1) Sub-dividing the CAD model into blocks; (2) Generating fabrication sequence for each block; and (3) slicing the blocks into layers, which is introduced in detail as follows:

*4.1.1 Sub-dividing the CAD model into blocks*

In order to calculate the deposition thickness and plan the fabrication sequence, the object should be first divided into several blocks by parallel planes perpendicular to the build orientation. Each block only has (part of) the material regions whose height is equal to the height of block. This can be done using a sub-division algorithm. For example, the CAD model for a CMPM shown in Figure 3 has five material regions and can be divided into four blocks by using this algorithm.

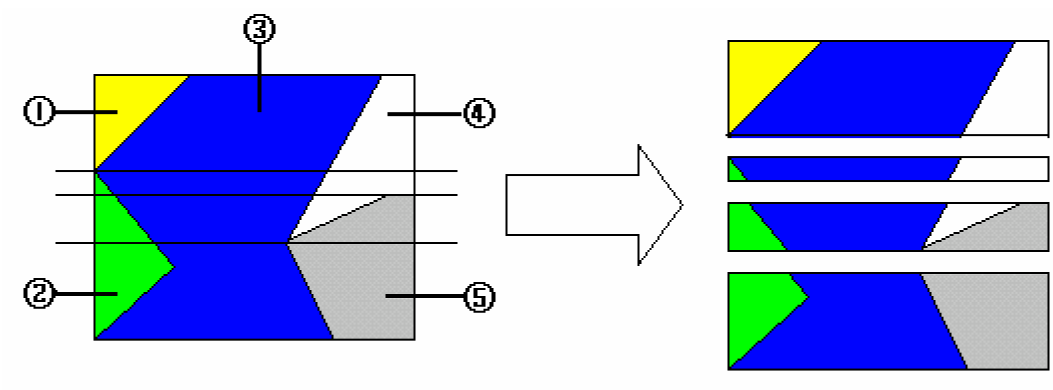



Fig. 3 Sub-dividing the CAD model into blocks

*4.1.2 Fabrication sequence generation for each block*

Since each block only has such material regions whose heights are equal to the height of block, the deposition thickness and fabrication sequence for one work cycle in each block can be calculated. For each block, the input data are its CAD model and layer thickness for each material region in this block.  The output data are the deposition thickness and the fabrication sequence in each work cycle. For example, assume that the optimal spraying thicknesses for periodic microstructures, FGM and composite materials are 0.2mm, 0.5mm and 1.5mm, respectively. Their lease common multiple is 3.0mm, which can be considered as the deposition thickness for a work cycle. The fabrication in one work cycle is illustrated in Figure 4. The cycle has 18 steps, and in each step the worktable moves down 0.1 or 0.2 mm. Once the worktable moves down 0.2mm, the periodic microstructure regions denoted by M will be sprayed. When the worktable moves down every 0.5mm, the FGM regions (denoted by F) will be sprayed. And when the worktable moves down every 1.5mm, the composite material regions (expressed using C) will be sprayed. In the case that different material regions have the same spraying height, the spraying operations are executed for different material regions one by one. In Figure 4, the hatches denote the spraying thickness.

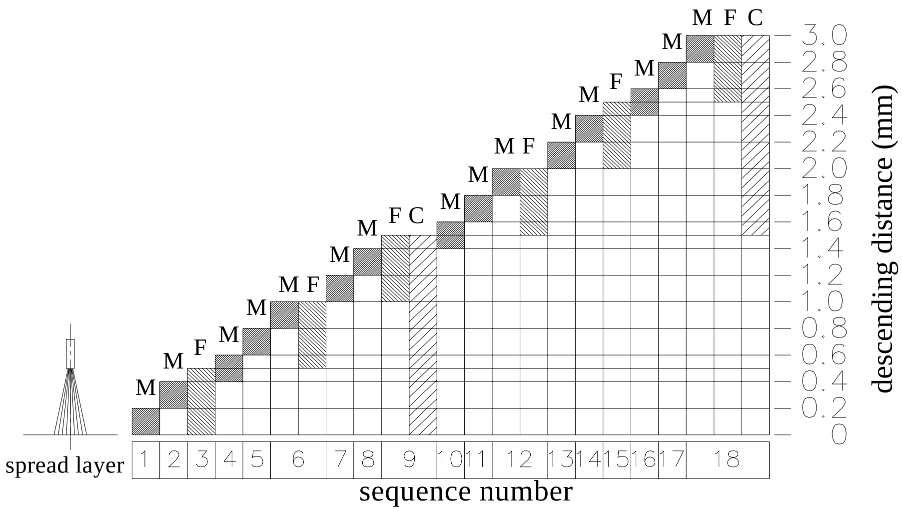



Fig 4. Fabrication sequence in one work cycle

*4.1.3 Fabrication sequence generation for the object*

Having used above mentioned approach to generate the fabrication sequence for each block, the fabrication sequence for the object can be generated by integrating the fabrication sequence of all blocks.

*4.1.4 Adaptive slicing operations*

Following the generated fabrication sequence, the adaptive slicing routine is called to yield the geometric profiles, generate spraying information and microstructures information for each material region at the calculated height, which have been reported in the literature [14], and outlined in the following sections.

## 4.2 Spraying information

The spraying data on each layer includes geometric and material information: i.e. the geometric boundaries of the spraying regions; the spraying thickness of each spraying region; the code names of material constituents and their compositions; the code names of composite inclusions and their volume fractions. These two types of information are described as follows:

*4.2.1 The geometric boundaries of material regions*

As discussed in adaptive slicing, the geometric boundaries can be obtained by intersecting the 3D geometric models of each material region in the CMPMs with the slicing plane.

*4.2.2 The material constituents and their volume fractions in each spraying region*

The code names of material constituents and their compositions and the code names of composite inclusions and their volume fractions can be retrieved from the CAD model of the CMPM. The constituent composition function in the CAD model, which is the function as to the coordinate values of spraying points (*x, y, z*) in the local coordinate system, should be first converted into the function as to the points (*X, Y, Z*) in the global coordinate system. Since the CAD model intersects with the plane $Z=Z_0$ ($Z_0$ is the height of the spraying surface), the final constituent composition function has been converted to a function as to 2D points (*X*, *Y*) in the global coordinate system.

## 4.3 Periodic microstructures information

The periodic microstructures information in each layer includes: spraying thickness, the 2D shape and position of the voids. The periodic microstructures information in the CAD model for the CMPMs covers the variational geometric model of the base cell, inserting functions of insertion positions, functions for calculating dimension and orientation, with which the entire region of the periodic microstructures can be described. The shape and position of the voids can be obtained by intersecting the base cell array of microstructures, which are determined by their inserting points, with the spraying plane.

Since the number of inserting points of a material region is very huge while the number of base cells intersected with the spraying plane is much less comparatively, an efficient scanning algorithm is required to reduce the time of searching the related inserting points. This paper applies an approach [14], with which the search space is restricted within a very narrow scope for saving computing time.  As shown in Figure 5, the inserting point array is sliced by a spraying plane with a thickness *S* and an angle *Φ* from positive *z*-axis. Two auxiliary planes parallel to the spread or slicing layer are used to determine the search scope. The distance between each auxiliary plane and the middle layer of spread layer is $L_{max}$, which is the largest difference of the vertical distances of inserting points from the middle layer of spread layer. This can ensure that all the base cells to be sliced on the layer should fall into the space between the two auxiliary planes.

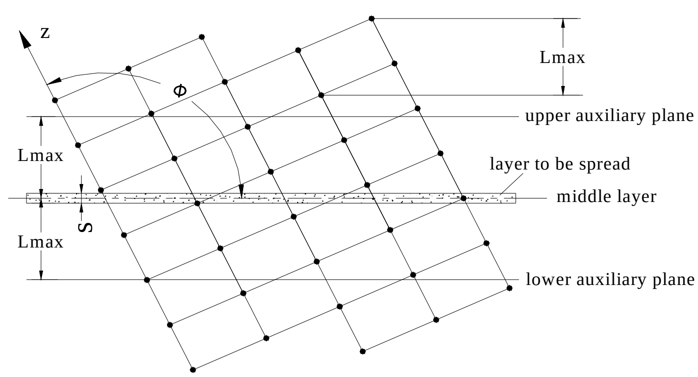



Fig 5. Search the base cells intersecting with the spraying plane

## 5. Data structure of layered manufacturing model

After generating the layered manufacturing model, the geometric and material information for each layer should be integrated and kept in the layer files, with which the NC codes can be programmed. Currently, many layer formats are available, including CLI, LEAF, SLC, HP-GL, and G_WORP etc. [15]. However, they only carry the geometric information, and hence cannot be applied directly as the layer format for the layered manufacturing model of CMPMs. As to those objects with material information, there is no suitable layer format to represent them yet, and this issue has actually become one of the bottlenecks in the rapid prototyping industry [7]. Aiming at this point, a frame of new data structure for the layered manufacturing model of CMPMs is proposed as shown in Figure 6. The information can be organized hierarchically into a tree structure.

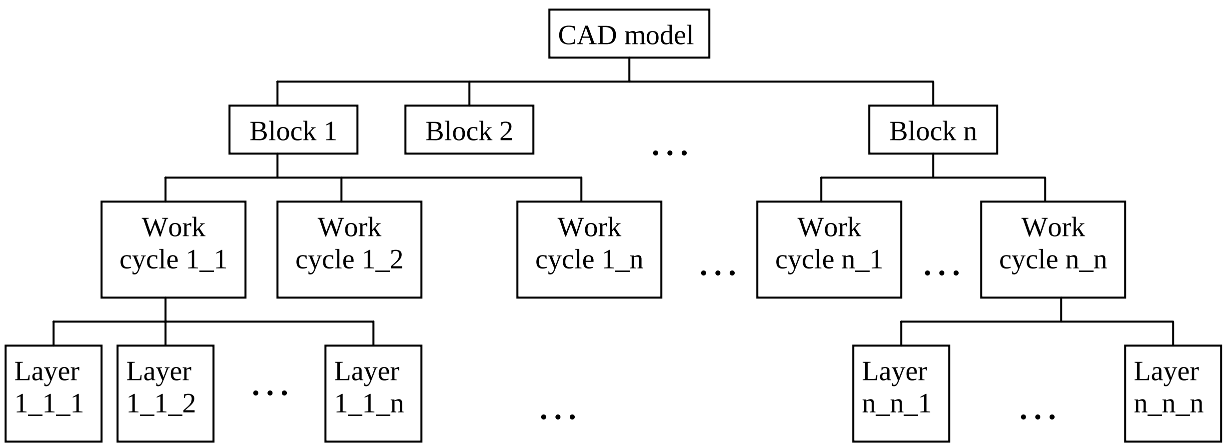



Fig. 6. The tree structure of the CAD model

In the model tree, each leaf is a layer, which is kept in a file. Note that not all of the layers should be stored, since the data of the whole CAD model is very huge. A "use and throw" strategy can be employed, in which only one layer is calculated and stored at a time. That is, when the current layer is under fabrication, the next layer is calculated and stored. When the fabrication moves to the next layer, the data for the current layer will be discarded and another layer will be calculated and stored, until all of the layers are finished.

A layer is the smallest unit in this data structure, which can be regarded as a class (shown in Figure 7) according to the object-oriented thought [16].

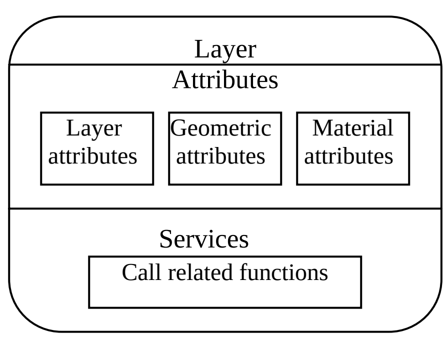



Fig. 7 A layer class

For example, as to the FGM layer, its class diagram is illustrated in Figure 8. When a material constitute composition function is specified, its corresponding sub-routine is called, the boundaries and material code names of one layer are inputted as parameters, then the material volume fractions at each position can be calculated correctly.

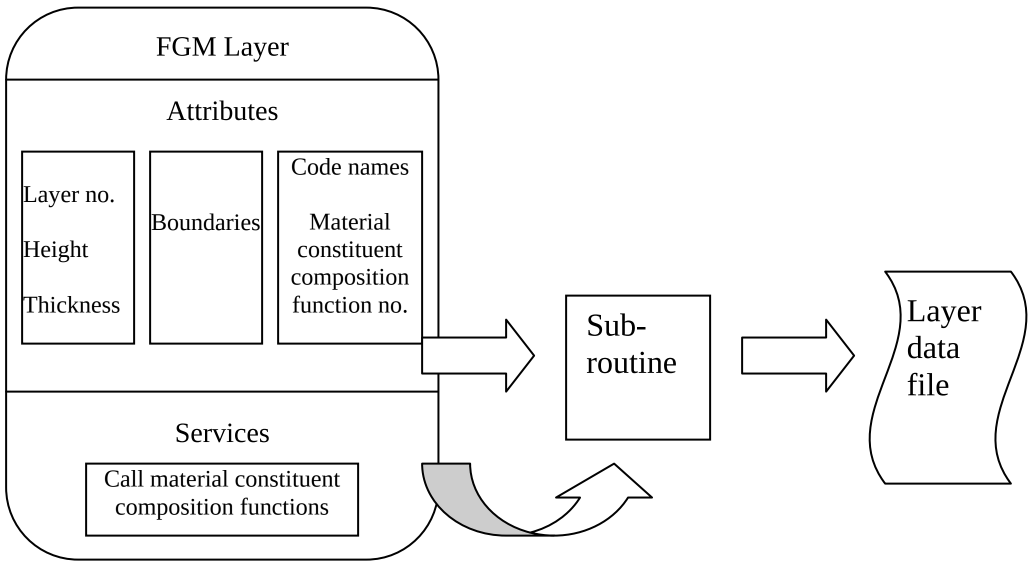



Fig. 8 The class for a FGM layer

The class for a composite layer has a similar diagram as that of a FGM layer, as shown in Figure 9.

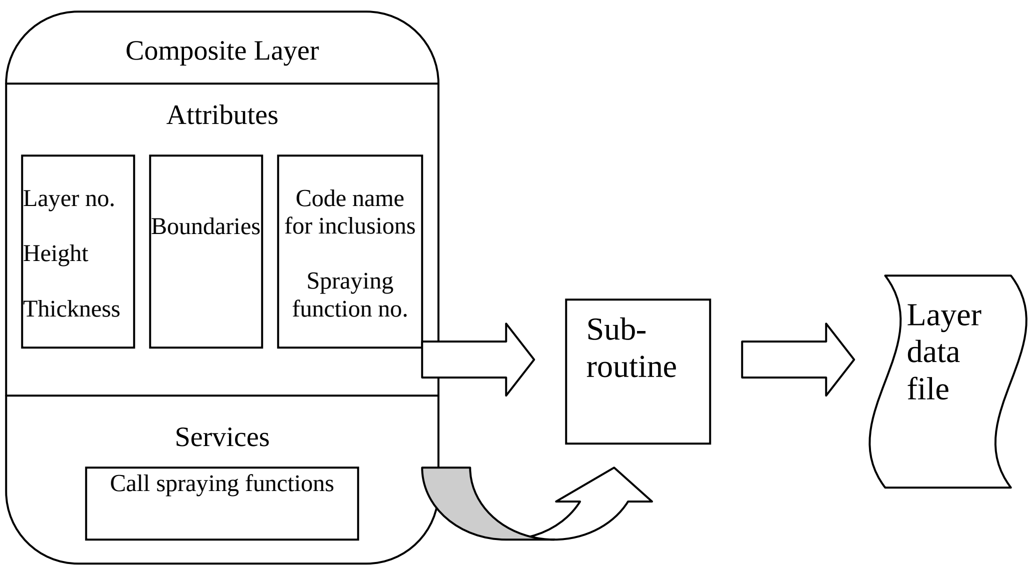



Fig. 9 The class for a composite layer

As to the HMPM layer, the data structure is quite different, as the layer has a lot of micro voids that cannot be specified and calculated by functions. Therefore, a bit-map like file is introduced to describe a HMPM layer. The format consists of a header file and a data file (Figure 10). In the header file, some layer information, such as layer no., thickness and height, is recorded; while in the data file, all of the material points are denoted by “1” and void points are denoted by “0”. Thus the entire layer is described using a bit-map.

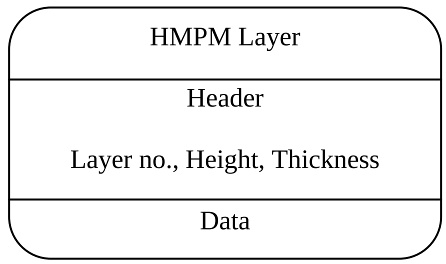



Fig. 10 The HMPM layer format

## 6. Implementation and example

Based on the new modeling method for CMPMs [2], a CAD modeling system was developed [3]. With the system, users can apply the functions of current CAD graphic software to build CAD models for their components designed with a multiphase perfect material and visualize both material and geometric information for any layer of the components they select.

Now the system has been extended for process planning and establishing LM models tasks. Using the system, users can determine the build orientation and divide the object into several blocks. Then the fabrication sequence is generated for each block and the CAD model can be converted into the LM model by adaptive slicing. All the data in the LM model can be kept using the proposed data structure.

Figure 11 shows its user interface, where the CAD model of a pipe in the work window ① is being processed and converted into a LM model. The internal surface of the pipe is made of a HMPM while its outside part is covered with a composite material, and the middle part is designed with FGM. Users can choose the orientation and layer thickness by dragging the scroll bar on the control panel ②, with which the slicing routine is carried out. After that, users are allowed to choose a work cycle to do fabrication sequence generation. The result is displayed in the work window ③ and all the information for LM model is stored in the form of the corresponding data structure.

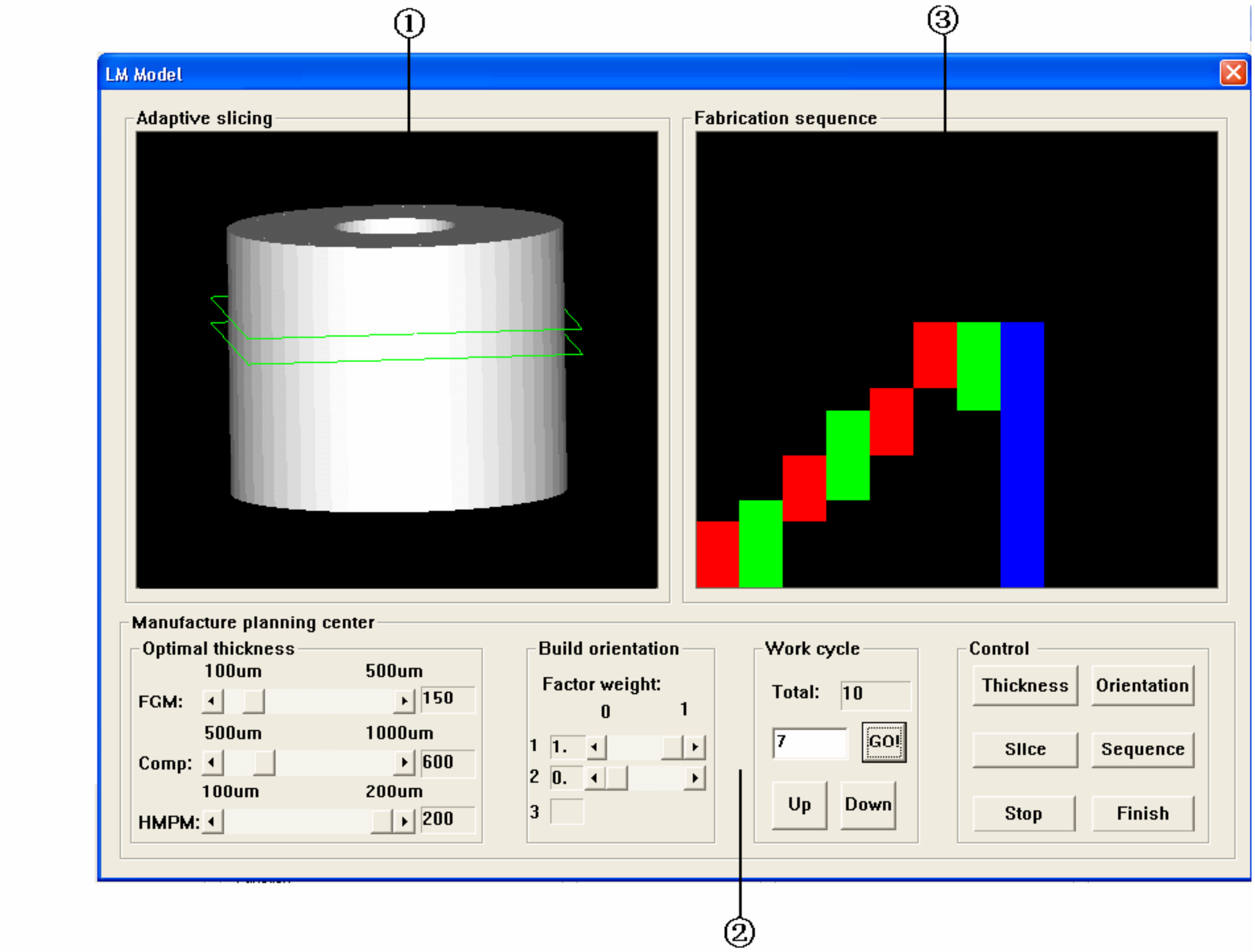



Fig. 11. The user interface

## 7. Conclusions

To manufacture the CMPMs, a hybrid manufacturing approach has been developed. Based on this approach, this paper further proposes corresponding process planning techniques, which include build orientation determination and adaptive slicing, with which, the 3D CAD model is converted into 2.5D layers. Then the geometric and material information associated to the layers is integrated as a layered manufacturing model, consisting of three types of data: (1) fabrication sequence; (2) spraying information; and (3) periodic microstructures information. With these data, the NC codes can be programmed properly.

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