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Virtual Manufacturing to Design a Manufacturing Technology for Components Made of a Multiphase Perfect Material

Feng Wang[1], Ke-Zhang Chen[2] and Xin-An Feng[3]

[1]Dalian Sanyo compressor Co. Ltd., wangfeng@graduate.hku.hk
[2]The University of Hong Kong, kzchen@hkucc.hku.hk
[3]Dalian University of Technology, xinanf1004@yahoo.com.cn

ABSTRACT

A component featuring an optimized combination of different materials (including homogeneous materials and three types of heterogeneous materials) in its different portions for a specific application, is considered as a component made of a multiphase perfect material. To manufacture such components, a hybrid layered manufacturing technology was proposed. Since it would be risky and expensive to make such a physical machine, virtual manufacturing is adopted to further optimize the hybrid layered manufacturing technology so as to provide the reliable foundation for future practical manufacturing with a much better prospect of success, a shorter lead time, and a much lower investment cost. This paper introduces the virtual manufacturing system developed for such components and the virtual manufacturing of three typical components by using the system to determine related parameters.

Keywords: virtual manufacturing, design, heterogeneous materials, manufacturing technology.
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1. INTRODUCTION

With the development of high technologies, it is required to apply components made of several different materials to satisfy the special requirements (e.g. negative Poisson's ratio and zero thermal expansion coefficients) in their different portions. The different materials may include homogeneous materials and three types of heterogeneous materials, i.e., composite materials (CMs), functionally graded materials (FGMs), and materials with a periodic microstructure (MPMs), according to the special functional requirements. To meet all the special requirements in different portions and make the best use of different materials, the combination of different materials must be optimized and should be optimal for a special application. Therefore, this can be considered as a "perfect" multiphase material, as a whole, for the special application. Thus, a component featuring an optimized combination of different materials (including homogeneous materials and three types of heterogeneous materials) in its different portions for a specific application, is defined as a component made of a multiphase perfect material (CMMPM). Such components can be compared to certain natural organisms (e.g. bamboos, teeth and bones), which have perfect combinations of materials and functions after a long time of evolution.

To design and represent such components according to the requirements from high-tech applications, a corresponding computer-aided design method [1-3] (including both geometric and material design) and a corresponding CAD modeling method [4-6] (containing both geometric and material information) have been successfully developed. Currently the research about how to fabricate such components is rarely reported in the published literature. To manufacture such components, a hybrid layered manufacturing technology [7] was proposed with plasma spraying, laser engraving, grinding, and milling. Since it would be risky and very expensive to make such a physical machine without detailed study and optimization, virtual manufacturing [8-10] is first adopted to do further research so as to provide the reliable foundation for future practical manufacturing with a much better prospect of success, a shorter lead time, and a much lower investment cost. This paper introduces the virtual manufacturing system developed for the CMMPMs and the manufacturing of three typical components by using the virtual manufacturing system to determine related parameters.

2. HYBRID LAYERED MANUFACTURING TECHNOLOGY OF CMMPMS

Since a CMMPM is composed of different types of materials, the corresponding manufacturing technology should satisfy all the requirements for fabricating each type of material. For a component with CMs, its fabrication technology must be able to add the materials needed to build a matrix layer and to add the inclusions into the matrix layer according to their required distribution and quantity. For a component with FGMs, its fabrication technology must be able to add different materials with required volume fractions simultaneously for every point according to the specified composition function. For a component with MPMs, its fabrication technology must be able to add materials for building a very thin layer with high precision first, and then remove the material from the layer to create the necessary voids for periodic microstructures. According to these requirements, a hybrid layered manufacturing technology had been proposed [7], and it applies plasma spreading, milling, grinding, and laser engraving technologies.

Based on the manufacturing technology, a virtual prototype of corresponding manufacturing facility was designed and developed as shown in Fig. 1. The prototype possesses three working stations for spreading (middle), grinding/milling (left), and engraving (right), respectively [7],[11]. The workpiece is fixed on the platform that can be moved transversely (in X direction) and laterally (in Y direction) in a zigzag manner for tracing the cross-section of the workpiece, and vertically (in Z direction) in an up-down manner for building layers, according to the instructions of its numerical control (NC) servo system.

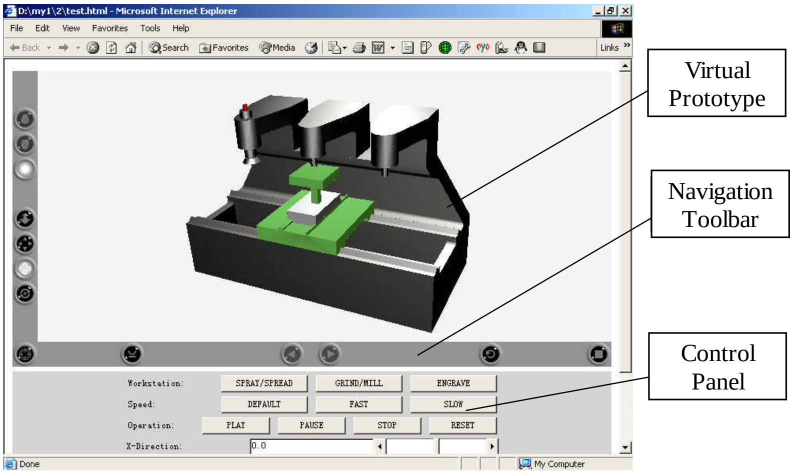


Fig. 1: Virtual prototype of the manufacturing facility.

The working cycle for a layer in a FGM or CM region is from the grinding/milling working station (to mill the superfluous material from the layer to obtain precise boundary of the layer) to the spraying station (to spray required materials) and then to the grinding/milling station (to grind the surface of the layer to obtain a required thickness). The working cycle for a layer in a MPM region is from the grinding/milling working station (to mill the superfluous material from the layer to obtain precise boundary of the layer) to the spraying station (to spray required materials), to the grinding/milling station (to grind the surface of the layer to obtain a thickness a bit thicker than the required), to laser beam engraving station (to engrave voids for the required microstructure), to spraying station (to spray softer materials into the voids), and finally to grinding/milling station (to grind the top surface of the material layer again to remove superfluous softer materials and the burrs formed, so as to ensure that the required thickness and flatness of the material layer are produced).

3. VIRTUAL MANUFACTURING SYSTEM OF CMMPMS

A virtual manufacturing system [11] has been designed and developed according to the proposed hybrid layered manufacturing technology. The elements and workflow of the virtual manufacturing system for CMMPMs are shown in Fig. 2.

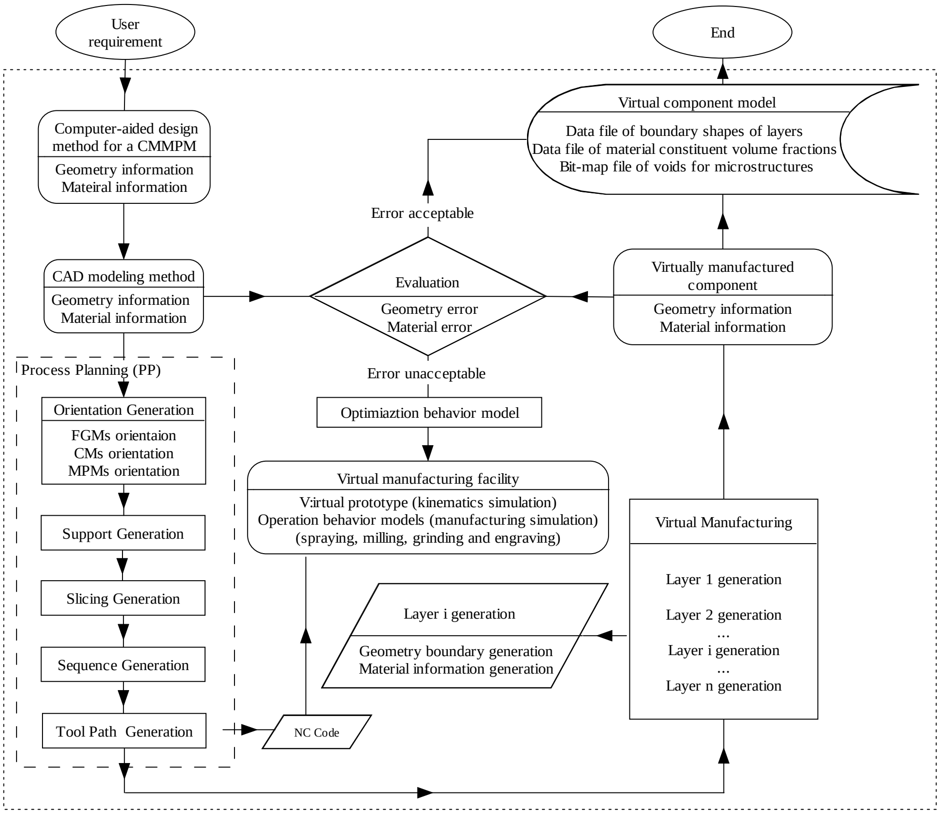


Fig. 2: Elements and workflow of the virtual manufacturing system for CMMPMs.

It mainly includes a virtual manufacturing facility and corresponding manufacturing software. The virtual manufacturing facility includes a virtual prototype of hybrid layered manufacturing facility as shown in Fig. 1 and four behavior models of its operations (i.e., plasma spraying, laser engraving, grinding, and milling). The behavior model of plasma spraying [11-13] is the practical spraying function $F(x,y)$, with which the feed rates of different material powders can be controlled to ensure that the volume fractions (VFs) of sprayed materials satisfy the original design requirements, i.e., $f(x,y)$. The relationship between the design and the practical spraying functions has been deduced as:

$$f_i(x,y) = \frac{1}{V_0} \iint_D F_i[(x+u),(y+u)]W(u,v)dudv \tag{3.1}$$

where x and y are the coordinates in a global Cartesian coordinate system (X,Y,Z); w, u, and v are the coordinates in a local Cartesian coordinate system (U,V,W) with the center of a spraying deposit as its origin, D is the area of a spraying deposit, and V_0 is the material volume of a spraying deposit. If the mathematic model of the distributed material surface is a Gaussian-shaped distribution [14], w can be further expressed as:

$$w(u,v) = h_{\max} e^{-(u^2+v^2)/2\sigma^2} \tag{3.2}$$

where $h_{\max}$ expresses the height peak of a deposit, σ is its flattening, and the integral region D is taken as 6σ (i.e. corresponding to about 99.78% of the material distribution) [14]. The behavior model of the laser engraving [15] expresses the relationship between the scanning velocity of the laser beam and the engraved depth, which is used to control the scanning velocity of the laser beam to generate the accurate depth, size, and shape of the voids for microstructures, and has been deduced as:

$$v = \frac{\pi d}{4T} \cdot \frac{1}{\sum_{i=1}^{q} \left(f_i e^{\frac{1}{\alpha_i}(\ln H - \ln h_i)} \right)} \qquad (i=1,2,\ldots,q) \tag{3.3}$$

where d is the diameter of a spraying deposit, T is the period of a pulse, f_i is the volume fraction of the i-th material constituent, q is the number of material constituents, h is the engraving depth of the first pulse, H is the required machining depth, and α is constant for a given material. The behaviour model of milling operations is the equation of a layer boundary to be milled and is expressed in the following equation:

$$\begin{cases} B(x,y,z) = 0 \\ z = z_m \end{cases} \tag{3.4}$$

where x, y and z are the coordinates in a global Cartesian coordinate system (X,Y,Z), and z_m is the height of a layer to be milled. The behavior model of grinding operations is the equation of a plane to be ground as shown below:

$$\begin{cases} S(x,y,z) \le 0 \\ z = z_g \end{cases} \tag{3.5}$$

where x, y and z are the coordinates in a global Cartesian coordinate system (X,Y,Z), and z_g is the height of a layer to be ground.

The corresponding manufacturing software includes three sub-systems: one for process planning, one for numerical control (NC) coding, and one for quality assessment [11]. According to the CAD model of a CMMPM, the first sub-system will create its manufacturing process plan, based on which the second sub-system will generate NC codes, with which the facility can be controlled to manufacture the component. Fig. 3 shows a layer with multiple fabrication features that include spraying, engraving, milling and grinding operations, which are all performed by the developed virtual manufacturing system. The component made by the virtual manufacturing system is not a physical one and is a set of its geometric and material information which is recorded into a model of the virtual component, in a specified data format, during its virtual manufacturing. Such a model can be visualized according to the users' requirements. Then, the third sub-system can compare the CAD model with the virtual component model as a quality assessment system. After the analyses of the errors, its manufacturing process and related parameters can be further optimized to provide the reliable base for the design and applications of the physical manufacturing facilities.

4. VIRTUAL MANUFACTURING OF CMMPMS

For a CMMPM, the accuracies of its geometry and material volume fractions (VF) are the issues of major concern in terms of CAD/CAM [16,17]. The VF errors of material constituents are mainly resulted from two basic causes: one is that the sprayed materials are not focused on a theoretical point and spread on a bigger area, and the other is that the layer generated by the slicing has a certain thickness. When the changes of material constituent VFs are on the x-y plane, the former error will be introduced into the component. Therefore, the first case study will investigate the component with the changes of material constituent VFs on the x-y plane. When the changes of material constituent VFs are along the building direction (i.e., z direction), the latter error will exist in the component. Therefore, the second case study will investigate the component with the changes of material constituent VFs along the *z* direction. As for the geometry issue, Cases 1 and 2 are for cuboid components, and thus Case 3 will investigate a cylindrical object with the radial change of material constituent VFs.

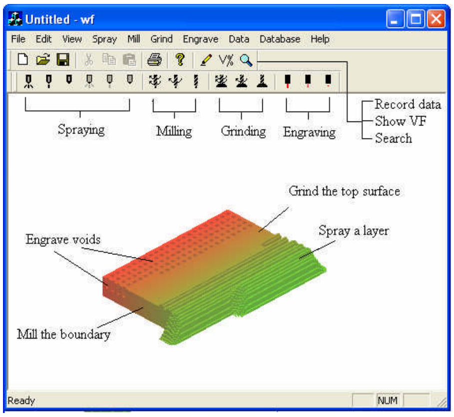


Fig. 3: Interface of the virtual manufacturing system.

4.1 Case Study 1

Fig. 4(a) shows a cuboid component to be manufactured for Case 1. Its left part is a type of MPM (microstructures built in material m1), and its right part is a type of CM (material m2 as matrix and material m3 as inclusions). To prevent cracks at the interface between the two types of materials, a FGM is applied between m1 and m2, and their material composition VFs are linearly changed as shown in Fig. 4(b).

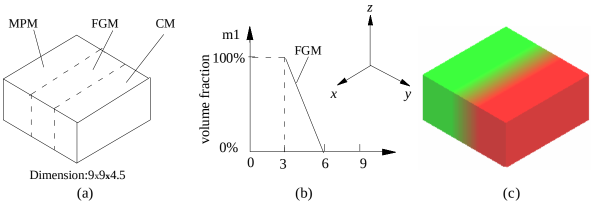


Fig. 4: A cuboid component for Case 1.

During its virtual manufacturing process, the data of the component's geometry and material are stored, layer by layer, into a virtual component model [11]. Since the virtually manufactured component is a collection of multiple layers, its information can be checked in a layered mode. For a layer with a given z-coordinate, its boundary shape can be visualized in Area ④ of the interface of inquiring system shown in Fig. 5. By checking the boundary of the section view in the interface in mouse pickup mode to compare this outline with the corresponding one in the CAD model indicated by ⑤, no difference between them was found since the geometry accuracy is ensured by the milling operation.

For material evaluation, the VFs of material constituents in the MPM and the CM region are constant and can be easily ensured by controlling the feed speeds of different material constituents. The VFs of material constituents in the FGM region are variable along *y*-axial, as mentioned earlier, thus the spraying operation will cause VF errors. In order to reduce the VF error, the related manufacturing parameters (including the feed scheme, spraying row spacing, and spraying distribution) are optimized until the error is allowable [13],[18]. The details of the error analysis of the material VFs implemented by the quality assessment system can be referred to Ref.[13],[18], and will thus not be introduced further due to the paper length limitations. As an example, the comparison of the VFs of m1 with different feed schemes is shown in Fig.6. According to the analysis of feed schemes [13],[18], the reasonable selection of feed schemes (i.e. starting the spraying of m2 earlier at a certain position and stopping the spraying of m1 later at another certain region) can greatly reduce the errors of material VFs. The feed scheme for an *np* means that the spraying of m2 is started at the *n*-th spraying steps.

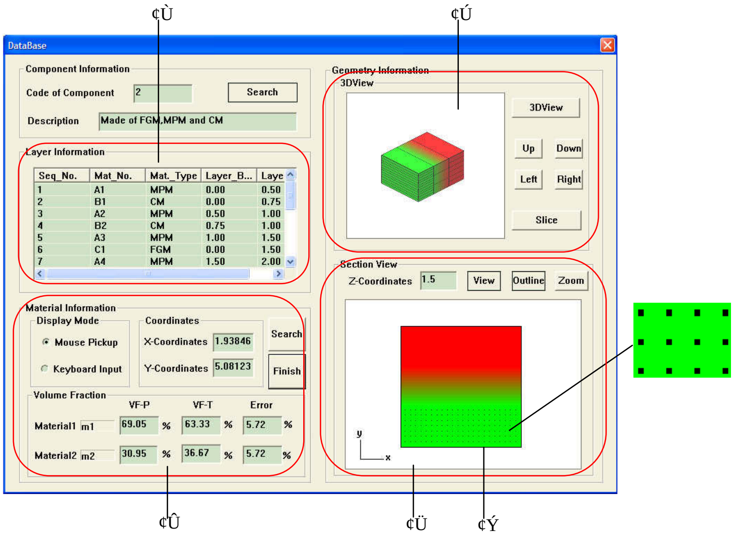


Fig. 5: Interface of inquiring into the virtually manufactured component for Case 1.

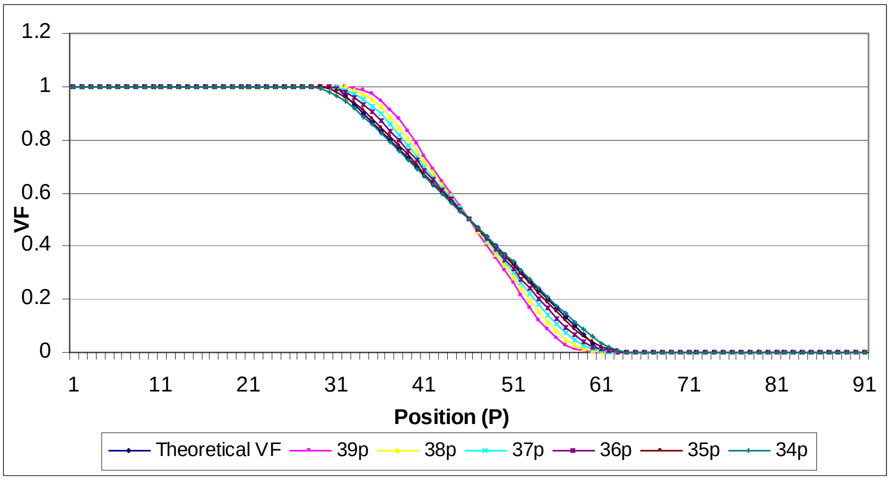


Fig. 6: The comparison of the VFs with different feed schemes.

Based on the results shown in Fig.6, the values of VF errors (σ_{VF}) for the different feed schemes are plotted in Fig.7. It can be concluded from Fig.7 that the feed scheme for 35*p* produces the smallest VF error. Therefore, the feed scheme for 35*p* can be selected as the best feed scheme for this case.

After the optimization, the component is finally manufactured as shown in Fig. 4(c) and Area ② in Fig.5, and its information can be checked and visualized through the inquiry system of the virtually manufactured components, as shown in Fig. 5. Area ① in Fig.5 lists the layer information according to its manufacturing sequence and Area ④ shows a cross section selected by inputting the height *z*. From Area ③, the VFs of material constituents and their errors for a certain point selected by using a mouse or inputting its coordinates can be read directly. It is verified that all the errors have been very small within the allowable ranges.

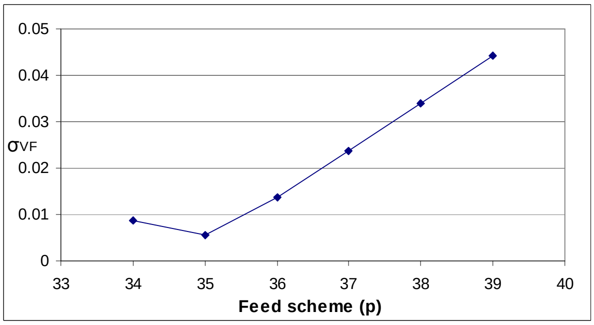
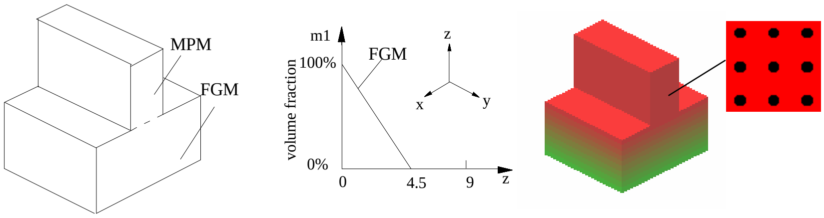


Fig. 7: The curve of σ_{VF} for the different feed schemes.

4.2 Case Study 2

Fig. 8(a) shows a gibbose component to be manufactured for Case 2 and Table 1 lists its specifications. The component has a FGM on the bottom and a MPM on the top. The FGM contains two materials: m1 and m2 and their material composition changes linearly along the *z*-axial as shown in Fig. 8(b). In this case, the VFs of material constituents change along the *z*-axial and the layer thickness of each material region is determined by the manufacturable thickness d_M or the material resolution d_m. As for the FGM region, since d_m is the minimum of d_M, d_m (i.e. 0.45) is chosen as the layer thickness. For the MPM region, since d_m is less than the minimum of d_M, the minimum d_M (i.e. 0.45) is chosen as the layer thickness.



(a) Dimension: upper 9x3x4.5
lower 9x9x4.5

(b)

(c)

Fig. 8: A gibbose component for Case 2.

Material regions	*FGM*	*MPM*
VFs of material constituents	m1: f_1 = 1 - z/4.5 m2: f_2 = z/4.5	m2: matrix (70%) m3: softer material (30%)
Material resolution (d_m)	0.45	0.40
Manufacturable layer thickness (d_M)	0.45 ~ 2.0	0.45 ~ 2.0

Tab. 1: Specifications of the component for Case 3.

After its virtually manufacturing, the virtual component is obtained as shown in Fig. 8(c) and Area ② in Fig. 9. The information of its geometry and materials is displayed in corresponding areas of Fig. 9. For the evaluation of its geometry, Area ④ in Fig. 9 indicates that this virtual component has no geometric errors since the outline of a layer is the same as the profile in its CAD model shown by ⑤. As analyzed previously in Case 1, its geometry accuracy is ensured by the milling operation.

At the aspect of material evaluation, since the change of material compositions is along the building orientation, the number of layers affects the material accuracy. To verify the relationship between the layer number and the VF errors, this component was fabricated with the different layer numbers and the corresponding VFs of m1 are plotted in Fig.

10. From Fig. 10, it can be concluded that the more the number of layers, the smaller the VF error is. However, the increase of the layer number will lead to the increase of the manufacturing time and cost. Therefore, there must strike a balance between the accuracy and the cost. According to the user's requirement, an appropriate layer number can be customized and the qualified components can be obtained.

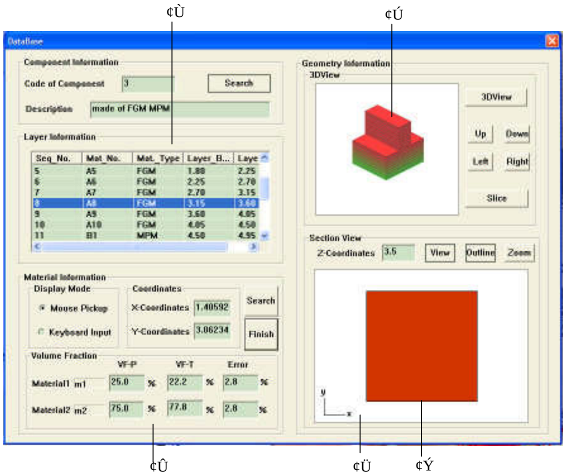


Fig. 9: Interface of inquiring into the virtually manufactured component for Case 2

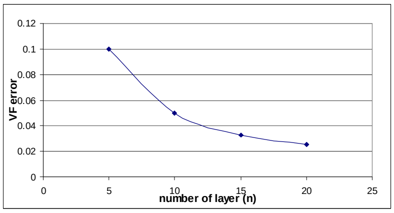


Fig. 10: The relationship between the layer number and the VF errors.

4.3 Case Study 3

The third example is about a cylinder, which is subjected to a high temperature and pressure on its outside surface. It is desirable to have ceramic on the outside surface due to its good high temperature property while it is also desirable to have metal in its middle part away from the outside surface owing to its good mechanical property. To meet the function requirement, a gradual change of material compositions from the metal (m1) in the middle to the ceramic (m2) on the outer surface is thus required, for which a FGM should be applied to this cylinder. Fig. 11(a) and Fig. 11(b) show its overall dimensions and material compositions respectively, and Fig. 11(c) is the result of its virtual manufacturing.

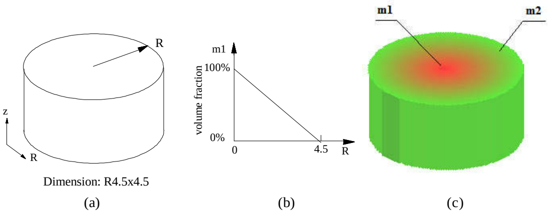


Fig. 11: A cylinder for Case 3.

For this case, the number of layers doesn't affect the material accuracy since there is no material VF change along the building orientation. Therefore, the layer thickness of each material region is mainly determined by the material resolution d_m and the manufacturable thickness d_M. In this case, d_m (i.e. 0.5) is less than the minimum of the manufacturable thicknesses d_M (i.e. 0.75), and the minimum d_M (i.e. 0.75) is thus used as the layer thickness d. Fig. 12 illustrates its virtual manufacturing process, where (a) is a part of a sprayed layer, (b) is a whole sprayed layer, (c) is a virtual component without the milling and (d) is the final virtual component after the milling.

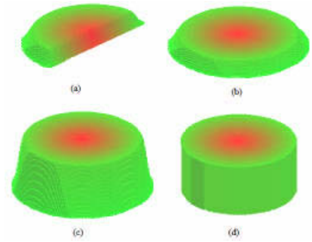


Fig. 12: The virtual manufacturing process for Case 3.

The query result is displayed in Fig. 13. Its geometry accuracy was ensured by the milling operation, and no geometric errors were found. Since the change of material composition VFs is along its radial direction, the material accuracy can be affected by the feed schemes instead of the number of layers.

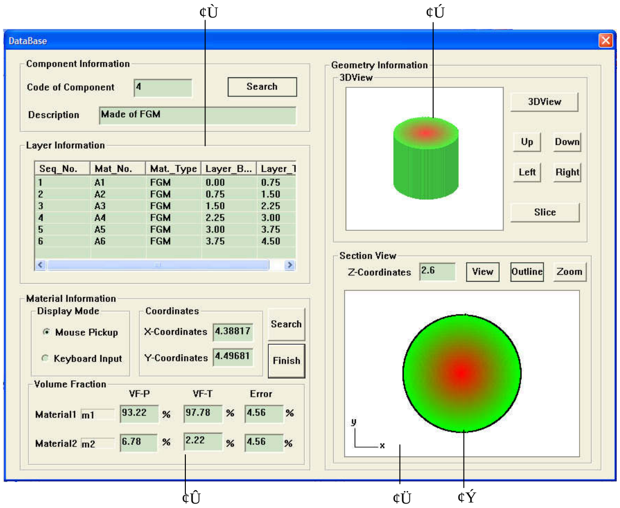


Fig. 13: Interface of inquiring into the virtually manufactured component for Case 3.

The feed schemes are illustrated in Fig. 14, where the boundary of the component is marked as Circle 0, the circles outside the boundary of the component are marked as negative circles (such as Circle -1), and the circles inside the boundary of the component are marked as positive circles (such as Circle 3). The space between two adjacent circles is one spraying step p. To clearly demonstrate them, the step p shown in Fig.14 is much larger than the practical one. Every marked circle means that the material, m1, starts to be sprayed when the center of the spraying nozzle enters this circle.

Taking Circle -1 as an example to demonstrate the feed scheme implementation of Case 3, the spraying nozzle moves first from the left to the right along the zig-zag tool path as shown in Fig.15, and only the material, m2, is sprayed before the centre of the nozzle enters Circle -1. When the nozzle center gets into Circle -1, the second material (m1) starts to be sprayed. When the nozzle center moves out of Circle -1, m1 stops to be sprayed and only m2 is sprayed. That is, only m2 is fed in the red region and m1 and m2 are fed simultaneously in the green region shown in Fig. 15, where their feeding rates are varied according to the material composition functions. This scheme is indicated by "n=-1". The relationship between feed schemes and VF errors (σ_{VF}) has been investigated as shown in Fig. 16, which shows that the value σ_{VF} is the smallest when n=-1 and indicates that the whole material accuracy of the component is the highest.

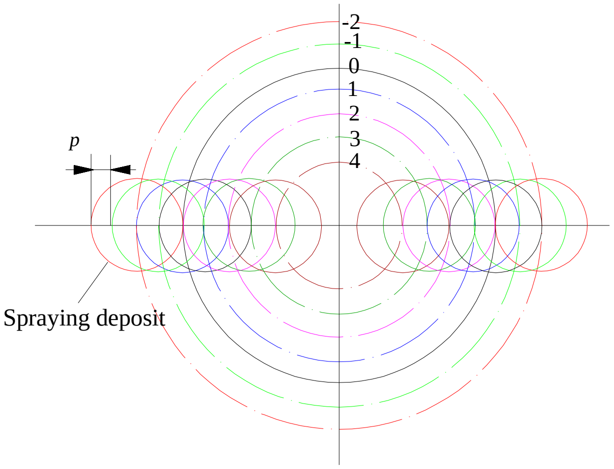


Fig. 14: The feed schemes of Case 3.

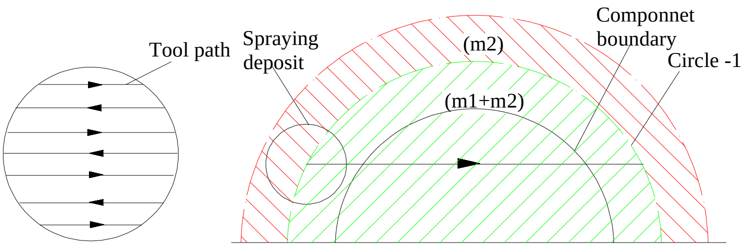


Fig. 15: The schematic diagram of the implementation of feed schemes.

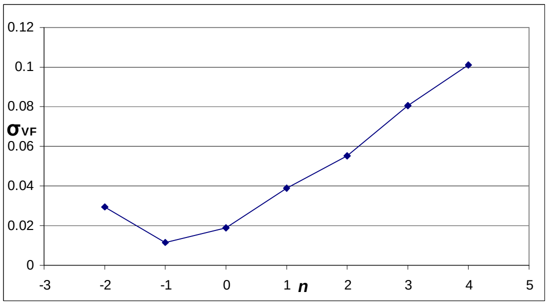


Fig. 16: The relationship between feed schemes and VF errors $\sigma_{VF.}$

5. CONCLUSIONS

This paper first introduces a hybrid layered manufacturing technology and a corresponding virtual manufacturing system developed for components made of a multiphase perfect material. To verify the validity of the developed virtual manufacturing system and determine related parameters, three typical application cases were studied. These components were first virtually manufactured, then visualized, and finally evaluated in terms of both the geometric and the material composition accuracies. The related technological parameters were further optimized based on the evaluation and the error analyses, which provides a reliable base for further development of the physical facility and real manufacturing of CMMPMs.

6. ACKNOWLEDGEMENTS:

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