BEHAVIOR MODELING FOR THE SPRAYING DEVICE IN THE LAYERED MANUFACTURING PROCESS

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ABSTRACT

A component, which has a perfect combination of different materials (probably including homogeneous materials and three different types of heterogeneous materials) in its different portions for a specific application, is considered as the component made of a multiphase perfect material. To fabricate such components, a hybrid layered manufacturing process has been developed. In order to accurately spray different materials with their required volume fractions for every pixel during fabrication, it is important to investigate its spraying operation. This paper establishes the behavior model of the spraying device and proves its validity using digital simulations.

Keywords: Behavior modeling; spraying device; layer manufacturing

1. INTRODUCTION

Rapid development in various fields has required components and products to possess a range of special functions (e.g. negative Poisson's ratio and zero thermal expansion coefficient). Since conventional homogeneous materials cannot satisfy these requirements, attention has been paid to heterogeneous materials, which may include composite materials (CMs), functionally graded materials (FGMs) and heterogeneous materials with periodic microstructure (HMPMs). However, different portions of a component may have different special requirements. If the component is made of a single homogeneous or heterogeneous material, the material used may not meet all the specific requirements in the different portions, and might be redundant in some portions even if the material can meet all requirements. To satisfy all the requirements for all portions without redundancy, it would be necessary to use the components made of different materials, including homogenous materials and the three types of heterogeneous materials (CM, FGM, and HMPM) in different portions, thus making the best use of different materials. 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 to be a component made of a multiphase perfect material (CMMPM).

To design such components according to the requirements of high-tech applications, a corresponding computer-aided design method [1, 2] (including both geometric and material design) and a corresponding CAD modeling method [3-5] (containing both geometric and material information) have been developed successfully. Furthermore, a hybrid layered manufacturing technology for fabricating such components, including the manufacturing process and the concept design of the corresponding manufacturing facility have also been proposed [6]. This hybrid manufacturing process applies spraying, engraving, and refinishing technologies, among which the spraying is the key technology for generating the layer of multi materials with their required volume fractions in every pixel. Therefore, it is important to investigate the spraying operation by means of virtual prototyping. This paper introduces the hybrid manufacturing process for CMMPMs, describes the spraying device for building layers of multi materials with variational volume fractions in different pixels, establishes the behavior model of the spraying device, and proves the validity of using digital simulations.

2. THE HYBRID PROCESS FOR FABRICATING CMMPMs

Based on the analyses of the requirements for fabricating homogeneous materials and the three types of heterogeneous materials, a hybrid manufacturing process combined with layered manufacturing, micro-fabrication, and mechanical machining have been developed under the guidance of Axiomatic Design [7]. This process [6] has the following steps:

(1) If there are 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 a precise boundary of the layer. This is necessary since the spraying area of a jet is much larger than a pixel and the practical area of the obtained layer is larger than the required area, and, at the same time, the formed chips are sucked out by the vacuum;

(2) Spread a material layer with the required thickness and constituent composition (for all material regions) and, at the same time, spray the inclusions with the required 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 plus a grinding depth), since metal cladding is not flat enough and the thickness of the added layer is not accurate enough, and, at the same time, suck out the formed chips or sludge by vacuum;

(4) Engrave or sculpt the layer to create the necessary voids for periodic microstructures with a required depth (layer thickness plus a grinding depth), and, at the same time, suck out the formed chips or sludge by vacuum;

(5) Fill the voids with a material with both lower strength and high melting point to avoid the refilling of the material spread for the next layer;

(6) Grind the top surface of the material layer again to remove superfluous lower strength material and the burrs formed in Step (3). This will ensure that the required thickness and flatness of the material layer is produced;

(7) Repeat Step (1) in order to spread material for next layer until the component is completely fabricated. The component 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.

3. SPRAYING DEVICE FOR GENERATING THE LAYER COMPOSED OF SEVERAL MATERIALS

The second and the fifth steps of the hybrid process involve a spraying operation. The required spraying device or system must be able to add the materials for building a matrix layer and to spray the inclusions into the matrix layer according to their required distribution and quantity for CMs; must be able to add different materials with variational volume fractions simultaneously for every pixel according to the specified composition function for FGMs; and must be able to add materials with very thin thickness for HMPMs. After investigation and analyses [6, 8], the plasma spraying technology has been selected for the spraying operation.

The plasma spraying system is designed as shown in Fig.1. It consists of a main powder feeder, an inclusion feeder, a plasma nozzle, and two pipes (A and B). Axial feeding pipe A connects the plasma nozzle with the main powder feeder, which is used to feed the mixture of several kinds of materials with their required volume fractions for FGMs, the matrix for CMs, and/or the soft material for filling the void of periodic microstructures. The main material powder feeder has several evenly distributed sub-feeders, which contain different required materials respectively as shown in Fig.1. Each sub-feeder is driven by a step motor, so that the feed rate of the powder contained in it could be easily controlled by changing the rotational speed of the motor and different material powders with their precise volume fractions could then be fed to the blender for mixing. After thorough mixing, using a spiral airflow, the mixed powder is transported by the airflow from the blender into the feeding pipe A. Pipe B is connected with the inclusion feeder and only used to spray the inclusion for CMs and its nozzle is away from the high temperature zone of the plasma flame in order to prevent the inclusion from being molten. Plasma gas, pneumatically fed along a cathode, is heated to plasma temperatures by a high intensity arc or flame operated between the cathode and a nozzle-shaped, water-cooled anode, and then leaves the nozzle as a plasma jet. The mixed powder suspended in a carrier gas is injected from pipe A into the plasma flame where the particles are accelerated and heated. The temperature of the particle surface is lower than the plasma temperature, and the dwelling time in the plasma flame is very short. The lower surface temperature and short duration prevents the sprayed particles from being vaporized in the gas plasma. As the molten particles splatter with high velocities onto a substrate, they spread, freeze, and form a more or less dense coating, typically forming a good bond with the substrate.

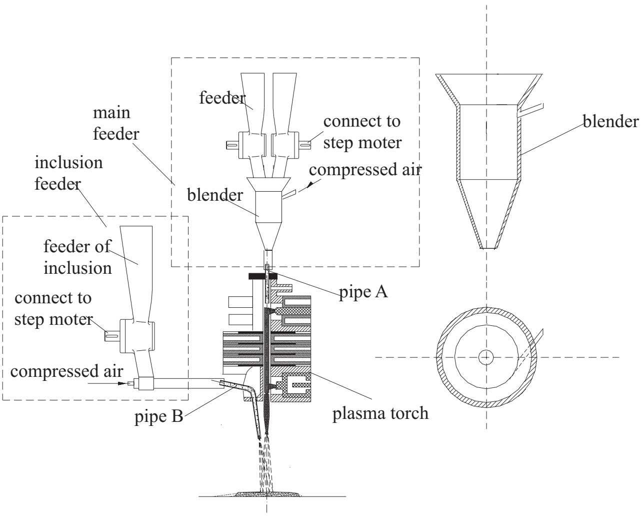

Figure 1: Schematic diagram of the plasma spraying system

4. BEHAVIOR MODELS OF THE SPRAYING DEVICE

In order to satisfy the requirement for generating the layer composed of several materials with variational volume fractions in every pixel during fabrication, it is important to investigate the behavior of the spraying devices.

For FGMs or the matrix of CMs, the mixed powder from the main feeder is sprayed onto the substrate to form a layer, and the volume fractions of different material powders in every pixel is required by the spraying function specified in the CAD model of the component. For example, if there are q types of material constituents, the volume fraction of the k-th material constituent at the position (x, y, z) in Cartesian coordinate system can be represented as:

$$\dot{v}_k = f_k(x, y, z) \text{ where } k = 1, 2, ..., q \quad (1)$$

For the inclusions of composite materials, the material from the inclusion feeder is sprayed onto the layer, and its volume fraction is required by the spraying function specified in the CAD model of the component. The volume fraction of the inclusion at the position (x, y, z) in Cartesian coordinate system can be represented as:

$$\dot{v}_c = f_c(x, y, z) \quad (2)$$

At every pixel, the sum of the volume fractions of all the material constituents should be equal to one and can be written as:

$$\dot{v} = \{\sum_{i \; 1}^{n} \dot{v}_i = 1, \big| \dot{v}_i \in (V_k, V_c), \dot{v}_i \geq 0\} \quad (3)$$

These spraying functions specified in the CAD model of a component are called theoretical spraying (TS) functions, and denoted as $f(x, y, z)$. Because Z-height is a constant in the spraying region, the TS function can be expressed as:

$$f(x, y) = \{ f_i = (x, y, z) \big| \, z = \text{constant}, \, i = 1,2,..., q + 1\} \quad (4)$$

During spraying, more material powders are accumulated in the center of spraying spot and less in the margin of the spot as shown in Fig.2. The surface shape formed by the sprayed materials can be expressed as:

$$w = W(u,v) \quad (5)$$

where w, u, and v are the coordinates in local Cartesian coordinate system (U,V, W), as shown in Fig.2. The origin of the local coordinate system is in the position (x, y) of the global coordinate system, where is the center of the spraying spot. If the surface shape or distribution is assumed as a paraboloid, w can be further expressed as:

$$w = \begin{cases} \frac{h}{R^2}(R^2 - u^2 - v^2) & if \quad \sqrt{u^2+v^2} \le R \\ 0 & if \quad \sqrt{u^2+v^2} > R \end{cases} \tag{6}$$

where R is the radius of the spraying spot circle and h is the peak height of the paraboloid. The volume V_0 covered by the paraboloid can be calculated as:

$$V_0 = \frac{h}{R^2} \iint_D (R^2 - u^2 - v^2)dudv \tag{7}$$

Therefore

$$h = \frac{V_0 R^2}{\iint_D (R^2 - u^2 - v^2)dudv} \tag{8}$$

By substituting the Eq. (8) into Eq. (6), Eq. (6) can be rewritten as:

$$w = \begin{cases} \frac{V_0 = (R^2 - u^2 - v^2)}{\iint_D (R^2 - u^2 - v^2)dudv} = KV_0(R^2 - u^2 - v^2) & if \quad \sqrt{u^2+v^2} \le R \\ 0 & if \quad \sqrt{u^2+v^2} > R \end{cases} \tag{9}$$

where $K = \frac{1}{\iint_D (R^2 - u^2 - v^2)dudv}$ (10)

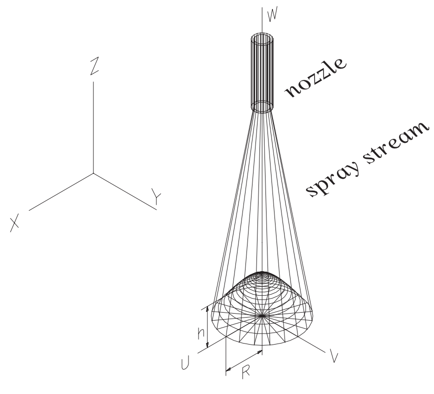

Figure 2: The distributed surface of the sprayed materials

Since every pixel point (x, y) is an infinitesimal unit and the spot size of the plasma spraying is several millimeters thick, the total material thickness actually obtained at the point (x, y) should be the integral of the materials sprayed onto point (x, y) from the nozzle in the positions where the spraying spots cover point (x, y, z). To ensure the required volume fractions of the required materials in every pixel, practical spraying (PS) function $F(x, y)$ should be different from TS function $f(x, y)$ and is its inverse function can be presented as follows:

$$f(x, y) = \frac{1}{V_0} \iint_D F[(x-u),(y-v)] W(u,v) du dv \quad (11)$$

By substituting Eq.(9) into Eq.(11), the following can be obtained:

$$f(x, y) = K \iint_D F[(x-u),(y-v)](R^2 - u^2 - v^2) du dv \quad (12)$$

The function $f(x, y)$ is known and can be obtained from the CAD model of the component. The boundary of integral region D is the circle of spraying spot with the radius of R, the center of which is the origin of the local coordinate system. The region D can then be denoted as:

$$D = \{(u,v) | u^2 + v^2 \leq R^2\} \quad (13)$$

According to the function $F(x, y)$ reverse deducted, the feed rates of different material powders can be controlled to ensure the original design requirement $f(x, y)$.

Example (1):

The TS function $f(x, y)$ is specified in the CAD model of a component is:

$$f(x, y) = ax + by + c \quad (14)$$

where a, b, and c are constant. Thus, Eq.(12) can be rewritten as:

$$ax + by + c = K \iint_D F[(x-u),(y-v)](R^2 - u^2 - v^2) du dv \quad (15)$$

Therefore, the PS function $F(x, y)$ can be reverse deducted from Eq.(15) as:

$$F(x, y) = ax + by + c \quad (16)$$

This is a special example, in which the TS function $f(x, y)$ and the PS function $F(x, y)$ have the same expression. At most situations, the function $f(x, y)$ is different from the function (x, y).

Example (2):

The TS function (x, y) is specified in the CAD model of a component as:

$$f(x, y) = a_0 + a_1 x + a_2 x^2 \quad (17)$$

where a_0, a_1, and a_2 are constant. According to Eq.(12), the following can be obtained:

$$a_0 + a_1 x + a_2 x^2 = K\iint_D F\,[(x-u),(y-v)](R^2 - u^2 - v^2)dudv \tag{18}$$

Therefore, the PS function $F(x, y)$ can be reverse deducted from Eq.(18) as:

$$F(x, y) = a_0 + a_1 x + a_2 x^2 - \frac{a_2 R^2}{6} \tag{19}$$

5. BEHAVIOR SIMULATION OF THE SPRAYING DEVICES

5.1 Digital model of the sprayed material distribution on the layers

Suppose that the layer to be sprayed is the hatching area and the plasma spraying device moves along the tool path, as shown in Fig. 3.

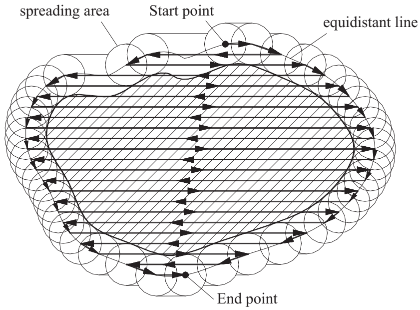

Figure 3: The tool path of the spraying process

The spraying operation is designed as a discontinuous one. The spraying device sprays once after moving each pixel p. The length of p is usually much larger than a step size of numerical control systems. If row spacing is also equal to p, the volume V_0 sprayed every time can be calculated as follows:

$$V_0 = \delta p^2 \tag{20}$$

where δ is the thickness of the sprayed layer. According to Eq.(3), the V_0 can be expressed as:

$$V_0 = \sum_{k=1}^{q} V_k + V_c \tag{21}$$

$$V_k = \dot{v}_k V_0 \qquad k = 1,2,...,q \tag{22}$$

$$V_c = \dot{v}_c V_0 \tag{23}$$

where Vk is the volume of k-th material sprayed every time and V_c is the volume of inclusion sprayed every time. According to Eq. (9), the distribution function w is in direct proportion to sprayed volume and Eq.(6) can be rewritten as:

$$w = \sum_{k=1}^{q} w_k + w_c \tag{24}$$

where w_k is the distribution height of the k-th sprayed material constituent and w_c is the distribution height of the sprayed inclusion, which can be calculated respectively as follow:

$$w_k = \begin{cases} \dfrac{V_k = (R^2 - u^2 - v^2)}{\iint_D (R^2 - u^2 - v^2) du dv} & if \quad \sqrt{u^2 + v^2} \le R \\ 0 & if \quad \sqrt{u^2 + v^2} > R \end{cases} \tag{25}$$

$$w_c = \begin{cases} \dfrac{V_c = (R^2 - u^2 - v^2)}{\iint_D (R^2 - u^2 - v^2) du dv} & if \quad \sqrt{u^2 + v^2} \le R \\ 0 & if \quad \sqrt{u^2 + v^2} > R \end{cases} \tag{26}$$

The digital model of the material distribution sprayed once is illustrated in Fig.4. The sprayed area is within a circle with the radius of R=0.5, for example, and can be divided into 88 grids by grid lines with the space equal to a spraying step or a pixel p=1.0. The material volume for every material at every grid is equal to the surface integral of the paraboloid w over its corresponding grid region. Given the coordinates of the center in i-th grid as ui and vi, the surface integral of the paraboloid w over its corresponding grid region can be expressed as:

$$Q(u_i, v_i) = \int_{u_i - \frac{p}{2}}^{u_i + \frac{p}{2}} \int_{v_i - \frac{p}{2}}^{v_i + \frac{p}{2}} w du dv \tag{27}$$

By substituting the Eq.(24) into Eq.(27), Eq.(27) can be rewritten as:

$$Q(u_i, v_i) = \sum_{k=1}^{q} Q_k(u_i, v_i) + Q_c(u_i, v_i) \tag{28}$$

where:

$$Q_k(u_i, v_i) = \int_{u_i - \frac{p}{2}}^{u_i + \frac{p}{2}} \int_{v_i - \frac{p}{2}}^{v_i + \frac{p}{2}} w_k du dv \qquad k = 1,2,...,q \tag{29}$$

$$Q_c(u_i, v_i) = \int_{u_i - \frac{p}{2}}^{u_i + \frac{p}{2}} \int_{v_i - \frac{p}{2}}^{v_i + \frac{p}{2}} w_c du dv \tag{30}$$

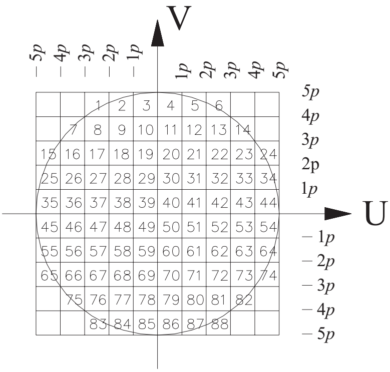

Figure 4: The spraying digital model (n = 88)

Dividing Q by the grid area, the total height of the grid can be obtained as:

$$h(u_i, v_i) = Q(u_i, v_i) / p^2 \tag{31}$$

By substituting Eq.(28) into Eq.(31), the total height is decomposed into the height of sprayed material constitutes h_k and the height of sprayed inclusion h_c, that is

$$h(u_i, v_i) = \sum_{k=1}^{q} h_k(u_i, v_i) + h_c(u_i, v_i) \qquad k = 1,2,...,q \tag{32}$$

where

$$h_k(u_i, v_i) = Q_k(u_i, v_i) / p^2 \tag{33}$$

$$h_c(u_i, v_i) = Q_c(u_i, v_i) / p^2 \tag{34}$$

The data format of the digital model of the sprayed material distribution on the layer is designed as follow:

$$(u_i, v_i, h_i, h_i \mid i = 1,2,...,n;\ k = 1,2,...,q) \tag{35}$$

where i is the serial number of the grids, k is the serial number of the material constituents, and n is equal to 88 as indicated in Fig.4.

5.2 Initialization of the data file of the spraying simulation

As shown in Fig.3, the hatching region is divided by grid lines with step length p, and N grids can be obtained. The file format of the sprayed material distribution simulation is as follow:

$$(X_i, Y_i, h_i, h_i \mid j = 1,2,...,N;\ k = 1,2,...,q) \tag{36}$$

where j is the serial number of the grid in the global coordinate system. The initialization of the simulation file goes through the following steps: (1) sort out the global coordinates X_j and Y_j of the N grids in a descent order according to the value Y and then in an ascending order according to the value X, (2) fill them into the simulation file in Format (30), and (3) let the height of each grid $h_{jk}=h_{jc}=0$ ($j=1,2,\ldots,N$; $k=1,2,\ldots,q$).

5.3 Dynamic calculation of the thickness of each grid

During the spraying process, the nozzle of spraying device moves along the spraying path from the start point to the end point. When the nozzle moves one spraying step, the heights of the accumulated materials on each grid can be calculated according to the following procedure:

(1) $j=0$,

(2) $j=j+1, i=0$

(3) Set $X_p=X_j$, $Y_p=Y_j$

(4) Renew the spraying digital model (35) for the spraying position (X_p, Y_p) according to Eq. (33) and (34)

(5) $i=i+1$;

(6) Retrieve q values of $h_k(u_i, v_i)$ and one $h_c(u_i, v_i)$ for i-th grid from the spraying digital model (35)

(7) Set $A_x = X_p + u_i$ $A_y = Y_p + v_i$

(8) Calculate the accumulated height at the position (A_x, A_y) in the simulation file (36) as follow

$$\begin{aligned} h_{jk}(A_x, A_y) &= h_{jk}(A_x, A_y) + h_k(u_i, v_i), \\ h_{jc}(A_x, A_y) &= h_{jc}(A_x, A_y) + h_c(u_i, v_i) \end{aligned} \qquad k = 1,2,\ldots,q$$

(8) Calculate the accumulated height at the position (A_x, A_y) in the simulation file (36) as follow

(9) if $i < n$, goto (5);

(10) if $j < N$, goto (2)

(11) End

5.4 Visualization simulation of the layer thickness

According to the digital model of sprayed materials, the visualized simulation for dynamically building the sprayed layer was programmed and performed by Java3D [9] and VRML [10]. The black thin lines with arrowheads in Fig.5 indicates that the nozzle: (1) sprays and moves along the x-axial from left to the right, (2) stops spraying and moves one pixel along the y-axial positive direction, (3) sprays and moves along the x-axial from right to left, and (4) stops spraying temporarily. The spraying result is shown in Fig. 5 and the surface of the layer is quite rough because it is composed of many top-surfaces of the cube by adopting the Level of Detail (LOD) technology of the Virtual Reality (VR) [9]. In fact, the pixel of the layer is very small and densely packed, so that the real spraying surface is smooth enough. The thick arrow in the Fig.5 can be dragged by moving a mouse to point at any pixel. If the input position of this pixel is taken as reference, the corresponding volume fraction of material constituent at this position can be seen on the left side of the arrow. Compared to the simulation result with the theoretical value from the Eq. (1) and (2), their difference can be obtained. According to the difference, the behavior model of the spraying can be repeatedly modified until the difference is as small as possible, thus satisfying the design requirement of the component.

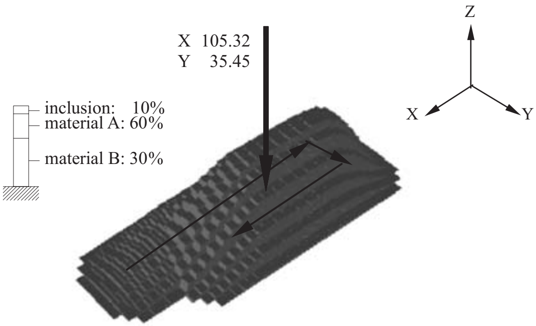

Figure 5: The visualized simulation for the sprayed layer

6. CONCLUSIONS

This paper introduces the behavior modeling of the spraying device in the layered manufacturing process for components made of a multiphase perfect material; establishes the digital model of the sprayed materials; and performs a visualized simulation of generating the sprayed layer. According to the relation between the PS function $F(x, y)$ and the TS function $f(x, y)$, $F(x, y)$ can be reverse deducted, thus providing the necessary foundation for controlling the spraying device during the manufacturing process to meet the requirements specified in component design. The visualized simulation for dynamically building the sprayed layer can testify the behavior model of the spraying device.

7. ACKNOWLEDGEMENTS

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