Morphing based approach for process planning for fabrication of geometries and the control of material composition

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Abstract

The inherent limitation of most of the solid freeform fabrication is the deposition in form of layers. Artificial imposition of the process for the desired geometric morphology and the functional gradience of material limits the accuracy of the workpiece. Mathematical morphing of geometry and the material gradience allows a smooth variation across the part geometry and the material composition of the part. The paper describes a framework for process planning and implementation of fabrication of geometries and control of the material composition. Simulation results for the suggested approach are described in the paper.

1. Introduction

Of the various features associated with the Solid Freeform Fabrication, what makes it unique is the ability to control material composition and fabricate the hidden geometric features. In Solid Freeform Fabrication the deposition of the material takes place in the form of layers. The path for material deposition head, along each layer, is based on the distribution of two-dimensional curves. The layered metal addition allows the process planning to be independent of the part morphology. For a major class of the parts fabricated by SFF, the layered deposition and subsequent independence of the process with respect to the part morphology is acceptable. For Functionally Graded Material (FGM) parts, the experimental setup limits the accuracy of desired composition of the part due to frequent variation of the composition of material.

Direct laser metal deposition has recently become very popular method for metal deposition for Solid Freeform Fabrication especially for the fabrication of FGM parts. In the direct laser based metal deposition, the build metal is delivered directly to the weld pool via a powder stream. Use of suitable hardware and software allows the real-time adjustments to the mixture of metal powder entering the molten pool, and hence later the deposited material's composition [1].

Issues inherent towards getting the desired composition include the time lag between the asking for a given composition and when the composition is actually injected into the molten pool [2]. The most significant parameters that affect the timings include the geometry of the tubing used to carry powder from the feeder to the deposition head [2] and the speed of the powder stream. Yet another issue includes the suitable mixing of different powders before delivery in the molten pool.

We present in this paper an approach to optimize the powder delivery so as to minimize the frequency of variation in the metal composition during the delivery. The initial part of the paper discusses different methods used to represent the FGM parts. The second part elaborates different approaches of path planning. The third part of the paper elaborates a new approach for the implementation of the process and the simulation results.

2. Issues Associated with the Fabrication of Functionally Graded Material Parts

The desired geometry of the part is obtained by relative motion of the substrate and the metal deposition head. In essence, the relative motion is implemented by the control of input signals for the electric drives that control x-, y-, z- motion of the substrate. Similarly the control of the part composition is based on the control of the electric drives that control the delivery of the volume of the constituents. The basic intent of process planning is to transform the computer model of the part to a model that is suitable for implementation using the machine.

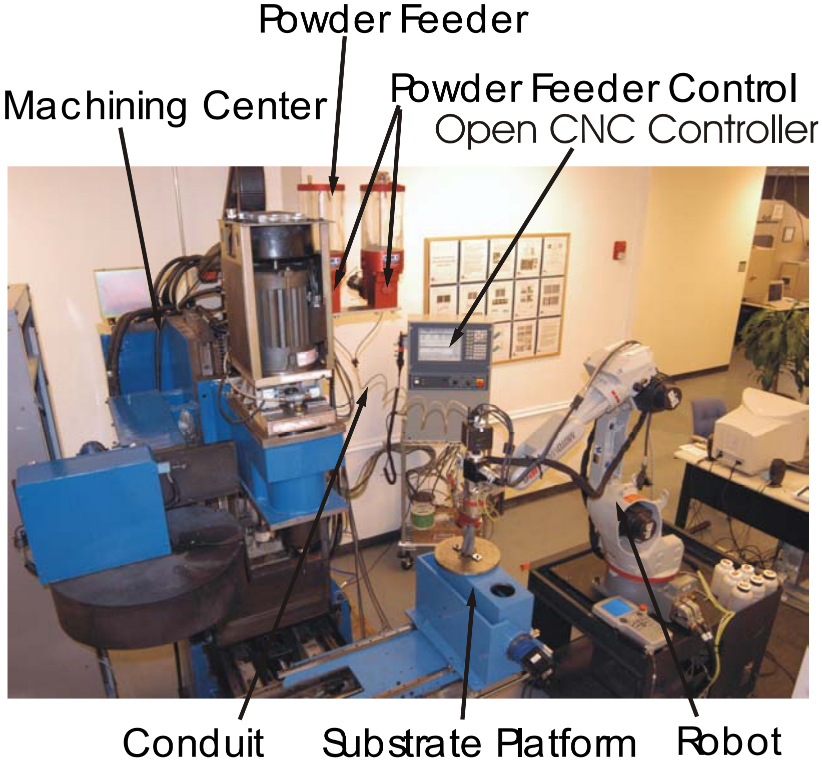

Figure 1. MultiFAB^{TM} used for the fabrication of FGM

Research Center for Advanced Manufacturing is developing a machine MultiFAB^{TM} that integrates various deposition and machining techniques for part fabrication. One of the features of the machine includes the fabrication of FGM parts. Figure 1 shows the MultiFAB^{TM} used for laser-based deposition for the fabrication of FGM parts. The powder feeder stores the powder. A computer-based controller mounted on the powder feeder controls the delivery rate. The metal deposition head is mounted on a 6-axis robot and the substrate is mounted on a platform that is manipulated in the space. Coordinated motion of the robot and the substrate fabricates the desired geometry.

Different approaches for the representation of the FGM parts have been reported in the past. While the multi material solids essentially depict a sharp contrast in the material distribution across the spatial boundaries, composition of the functionally graded material varies smoothly in the spatial domain. The need for a suitable representation that allows a smooth usage of the data for the process implementation is required. Most of the popular techniques of representation are based on the spatial and the subsequent material distribution in the space.

The approaches for representation of the FGM parts that have been reported recently include decomposition-based method, B-rep method, extended cell-tuple structure based method and the Distance Field Method. The decomposition-based method is based on the subdivision of the space into multiple sub-regions and associating material information to the sub-regions [3]. B-rep method is based on describing the solids in terms of the bounding topological entities followed by finite subdivision of the of the solid into material domains and associating a material variation function over the domain [4]. In extended cell-tuple structure based method, a model is represented by a set of topological entities such as vertex, edge, face and region called cells that are connected through a graph and composition information is associated with each cell [5]. Central notion of the use of distance field is based on the parameterization of space by distance from material features either exactly or approximately [6]. In addition to the geometry of part, the composition of the constituent material makes the fabrication of FGM, in essence the actual process implementation challenging. Not many methods addressing the issues pertaining to the actual process implementation have been presented.

An approach based on establishing the one to one correspondence between the spatial regions inside the solid and composition of the constituent materials result in undesirable C^0 continuity. Inclusion of the time to express the spatial motion of the metal deposition head and material composition as a function of time ensures a higher order of continuity across the part domain.

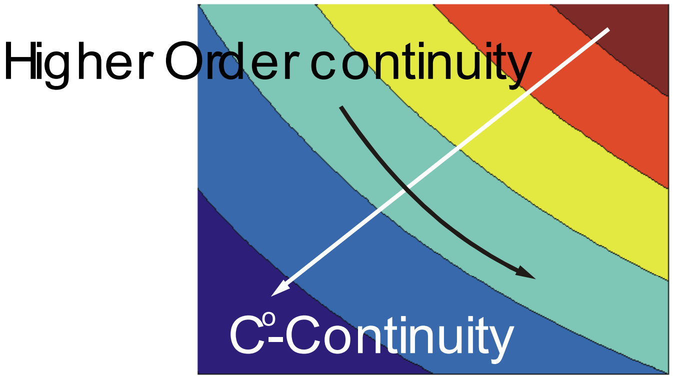

Figure 2. Continuity of the material composition in a FGM

As described in the earlier sections, the method used for the material deposition in our experiments is based on the laser based metal deposition. Metal, which is added in the form of powder stream, can be mixed, on the fly, to the desired composition. Owing to the finite size of the molten pool and the subsequent width of the deposition, the set of curves that comprise the tool-path is a set of points P such that $P \subset S$. S is the set of points that constitute the solid. Assuming that the composition of metal powder is homogeneous and is distributed evenly when delivered at the given spot, the variation in the material composition is possible only along the tangential direction of the path-curves. As shown in the Figure 2, the control of the material composition is limited along the normal direction of the curves. A high order continuity of material variation is sustained along the tangential direction of the tool path whereas the nature of variation along the normal direction is limited and can be classified as C^0. Also the minimum resolution of the composition variation along the normal direction is limited by the size of the molten pool.

Another set of parameters that must be taken into account during the process planning includes the length of the conduits and the pipes that carry the stream of metal powder. Sufficient time must be provided unless the composition of the metal powder becomes homogeneous and the rate of flow is consistent.

For certain regions, a smooth variation of the composition may allow the part fabrication by a coordinated control of the electric drives. The same may not be possible for other regions where the change in composition of material is discontinuous. The shift of regions and discontinuity in the metal deposition enforces inclusion of sufficient time to discharge the metal already present in the conduits and the time required before another set of materials or composition becomes stable.

The above discussions suggest the following list of factors that the path planning method should be able to address:

1. The path should be directed along the direction of minimum decent of the composition variation.
2. The time required before the delivery of the desired composition of material becomes uniform and the time before excess material is removed must be determined in advance.

The time required for the discharge of the metal is given by:
$t = \max(l_1, l_2 \ldots l_m) / \min(v_1, v_2 \ldots v_m)$

where v_i corresponds to the speed of the *ith* metal powder stream and l_i is the corresponding length of the conduit. The min() and max() correspond to the minimum and maximum value functions.

3. Process Planning for Functionally Graded Material Parts

A FGM can be expressed as a manifold $M \in R^{3+m}$ comprising of the x-, y-, z- coordinates and the number of materials, *m*, essential towards its geometric topology and the material composition. The concept of manifold in essence captures the intent of spatial and material-composition continuity. The projections of the manifold along the individual coordinates provide the input for process implementation.

For all practical purposes, the manifold M is a topological manifold. A manifold X is a topological manifold if :
X is locally Euclidean with constant local dimension, 3+m, in the present case.
X is second countable,
X is a Hausdorff space

The part to be fabricated may be described as $P \in M$ For a feasible representation of the solid; the point sets used to model the solid should be described by a finite amount of data. It should also be possible to attribute the material information by a finite amount of data. The following sections elaborate the methods used to implement the above requirements in detail.

3.1 Path Planning Approaches

The path planning technique for fabricating FGM must take into account the requirements for the part geometry as well as material composition. The existing approaches are based on the trivial assumption of material homogeneity. This imposes the requirement of path planning for FGM to be viewed from entirely different point of view. Some of the fundamental requirements from the path-planning algorithm may be listed down as:

1. The torch path should be directed along the direction of the least gradience of the material composition.
2. The path generation algorithm must be able to take into account the minimum allowable distance due to the finite width of the molten pool between two path segments.

Any variation in the material composition requires change in the settings of drives for the powder feeder and the spatial movement. However the stability in the flow rates and the composition requires a finite time. Therefore a smaller gradience of composition is more suitable for the metal deposition head path.

The dimensions of the molten pool are finite. Also, the smoothness of the surface depends on the extent of overlap between the deposited beads. Another advantage that can be attributed to the overlap of the beads is the remelting and mixing of the material thus allowing a better and near net desired gradience of the material composition.

The first step towards the part fabrication is slicing the solid into a set of layers. The next step is to generate path for each layer. The existing strategies for the path generation may be classified into evolving curves, which includes zigzag type and contour type, spirals and the space filling curves [9]. The same idea may be extended to the path planning for FGM with certain modifications. Any cross-section is divided into different regions based on the iso-composition contours. The iso-composition contours refer to the curves obtained by connecting the points that have similar composition. Yet another factor that determines the distance between the iso-composition contours is the width of the deposition bead and the allowable overlap between the adjacent beads.

Contrary to the popular methods of representation that are based on the subdivision of the volume of the original solid into a set of subvolumes and attributing the material to each subvolume, we propose here an algorithm based on the representation of the solid by spatial curves corresponding to the torch path and attributing material properties to each curve. The algorithm may be described as:

Step1: Slice the solid
Step2: For each slice, determine the iso-composition contour curves based on the material composition.
Step3: Approximate each iso-composition curve as a mathematical function and attribute composition to the curve.
Step4: Arrange the order of build for each curve based on the minimum variation of the material composition.

The advantage of representing the curves, as mathematical function is that, time derivative of the function may be determined for the velocity or the input for spatial manipulator. Similarly the arrangement of the curves in order of composition variation allows continuity in the state of drives that control the delivery of material.

3.2 Morphing based Approach Towards Path Integration

While above suggested approach is applicable to a large class of products, it may not be applicable to all the FGM parts due to irregular and complex geometry. The distance between the adjacent iso-composition contours may not be uniform. We suggest a modification in the approach that is based on the morphing.

Let D_r be the radial distance between two adjacent iso-composition contours and w be the allowable distance between two path segments. If $D_r \geq w$ then generation of intermediate path segment is required. Let χ_{ij} correspond to the composition of the *ith* material in the *jth* contour. The number of intermediate segments required is $L = g\,\text{int}(D_r / w) - 1$ where $g\,\text{int}$ corresponds to the greatest integer function. Then the composition of the *rth* segment such that $1 \leq r \leq L$ is given by

$$\chi_{ir} = I(r)\chi_{i1} + I(L-r)\chi_{iL}$$

I is a suitable interpolation function. Depending on the desired composition and the accuracy of the composition, the function I may be a linear or non-linear function.

4. Results

A Matlab based code was developed for the process planning. The input for the code is a solid model that stores the spatial geometry of the part and the material composition. The model is sliced and the path curves for each layer is generated by connecting the points of similar material composition such that the minimum allowable distance between the two adjacent curves is the process specific fraction of the bead width and is constant over the deposition process.

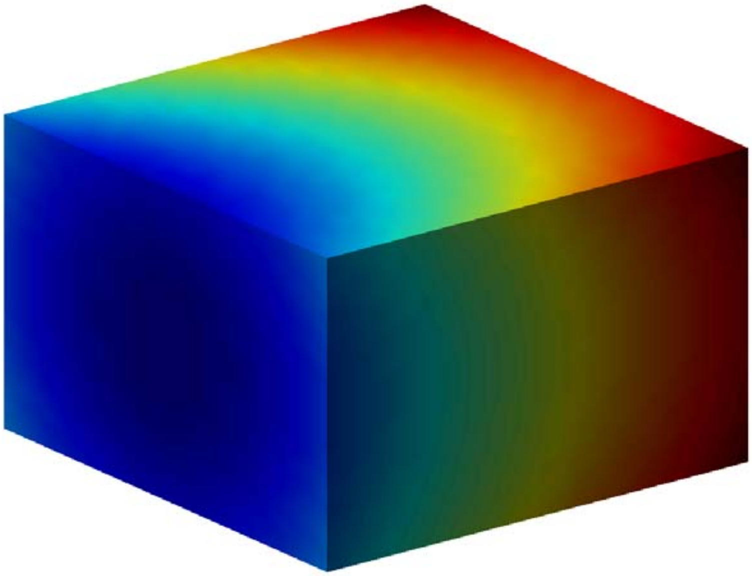

Figure 3. Desired composition of the FGM

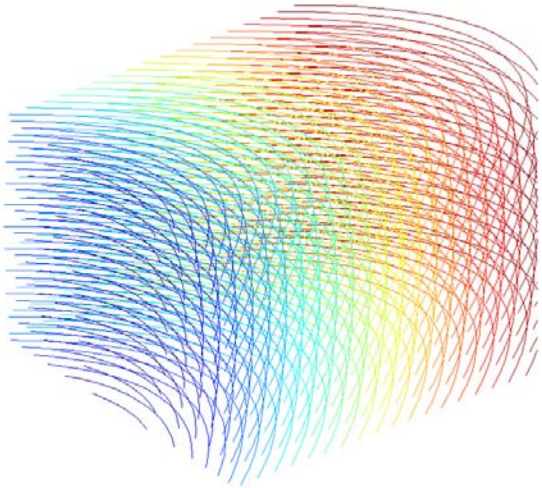

Figure 4. Part slicing and iso-composition contours for different layers

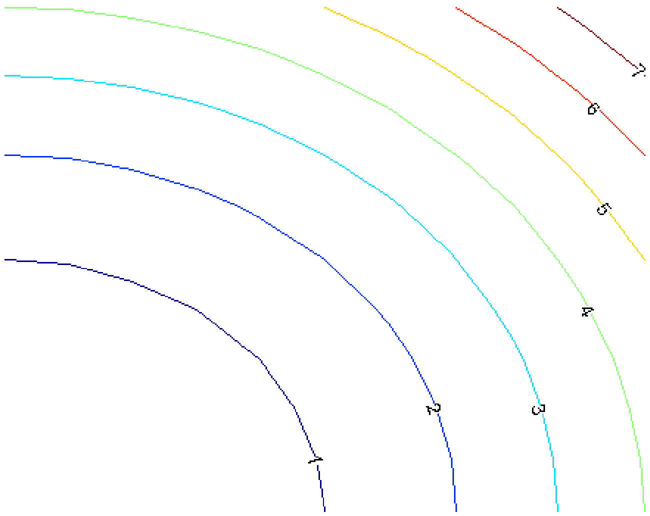

Figure 5. Arrangement of the contours in a sequence for the deposition

Figure 3 shows a functionally graded solid part and the desired material composition gradience. Figure 4 represents a slice and the corresponding profile of material distribution. The iso-composition contours (Figure 5) are generated by connecting the points having similar composition. The minimum distance between the contours is controllable and is governed by the allowable bead width. Figure 5 shows the order of the iso-contours to be built. The order depends on the minimum variation of the material composition.

Figure 6 describes a region where the distance between two iso-contours exceeds the allowable distance between two adjacent path curves. The intermediate path curve is generated by the linear interpolation of the composition. A plot of the curve location and the desired composition depicts that the variation in the material composition is negligibly small and is confined to a small region.

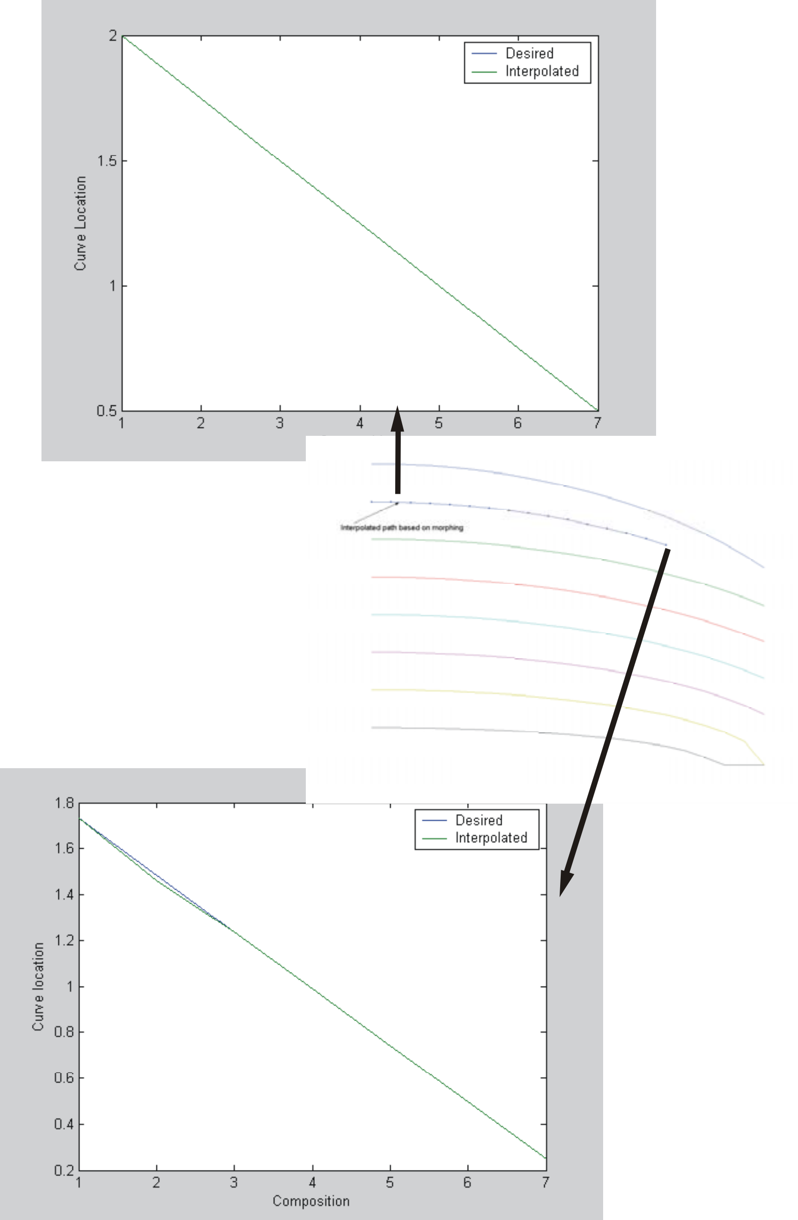

Figure 6. Linear interpolation of the contour geometry for the path generation.

5. Conclusions and Future Work

A process planning approach for the fabrication of the FGM parts has been suggested. Implementation of the algorithm is done using a Matlab based code. For a given FGM part the path is generated and described. The future work includes, extensive experimental verification and characterization of the method.

6. Acknowledgements

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7. References

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