The Heterogeneous Compensation for the Infiltrative Error of the Binder Jetting Additive Manufacturing Processes

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Abstract:

In binder jetting additive manufacturing, such as Three Dimensional Printing (3DP) and Patternless Casting Manufacturing (PCM, a process similar as ExOne and VoxelJet), the building error is mainly caused by the infiltration by the binder in the powder bed, and appear heterogeneous magnitude along different orientations because of the different infiltrating depth of the printed binder between the building direction and the binder printing direction. Current methods to compensating these error are mostly based on the contour equidistant offset and the model shrinkage, which couldn't deal with the heterogeneous infiltrative error. In this paper, we will propose a novel compensation method, in which the STL model will be counteracted heterogeneously in different directions to compensate the heterogeneous infiltrative distances of the binder in the powder. By this method, a sphere STL model will be transferred into an ellipsoid with variant axis length along different X/Y/Z directions. The method could greatly improve the dimensional accuracy of a series of additive manufacturing techniques which are based on the binder jetting onto powder bed.

1. Introduction

Additive manufacturing is a novel freeform fabrication mode, different with traditional removal fabrication, it is an accumulating manufacturing method from the top down driven by the three dimensional model. Rapid Prototyping(RP), Solid Freeform Fabrication(SFF), Three Dimensional Printing(3DP), Additive Manufacturing(AM) are different names of this technique above. Nowadays, there are various kinds of AM technique, such as 3DP, PCM, DSPC, SLA, LOM, FDM, SLS, et al[1]. In the binder jetting additive manufacturing technology, including 3DP[2, 3], DSPC, PCM[4] et al, the binder is printed onto the powder bed to selectively bond the powder to form the prototype.

In binder jetting AM technology, the droplet of binder is generated in a printhead, in which two different technologies are employed[5]: drop on demand(DOD) and continuous jetting. Continuous jetting continuously discharges a stream of fluid, which is broken into droplet by vibration. The technique is accomplished by selectively catching certain droplets as they pass through a collection equipment. On the other hand, in DOD technique, electrical pulses drive the piezo actuator in printhead to create separated droplet directly. By integrating multiple piezo actuators as a nozzle array into a printhead, the building efficiency is increased greatly. In recent market, ExOne (Huntingdon, PA), Voxeljet (Augsburg, Germany) and Z-Corporation (Burlington, MA)[6] provide the various 3D printing systems based on DOD binder jetting technology and nozzle array printhead, which are capable to manufacture the molds or sand models for metal casting.

The feature size and fabrication rate of a part printed by the binder jetting AM technique are affected by the binder droplet size. The droplet size is the most important parameter for the balance between the building accuracy and fabrication rate. With the smaller droplets, the dimension accuracy becomes higher, but printing layer thickness becomes thinner and the fabrication time of a part will become longer. If increasing the droplets and its infiltrative depth, the layer thickness could become thicker and the fabrication rate is showing to advantage, but the transverse infiltrative distance will increase either and the error caused by binder droplet infiltration turns out to be considerable. So if we can compensate the infiltrative error, the bigger droplet and less expensive printhead could be adopted. Furthermore, the binder jetting AM technique may become more reliable and efficient.

With a DOD printhead integrated a nozzle array, a raster scan mode is usually applied, in which the printhead moves always fast in transverse direction, like X direction, and intermittently in longitudinal direction, like Y direction. Since the anisotropic motion of printhead and gravity affect in vertical direction, like Z direction, it is noted that the droplet infiltrative distances become anisotropic and cause the error anisotropically as well, which is observed in the Patternless Casting Manufacturing (PCM) technique developed by Tsinghua University in 2002[7]. In this paper, the anisotropic infiltration error is investigated and a heterogeneous compensation method is presented.

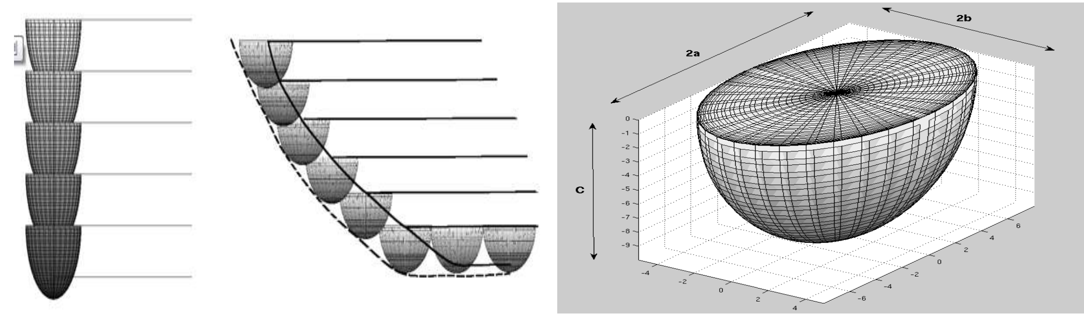
2. Dimension Error

In traditional binder jetting AM technology, a model with STL file format, which is a de facto standard widely used in CAD and AM field[8], is sliced along the direction of fabrication(Z axis) into a serial of discrete 2D contours. An error compensation is implemented in the directions of X/Y axes on two dimensional plane, the 2D layer contours take an equidistant shrink, and all are applied with an offset operation of the same distance. In this method, that the Z axis error is not handled causes a significant error in Z direction. To compensate this error in Z direction, a model shrinks inward with the same distance before slicing operation. Once the sliced 2D contours are compensated with offset operation, the contours are converted to the bitmap images which can be recognized by the AM machine.

A real infiltrative process of the printed binder appear heterogeneous magnitude along different orientations because of the different infiltrating distance in X/Y directions, the traditional compensation method does not deal with the difference of the heterogeneous error. This limitation will significantly affect the accuracy and quality of the fabrication, hindering the industrial applications of binder jetting AM technology.

2.1 Infiltration Error

A complete component fabricated by binder jetting AM technique can be viewed as a serial of single binder drop primitives stitched together to make a cohesive structure. It is apparent that the size and shape of the primitive will ultimately determine the minimum feature size in the X, Y, and Z directions, as well as the surface finish of the component, all of which are critically important in making a high quality part.



(a) The infiltrative error (b) The primitive of a binder drop

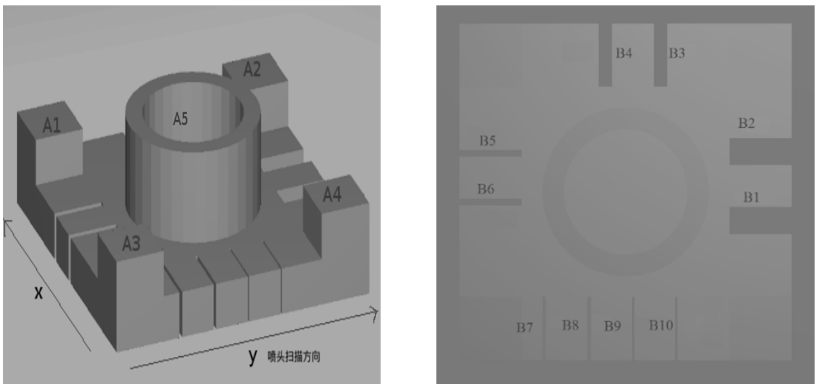
Figure 1. The phenomenon of infiltration of a binder drop in powders

The actual infiltration of a binder drop in the powders is not equidistant along the X, Y, and Z directions. It is obviously different between the depth of Z direction and the distance of X or Y direction, while in fact it is also different between the depth of X direction and the depth of Y direction. So the binder infiltration has heterogeneous magnitude along different orientations. The binder drop primitive in the powders is definitely a half of ellipsoid as showed in Figure 1. The ellipsoid's equatorial radius and polar radius, *a*, *b* and *c,* are the infiltrative distance in X, Y, and Z directions, determined by the real situation. And it is relative with the physical property of binder and powders. The primitive is a form of ellipsoid with different equatorial radiuses and polar radius, usually *a* is approximate with *b*, but *c* is considerably different with *a* and *b*.

2.2 Experiments

In this paper we used PCM technique to research the infiltrative error, so the binder is furan resin and the powder is the sand for foundry about 200 meshes. In PCM technique, the resin is injected onto the sand bed by the printhead, and the catalyst is mixed into the sand in advance. So after removing the un-printed sand, the part attained will be solidified through chemical reaction.

To investigate the different distance of binder infiltrative error in X, Y, and Z direction, an experiment part with a few of geometric feature is designed as Figure 3. In Figure 3, the features named A1 to A5 are simple geometric body, just cubes and cylinders; the features named B1 to B10 are gaps with the width from 0.4 to 6.4 millimeters. We fabricated two parts, part A and part B, the part A has the original dimension, while the part B has an offset of every layer contours with 1.2 millimeters. The offset value is chosen tentatively.



(a) Length of X/Y/Z (b) Gap Width of X/Y

Figure 3. The features on the experiment part.

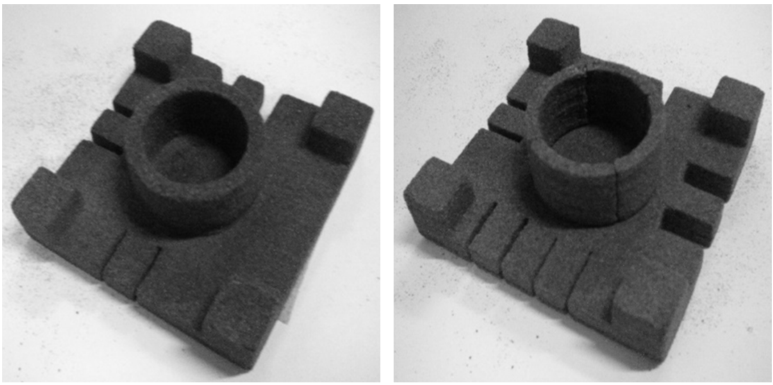


Figure 4. The experiment part A and part B manufactured by PCM technique.

We measured the two parts' feature size, features of A1 to A5, in X, Y, and Z directions, in Figure 4. Compared with the designed dimension size, the actual size distribution and error distribution are showed in a histogram in Figure 6. The most feature size of part A has a positive error value in X and Y direction, while the part B has a negative error value. It explains two points that there is an infiltrative distance in both X and Y directions and the part B with the contour offset of 1.2 millimeters has an excessive compensation. In Z direction, part A and B both have a positive error value, because the traditional compensation method does not handle the errors in Z directions. In table 1, the average feature lengths in X, Y, and Z direction are calculated. The average error is also figured out, listing in table 2. Finally we get a consequence of different error sizes in X, Y, and Z directions, a proof of the heterogeneous infiltrative error in PCM technique on behalf of binder jetting AM technology. In our case, there is a difference of 0.4 millimeters between X error and Y error in a good agreement of both part A and B. The error value in Z direction presents a proximity for a lack of compensation in both part A and B.

Table 1. The dimensions of the experiment parts (mm)

	A1-A4			A5				
	X	Y	Z	X-Outer	Y-Outer	X-Inner	Y-Inner	Z
Target	15	15	20	40	40	30	30	30
Part A	15.40	15.18	20.40	40.27	39.89	30.45	29.93	30.51
Part B	14.33	14.12	20.69	39.20	38.84	29.36	28.85	30.80

Table 2. The errors on direction of X/Y/Z (mm)

	Delta X	Delta Y	Delta Z
Part A	0.38	0.09	0.42
Part B	-0.69	-0.98	0.51

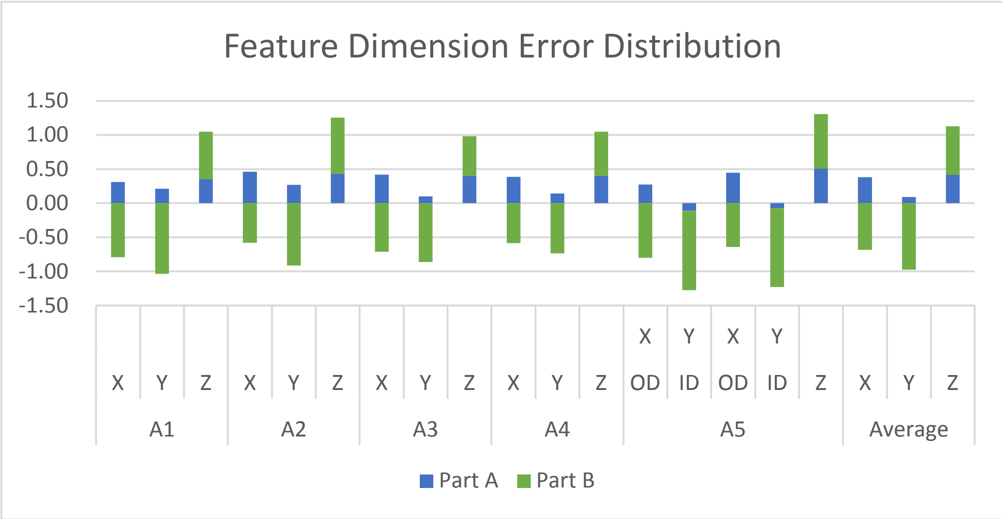


Figure 6. The dimension errors distribution of the features named A1 to A5

The gaps with a serial width from 0.4 to 6.4 millimeters, parallel with Z direction, are designed to inspect the manufacturing capability of the PCM machine. Since having an excessive offset compensation, the part B has a larger gap width than the target size. While the part A has an insufficient gap width distinctly for a lack of compensation. A phenomenon of gap disappearance is observed in part A, shown in Figure 9, illustrating that there is an infiltrative scope not less than 0.4 mm. The gap widths of X direction and Y direction are listed in table 3. There is also a difference about 0.3 millimeters between X and Y directions in gap widths statistics.

Table 3. The dimensions of the test part marked with B (mm)

	X	Y	X	Y	Y	DX	DY
Target	6.4	3.2	1.6	0.8	0.4	0	0
Part A	4.25	1.47	0.79	NONE	NONE	-1.48	-1.73
Part B	7.50	1.47	0.79	1.28	0.66	0.63	0.31

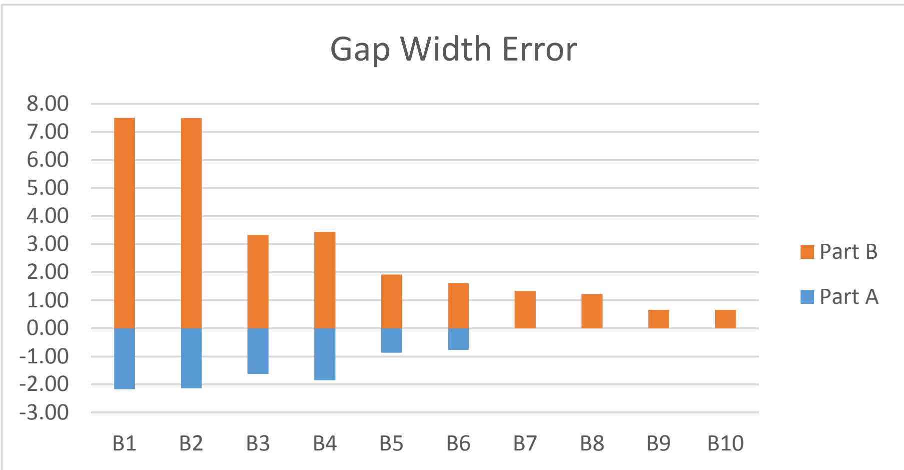
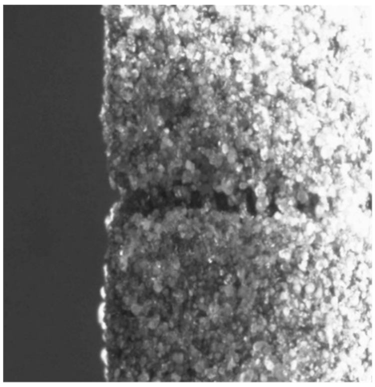
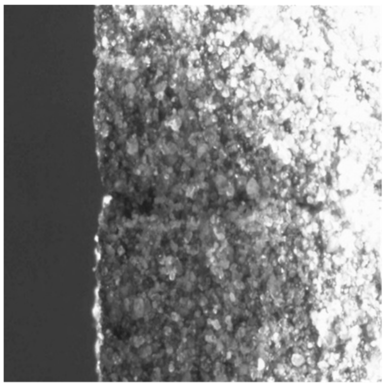
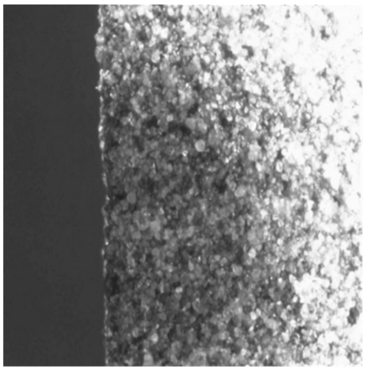


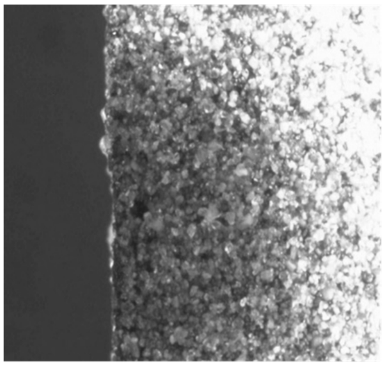
Figure 8. The gap width error distribution of the features named B1 to B10





(a) B7 width=0.8 mm (b) B8 width=8 mm





(c) B9 width=0.4 mm (d) B10 width=0.4mm

Figure 9. The disappeared gap in experiment part B

3. Compensation Method

Since the heterogeneous infiltrative error is confirmed, we propose a new compensation method to make up the deficiency of the traditional 2D method. By the new heterogeneous compensation method, a sphere STL model will be transferred into an ellipsoid with variant axis length along different X/Y/Z directions. The method could greatly improve the dimensional accuracy of a series of binder jetting AM techniques.

3.1 Heterogeneous Compensation

The new compensation method adopts the original STL model as data source to be dealt with, every triangular facet will be offset a distance which is calculated by its normal vector and infiltration vector. The offset distance varies according to the facet's position and direction, so the STL model will be counteracted heterogeneously in different directions to compensate the heterogeneous infiltrative distances of the binder in the powder.

The new compensation method is applied before slicing in traditional processing. After compensation, the new STL model will be used to the next processing without a compensation any more. The concept of line width in traditional compensation method is disappearing, and independent compensation in Z direction is also not needed again. Once the bitmap image is created, it can be directly used to control the AM machine.

The new infiltrative compensation method includes a few steps as follows:

(1) Construct the topological triangular mesh from the original STL data. Transformation of facets or vertices will not be done in this processing, it just find the topological information

among vertices, edges and facets which is used to guarantee the validity of the STL model for transformation in next step.

(2) Read a triangular facet one by one into program, and calculate each one's offset distance which depends on the normal vector and infiltrative vector. The compensating offset value is defined as distance between the envelope plane formed by the stacked half infiltrative ellipsoid and the plane formed by the all ellipsoids' center points, just shown as Figure 10.

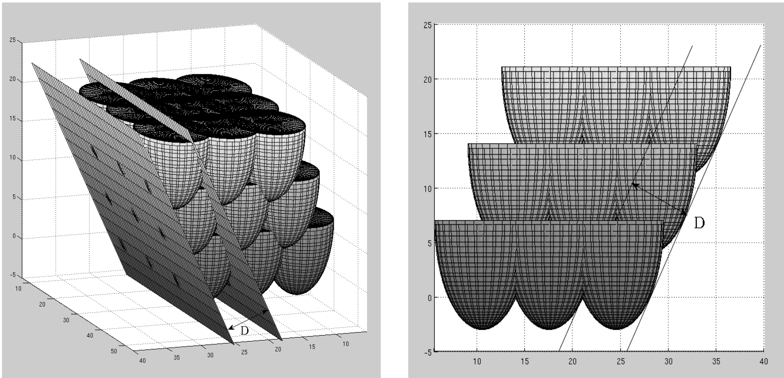


Figure 10. A sketch view of the compensating offset

(3) Read the vertex into program one by one, calculate each one's offset point through the offset distances of the triangular facets adjacent to the current vertex. The transformation based on vertices can keep the topological structure of all elements in STL model spontaneously. Of course, there may be no solution vertex satisfying the offset distances of adjacent facets, thus a vertex fission technique can be used to find a compromised solution with several vertices. There maybe are facets not a triangle created in this processing, this situation does not satisfy the rules of a STL model, so the triangulation is applied to the facets that does not match the rules.

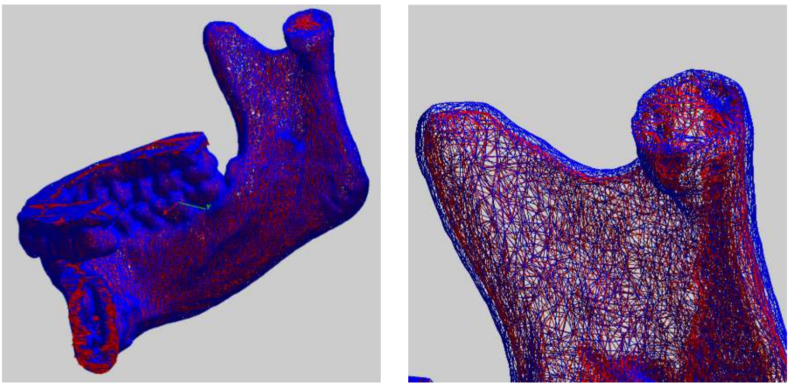
(4) Repeat the step 2 and step 3, until all facets and vertices are processed.

(5) Checkout the validity of the STL data, including the correction of topological information and the correction of the facet normal vector. Then a new valid compensated STL model is gained.

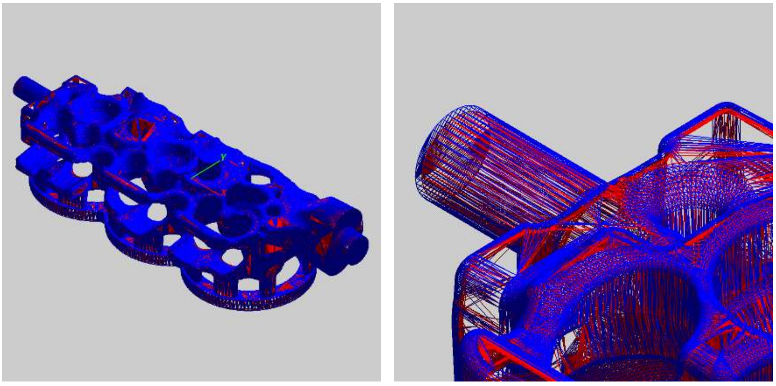
(6) Furthermore, the next steps of data processing, including slicing STL model, do not need a compensation any more. Thus the concept of line width disappears, and the data can be used to create a bitmap image for the AM machine directly.

3.2 Case Study

The infiltrative compensation method described in this paper has been implemented simply using a program language of C++. The compiler is gcc-4.7.3, the computer OS is Ubuntu 12.04 64bit. Several models are tested to see the performance of the new compensation method shown in Figure 12.



(a)A jaw model of STL with compensation



(b)A factory part of STL with compensation

Figure 12. The examples of model compensation

4. Conclusion

The new infiltrative compensation method changed the data processing mode for compensation. With the new method, the dimensional accuracy the surface finish, especially the fabrication rate of a series of additive manufacturing techniques which are based on the binder jetting AM technology is supposed to be proved greatly.

参考文献

[1] Vaezi M, Seitz H, Yang S. A review on 3D micro-additive manufacturing technologies[J]. The International Journal of Advanced Manufacturing Technology. 2013, 67(5-8): 1721-1754.

[2] Sachs E, Cima M, Cornie J. Three-Dimensional Printing: Rapid Tooling and Prototypes Directly from a CAD Model[J]. CIRP Annals - Manufacturing Technology. 1990, 39(1): 201-204.

[3] Technikon. Digital Sand Core Manufacturing Study[R]., 2004.

[4] X Dan. Study and Development of Patternless Casting Manufacturing and Machine[D]. Tsinghua University, 2002.

[5] Sachs E, Vezzetti E. Numerical simulation of deposition process for a new 3DP printhead design[J]. Journal of Materials Processing Technology. 2005, 161(3): 509-515.

[6] Utela B, Storti D, Anderson R, et al. A review of process development steps for new material systems in three dimensional printing (3DP)[J]. Journal of Manufacturing Processes. 2008, 10(2): 96-104.

[7] Research Status and Development Trend of Rapid Precision Casting Technology[J]. FOUNDRY

TECHNOLOGY. 2013, 34(12): 1690-1693.
[8] Stroud I, Xirouchakis P C. STL and extensions[J]. ADVANCES IN ENGINEERING SOFTWARE. 2000, 31(2): 83-95.