Dimensional Variability Analysis In Post-Processing Of Rapid Tooling

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Abstract

Rapid tooling for sand casting can be made by creating pattern with elements made by solid freeform fabrication (SFF) devices. Using this approach, post-processing and hand finishing remain as necessary steps to improve the surface finish quality of the pattern. For rapid tooling using laminated object manufacturing (LOM) models, post-processing includes decubing, sanding and sealing followed by integration with a match plate and/or conventional cope & drag pattern elements. Since the critical finishing operations are intensively manual, it is difficult to estimate the dimensional capability of rapid tooling by LOM process. The objective of this paper is to use statistics to evaluate dimensional variability associated with post processing using the accepted industry best practice.

1.0 INTRODUCTION

Solid freeform fabrication (SFF) refers to the physical modeling of component or tooling geometry using layered manufacturing technologies. These technologies make it possible to quickly generate polymer, wax, or paper-based prototype parts from solid model computer-aided design (CAD) representations. Parts are typically generated by building up one layer at a time with the thickness of each layer determining the accuracy of the part and the time required to build it. Initially used for the production of parts for design validation, the use of SFF technologies logically extends to rapid fabrication of tooling for casting processes such as investment casting, die casting, and sand casting.

Over the past decade, rapid tooling (RT) based on SFF models has found an increased number of industrial applications. For example, the QuickCast system, developed by 3D Systems Inc. [1], is already used in the automobile product development in Ford Motor Company. Gustafson [2] uses laminated object manufacturing (LOM) models as elements of patterns for sand casting.

For rapid tooling with LOM, the dimensional capability of the tool making process is a key factor influencing industrial applications. While rapid tooling with SFF can help to realize significant time and cost savings, the dimensional capability and stability is not as competitive as that achieved with computer numerical control (CNC) machined pattern production. To understand the dimensional accuracy and consistency of rapid tooling using SFF methods, some research work has been done in this area. For example, Wang, *et al*, [3] studied the error sources in the rapid tooling process using the LOM models. Hopkinson, *et al,* [4] investigated the thermal effects on accuracy in the 3D Keltool^{TM} process.

In this paper, we briefly introduce the sand casting process and its established error sources. We then consider the sources of error in rapid tooling production using the LOM process. The dimensional variability associated with post processing is then addressed. Since the operations are manual, it is difficult to give an accurate estimation of the dimensional loss or increment in post-processing. Thus it is reasonable to employ the statistics to analyze the dimensional consistency and variability. While the focus of this paper is on rapid tooling using the LOM process, the results are also applicable to other rapid tooling processes.

2.0 SAND CASTING AND ITS ERROR RESOURCES

Sand casting is an old and widely used metal forming process in which parts are produced by casting molten metal into sand molds. It is estimated that more than 90% metal parts are produced by this process [5]. To improve the dimensional accuracy, the error sources must be identified. The error sources in the sand casting are illustrated in Figure 1 [6].

Traditionally, the pattern for sand casting is made by manual or computer numeric control (CNC) machining. Manual machining is a time-consuming and high cost method and needs experience, knowledge and skills. With this experience-dependent method, it is difficult to guarantee the dimensional accuracy and improve productivity. CNC machining is a good candidate to improve the efficiency and processing accuracy. It is being widely used in today's pattern making industry. Figure 2 gives a flowchart of product development steps for a sand casting process using laminated object manufacturing (LOM) pattern elements.

3.0 POST-PROCESSING ERROR SOURCES IN LOM RAPID TOOLING

The LOM process starts with a 3D computer-aided design (CAD) model of the desired tool or pattern. The model is then tessellated into triangular facets and sliced into layers each having the thickness of a sheet of paper. The LOM model is then constructed by laser cutting and gluing sheets of paper together. Surround material and material in regions of the part that are hollow must be removed in a subsequent "decubing" process. The surface of the resulting LOM model must then be sanded to smooth the "stair step" texture created by the layers of paper. Finally, the surface must be sealed with lacquer or an equivalent sealant to keep moisture from being absorbed into the model. Each step in this process introduces error as shown in Figure 3.

Of the sources identified in the figure 1, decubing error and post-finishing error are those associated with post-processing that can cause delamination or dimensional swelling. Since this operation is typically conducted manually, it is difficult to make an accurate quantitative analysis for the dimensional change before and after this process, since each would be subjective.

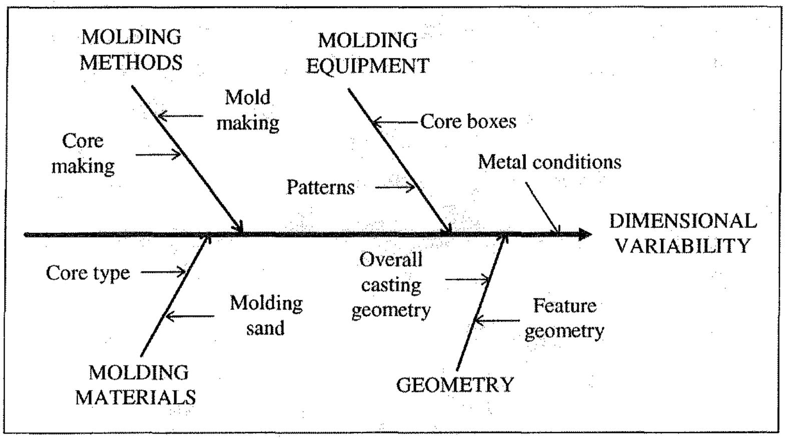

Fig 1 Fishbone diagram of major factors affecting dimensional variability of casting

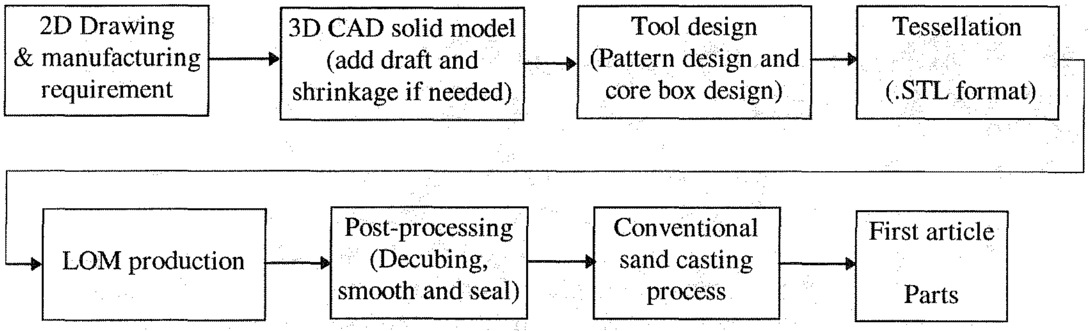

Fig 2 The sand casting process using rapid tooling (LOM)

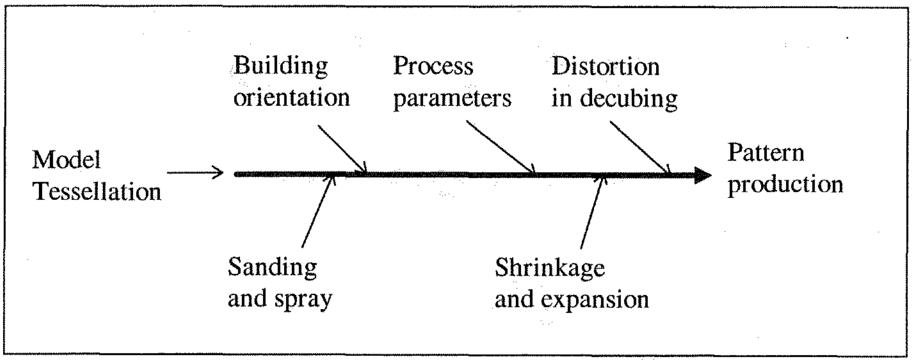

Fig 3 Fishbone diagram of error sources associated with the LOM process

3.1 Decubing Error

Residual stress can develop in the LOM build as the result of the temperature change. During the building process, the temperature of the workpiece will rise because of heat used to improve the adhesive bonding between paper layers. After the building process is finished, residual stress due to volume shrinkage develop within the model as it cools to room temperature. When the model is "decubed", constraints are released and the residual stresses are redistributed. This can result in shape distortion of the model and in some cases, delamination of layers. As with other sources of error in the LOM process, the dimensional error that may occur depends on the detailed geometry of the part, the part orientation with respect to build direction, paper thickness and other process factors. In general, distortion is greatest in thin wall parts [3].

3.2 Post-Finishing Error

After decubing, the model is usually sanded and sealed. Sanding is necessary to remove "stair step" irregularities and to smooth part features. The sealed lacquer coating seals the surface and strengthens the model. The lacquer coating is also sanded to smooth the surface finish of the model. These operations are usually performed manually by experienced operators. Error introduced during these manual procedures depends on operator skill and specific part geometry. Because of the number of hard to control factors involved, post finishing error is likely vary significantly with tool geometry.

4.0 EXPERIMENTAL INVESTIGATION

4.1 Test part

An experimental investigation was conducted to statistically analyze the errors discussed above. The test part selected is a thin wall aluminum sand casting used in an aerospace application. A 3D CAD representation of the part is shown in Figure 4. This part has many typical features including cylindrical surfaces and transitions, planes, and small through holes. Because of its thin walls, the part is sensitive to decubing and post finishing. Although this is a tooling master, not a casting model, it suits the purpose of our study. Our purpose is to determine the influence of post-processing on part dimensions. Generally the part is supplemented and extended in some dimensions to add the machining stock).

The models was built with the chord height of 0.001 inch. The LOM models were built using a LOM 1015 *Plus* machine. Tessellation and process parameters and resulting build time are given as follows:

Laser power: 43 W
Laser beam radius: 0.0050 in
Plotter speed: 10.0 in/s
Heater-slow-speed: 3.00 in/s
Heater-fast-speed: 5.00 in/s
Platform-slow-speed: 0.50 in/s
Paper thickness: 0.0044 in
Chord length: 0.001 in
Build height: 4.68194 in
Total layers: 1089
Elapsed time: 12 hrs 50'

4.2 Dimensional Measurement

To assess the effect of tessellation, the dimensions of a variety of features were measured before and after post-finishing using a Brown & Sharpe coordinate-measuring machine (CMM) [7] and compared with the CAD model nominal dimensions. Best metrology practices were used through out the investigation to ensure that measurement system error did not influence results. Each measurement was repeated five times using the CMM machine. For each trial, the touch points were randomly chosen and distributed around the surface or plane to insure that all variation was included. Figure 5 identifies the location of each dimension.

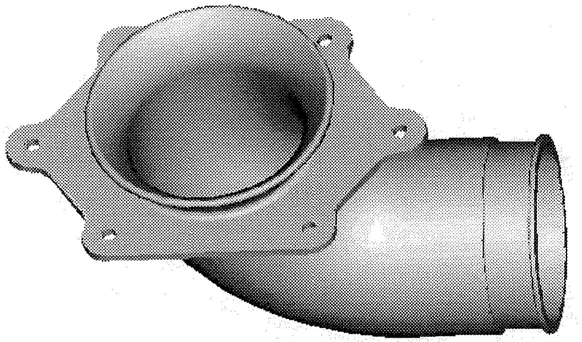

Fig 4 The solid model of the test part

To assess the measurement validity and reduce any influence from the measurement error, gage repeatability and reproducibility (Gage R&R) [6, 8, 9] has been implemented on the CMM machine.

4.3 Decubing Error Measurement

As discussed above, decubing error may occur due to residual stresses and delamination. To measure the distortion caused by the decubing operation, the concepts of flatness and roundness are introduced. Flatness is the condition of a surface having all points in one plane (generally measuring 4 points). Roundness is the condition where all points are in a circle (generally measuring 4 points). It is computed by subtracting the maximum point from the minimum point about the best fit circle [7, 10]. The flatness and roundness measured here are the flange plane and the right side of the elbow part (dimensions 13~16, see Figure 5). Each measurement has been repeated five times and the average value and standard deviation calculated.

4.4 Post-Finishing Error Measurement

The prototype is sanded and sealed to achieve a final finish according to the conventional post-finishing process. This is done by sanding-sealing-sanding-sealing iterations. Sanding and sealing are generally done manually. As such, it is difficult to consistently control dimensions of the part. In this study, the sand paper and lacquer are used to sand and seal. After post-finishing, the prototype can be used as the pattern in sand casting process. Then the same measurement can be performed on the pattern.

4.5 Analysis of Results

The dimensions measured can be categorized as five types: distance or thickness (1, 2, 4, 6, 7 and 12), internal cylindrical surface (8 and 10), external cylindrical surface (3, 5, 9 and 11), flatness (13 and 14) and roundness (15 and 16). The statistical analysis is performed by StatView [11] software. The results are shown in Table 1 and 2. Some typical dimensional distribution diagrams are shown from Figure 6~10.

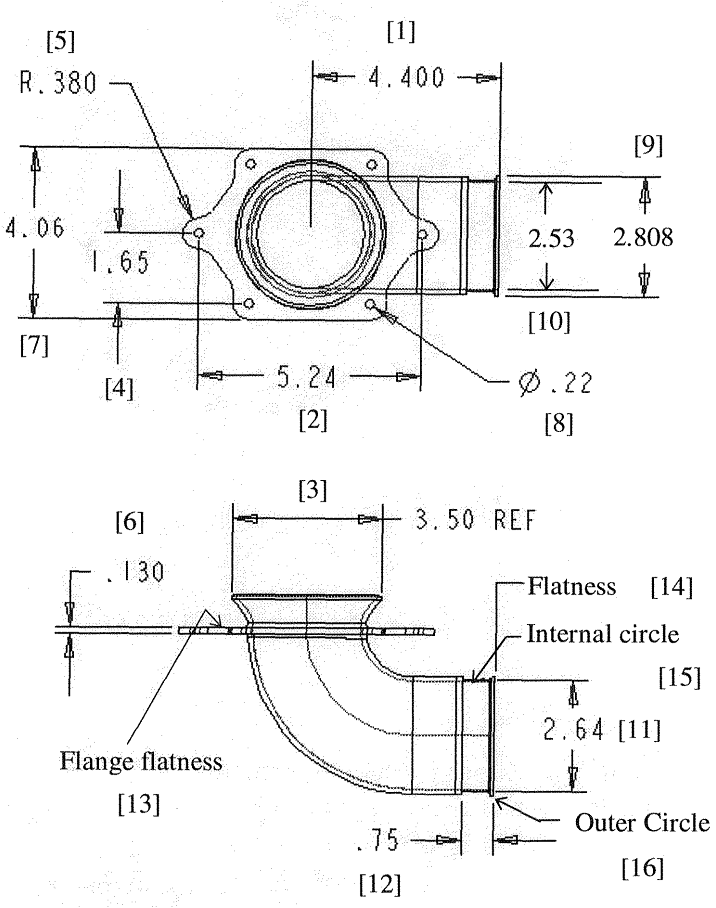

Fig 5 Test part dimensions measured by CMM

Comparing the items and values in Table 1 and 2 and refer to Figure 6~10, we can make the following observations:

Generally speaking, the variability of dimensions is the same before post-finishing as it is after post-processing. Of 16 dimensions, there are 6 dimensions greater in standard deviation before than after post-processing, 7 less and 3 equal. As such, there are no obvious trends demonstrating that the standard deviation increased or decreased with geometry.

Considering the standard error, there are 4 dimensions greater before than after, 8 less and 4 equal. This suggests that the standard error worsens as a result of post-processing.

For the range, there are 8 dimensions greater before than after, 6 dimensions less and 2 dimensions equal. This indicates that the total dimensional consistency is improved as a result of post finishing.

TABLE 1 Test Part Dimensional Variability (before sanding and sealing)
(The location of each measurement is indicated by number on Figure 3)

	Mean	Std. Dev.	Std. Error	Count	Minimum	Maximum	Range
dim1	4.395	.006	.003	5	4.387	4.404	0.016
dim2	5.250	.003	.001	5	5.246	5.253	0.007
dim3	3.524	.016	.007	5	3.503	3.546	0.043
dim4	1.650	.002	.001	5	1.649	1.654	0.005
dim5	.766	.003	.001	5	.761	.769	0.008
dim6	.136	.006	.003	5	.131	.146	0.015
dim7	4.065	4.479E-4	2.003E-4	5	4.064	4.065	0.001
dim8	.221	.002	.001	5	.219	.223	0.004
dim9	2.817	.002	.001	5	2.815	2.819	0.004
dim10	2.538	.005	.002	5	2.531	2.543	0.012
dim11	2.636	.003	.001	5	2.632	2.640	0.007
dim12	.749	.002	.001	5	.747	.751	0.005
dim13	.013	.001	.001	5	.012	.015	0.004
dim14	.003	.001	2.260E-4	5	.002	.004	0.001
dim15	.014	.001	3.720E-4	5	.013	.015	0.002
dim16	.006	.003	.001	5	.001	.009	0.008

TABLE 2 Test Part Dimensional Variability (after sanding and sealing)
(The location of each measurement is indicated by number on Figure 3)

	Mean	Std. Dev.	Std. Error	Count	Minimum	Maximum	Range
dim1	4.382	.006	.003	5	4.376	4.388	0.013
dim2	5.247	3.946E-4	1.765E-4	5	5.247	5.248	0.001
dim3	3.548	.002	.001	5	3.546	3.550	0.004
dim4	1.651	.001	.001	4	1.650	1.652	0.003
dim5	.763	.009	.004	5	.751	.772	0.022
dim6	.140	.003	.001	5	.137	.143	0.007
dim7	4.066	.001	3.710E-4	5	4.065	4.067	0.002
dim8	.217	.002	.001	5	.215	.219	0.004
dim9	2.819	.006	.003	5	2.810	2.827	0.017
dim10	2.542	.001	.001	5	2.541	2.544	0.003
dim11	2.660	.017	.008	5	2.633	2.673	0.040
dim12	.747	.004	.002	5	.743	.751	0.008
dim13	.008	.005	.002	5	.003	.014	0.012
dim14	.003	.001	3.274E-4	5	.002	.004	0.002
dim15	.005	.002	.001	5	.003	.007	0.004
dim16	.007	.001	.001	5	.005	.009	0.004

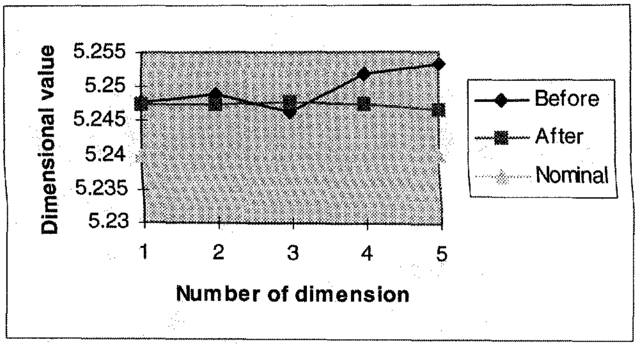

Fig 6 Diagram of dimensional distribution of Dim2

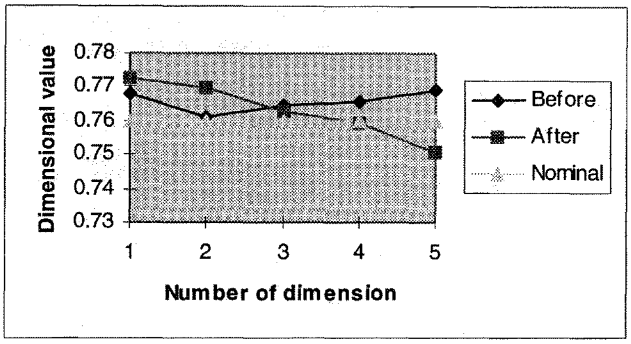

Fig 7 Diagram of dimensional distribution of Dim5

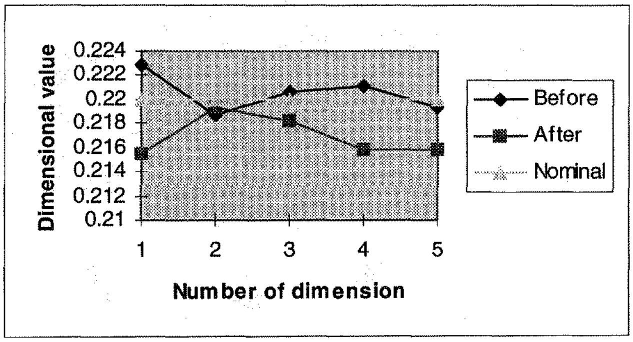

Fig 8 Diagram of dimensional distribution of Dim8

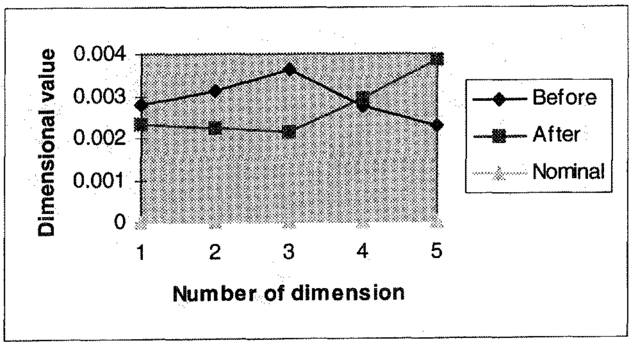

Fig 9 Diagram of dimensional distribution of Dim14

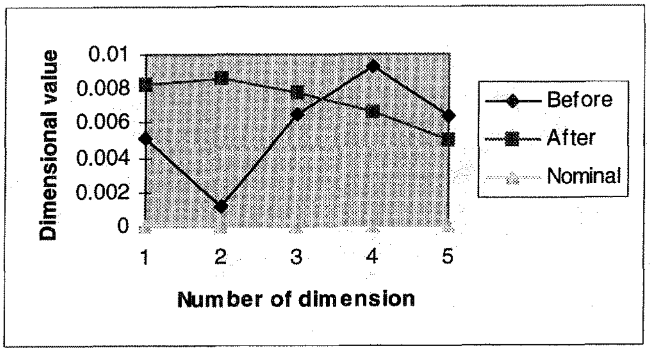

Fig 10 Diagram of dimensional distribution of Dim16

For the specific type of dimension, the difference is not outstanding either. For example, for distance and thickness dimensions, there are 3 dimensions greater before than after, 2 less and 1 equal in standard deviation. For the outer cylindrical surface dimensions, 1 greater and 3 less. For the inner cylindrical surface, 1 equal and 1 greater. For flatness, 1 less and 1 equal. For roundness, 1 greater and 1 less.

4.6 Discussion

From the above results, we present the following discussions to further clarify our findings:

- Post-processing can be useful and flexible to guarantee the dimensional accuracy. In comparison with CNC finish machining, post-processing can complement dimensional capability with its sanding-sealing-sanding-sealing process (e.g. overcut area). CNC finish machining is less forgiving if an overcut occurs. While comparing with manual making, the overall dimensional accuracy can be achieved and the productivity is relatively better.

- Post-processing can repair or reduce some systematic error sources inherited from previous process stages, i.e. paper thickness, tessellation, build direction, etc. As indicated by Wang, *et al* [3], systematic errors are not avoidable because of the nature of layered manufacturing. But post-processing can help to repair or reduce these errors by its sanding and sealing iterations, if the operator has a better understanding of the process and is experienced with mold making.

- Different rapid tooling processes may be more suitable to different geometry. According to our experience, the LOM process is good for block, thick wall and very complicated surfaces geometry, but not for small holes or bars, thin walls, shallow surfaces and difficult undercuts. Dimension 8 (diameter is 0.22 inch) has verified this. The error is evident even though the chord height is already the minimum. Other SFF processes (e.g. SLA, FDM) may be better suited to handle the geometry features that challenge LOM.

5.0 CONCLUSION

From the above analyses, we may find that there are no obvious relations of dimensions existing before and after post-processing. So it is hard to give the numerical equations of the dimensional consistency or the accurate relationship. But if we can understand this and make full use of the advantages of post-processing, the systematic errors maybe repaired or reduced and thus the dimensional capability may be improved. Geometry drivers for LOM process are also discussed. The flexibility in post-processing can be helpful for rapid tooling in processing accuracy and thus strengthen the pattern matches competitive position in the sand cast tool making market.

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