GEOMETRY AND PROCEDURE FOR BENCHMARKING SFF AND HYBRID FABRICATION PROCESS RESOLUTION

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ABSTRACT

Since the advent of SFF and RP a number of SFF benchmarking geometries and methodologies have been developed and employed with some similarities but limited standardization. Minimal information has been published in regard to a standard method of measuring the resolution limits or capabilities of SFF and SFF-based hybrid processes. In an effort to benchmark resolution limits of SFF and Hybrid Fabrication processes, several benchmarking geometries were developed to capture the resolution capabilities, specifically hole size and rod size range, of multiple hybrid fabrication path steps and a hybrid path as a whole. These useful geometries are shared with the SFF community and procedures for their use are described in this paper.

1. INTRODUCTION

A combination of procedure and benchmark geometries was developed for evaluating hybrid fabrication paths. This benchmarking approach is intended for, but not limited to, design parameter input of manufacturable optimized intertwined lattice structures, made up of rod and hole elements. When designing objects using an optimized intertwined lattice structure approach, sub-surface structure consists of two or more distinct phases. These phases are in the form of an intertwined, interconnected, lattice structure with a range of rod and hole sizes as well as a range of aspect ratios. Before designing subsurface lattice structures much must be known about the manufacturability of these rod and hole elements if they are to be successfully fabricated using SFF or SFF-based hybrid fabrication techniques.

Purpose

For optimized intertwined lattice structures to be designed for manufacturability, hybrid path capabilities and limitations must be well understood. In fact, before designing an optimized lattice structure, which may approach one million or more rod and hole elements, manufacturing process capabilities are required as a design input. In other words, the range of rod and hole sizes feasible, with a given hybrid fabrication path, must be known and provided on the input side of the design process. Other applications employing lattice structures or ultra fine features are in need of SFF process and hybrid path evaluation before widespread use and measurable quality improvements can take place. This paper shares a combination of procedure and benchmark geometries used for evaluating hybrid fabrication paths at MSOE. This combination is intended for, but not limited to, the design of manufacturable optimized intertwined lattice structures, made up of rod and hole elements.

Scope

The objective of this benchmarking approach is to determine the rod and hole size-range capabilities and aspect ratio limitations of individual steps of a hybrid fabrication path and the path as a whole. The resulting data provide critical input parameters for creating manufacturable designs. Benchmarking configurations with integrated rod and hole diameters were considered as well as daisywheel configurations but the effort of evaluating these complex objects and the potential for unnoticed defects steered geometries to simpler forms.

To develop the benchmarking geometries shown herein three criteria were applied with simplicity being a guiding factor:

- *covers one order of magnitude in feature sizes*
- *relatively easy to use and evaluate*
- *captures aspect ratios if needed*

Beyond the scope of this initial effort, though important, were material properties and internal defect considerations.

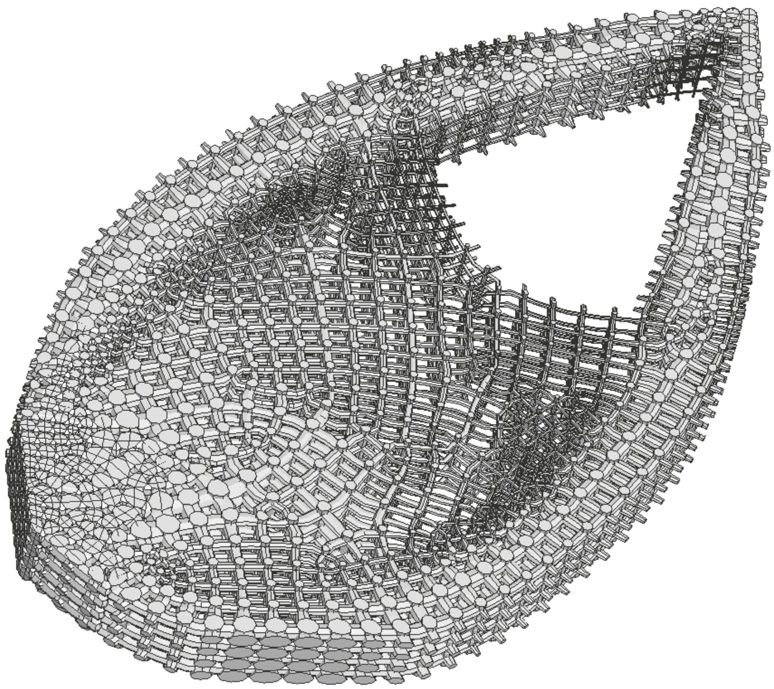


Figure 1. Optimized Lattice Structure consisting of "rods" and "holes"

Background

The direction of research on optimized lattice microstructures has been to develop a process to integrate optimization of a structural component's shape and topology with optimization of the composite material within, by treating the component's inner skeleton as part of the design domain. Rather than a solid cast component with optimized outer shape, one can produce a component with an inner skeleton – or microstructure – designed to maximize, minimize or vary stiffness, thermal conductivity, strength, or other properties.

The resulting microstructure –or- optimized intertwined lattice structure approach to creating objects with functionally graded material results in sub-surface morphology consisting of two or more distinct phases [1, 2]. These phases are in the form of an intertwined, interconnected lattice structure made up of rods and holes with a range of feature sizes and aspect ratios (figure 1). To design these subsurface lattice structures much must be known about the fabrication method and manufacturability of these rod and hole features.

A literature search provided the following list of process benchmarking, calibration, or evaluation methods, none of which specifically address rod and hole resolution capability:

- 3D Systems Windowpanes™ [3]
- 3D Systems ChristmasTrees™ [3]

- A number of RP benchmarking parts have been proposed and studies have been presented which focus on amplifying warpage [4]
- Detecting cure-through [5]
- Determining thermal gradient impact on dimensions [6]
- Providing overall comparisons of RP process capabilities
- Chrysler [7] published a study comparing the top RP processes in 1993, using a speedometer adapter-comparison part
- Jacobs suggests the presence of noise in all processes involving a phase change, calling it a "random noise shrinkage constant." [8]

Overall, RP-related publications were not directly helpful but did provide much useful information on sources of error and benchmark design approaches.

2. Procedure

The procedure for evaluating a single step of a hybrid path is illustrated in the flow chart shown in figure 2. The flowchart is applied to determine the rod and hole resolution capability of each process step as well as aspect ratio limitations. Up to four of six benchmarking geometries are employed depending on the type of process and hole or rod form. Upon completion of the flowchart for each process step, the step specific data are stacked to determine an overall hybrid path capability. If only SFF is used to generate the object for a given application, only one pass through the flowchart is required.

Aspect Ratio Sensitivity?

For some processes, aspect ratio sensitivity is very critical. For example, if a ceramic rod is formed with a high length-to-diameter ratio, the ceramic feature may be easily damaged during

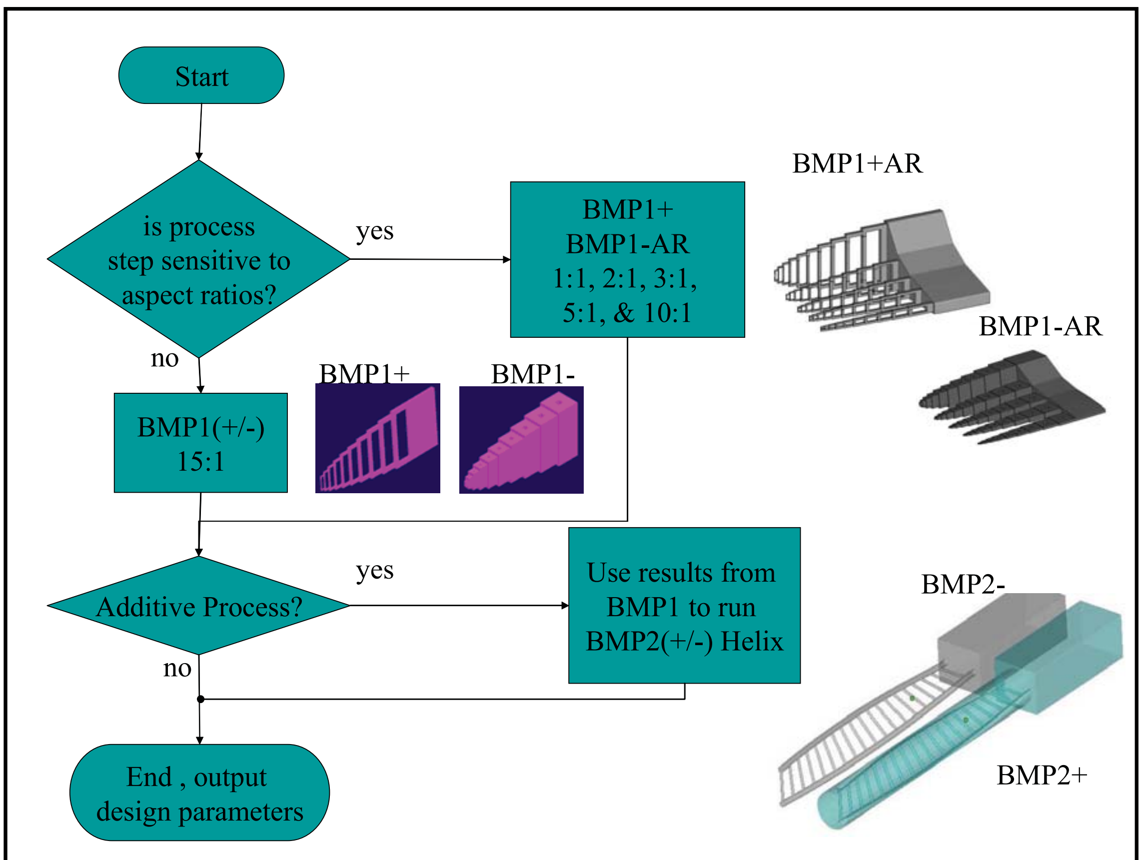


Figure 2. SFF and SFF-based hybrid fabrication path resolution flowchart.

processing. If an expendable pattern is used to initially form the feature the pattern material may expand due to moisture (from the ceramic mold slurry) or the pattern may thermally expand (during pattern burnout) damaging the ceramic mold feature in either case. In other cases, such as the selective laser sintering process or metal casting of rod features, aspect ratio is not as problematic since both processes are capable of large aspect ratios. In the case of stereolithography, the maximum unsupported feature length is well known by most machine operators, driving the maximum rod length. If the process step of interest is sensitive to aspect ratio, the BMP1AR is recommended. There are two forms of the BMP1AR and the user must determine which form will result in the desired feature shape, rod or hole, through the required number of transfers. It may take more than one transfer to test a particular step so the user may start with the same form that they end with. The BMP1-AR's are intended to uncover any aspect ratio limitations of a particular process step. The form of BMP1-AR is shown with 1:1, 2:1, 3:1, 5:1, & 10:1 ratios and can be scaled in the Z to provide higher aspect ratios. The BMP rung diameters range is size one order of magnitude and can be scaled. When generating BMP's to evaluate post SFF steps it is recommended that expendable patterns be produced with features 2-3 rung smaller that the process step is thought to be capable of. If it is not the SFF process being evaluated the pattern can be generated using the best build angle possible. Regarding the basic BMP1 design, each test feature diameter is 10 percent smaller than the largest feature in a linear fashion down to the smallest feature who's dimensions are 10 percent of the largest feature. Therefore, if the larger feature is scaled to 1 mm, the feature sizes would proceed from largest to smallest as follows: 1.0mm, 0.9mm, 0.8mm, 0.7mm, 0.6mm, 0.5mm, 0.4mm, 0.3mm, 0.2mm, to 0.1mm for the smallest rung. By using a range of sizes the "step-cutoff" or step limit can be brought into focus relatively quickly. The part could be modified to focus on a smaller range if needed.

If the aspect ratio for the rods or holes is not an issue the user proceeds to one or both BMP1's. BMP1 is a simple single aspect ratio latter-like form with 10 rungs, each consecutively 10 percent smaller than the largest. The two forms of the part are holes and rods. The use is very straightforward. Set the smallest feature 2-3 rungs smaller than the expected smallest feature and process the object through the needed step. Build BMPs at the "worst-case" build angle. There are two forms of the BMP1 and the user must determine which form will result in the desired feature shape, rod or hole, for the desired step, through the required number of transfers. It may take more than one transfer to test a particular step so the user may start with the same form that they end with. It is recommended to start with both forms and follow through all steps to get a complete picture of process capability. 5 Copies are recommended for each step.

Additive Process?

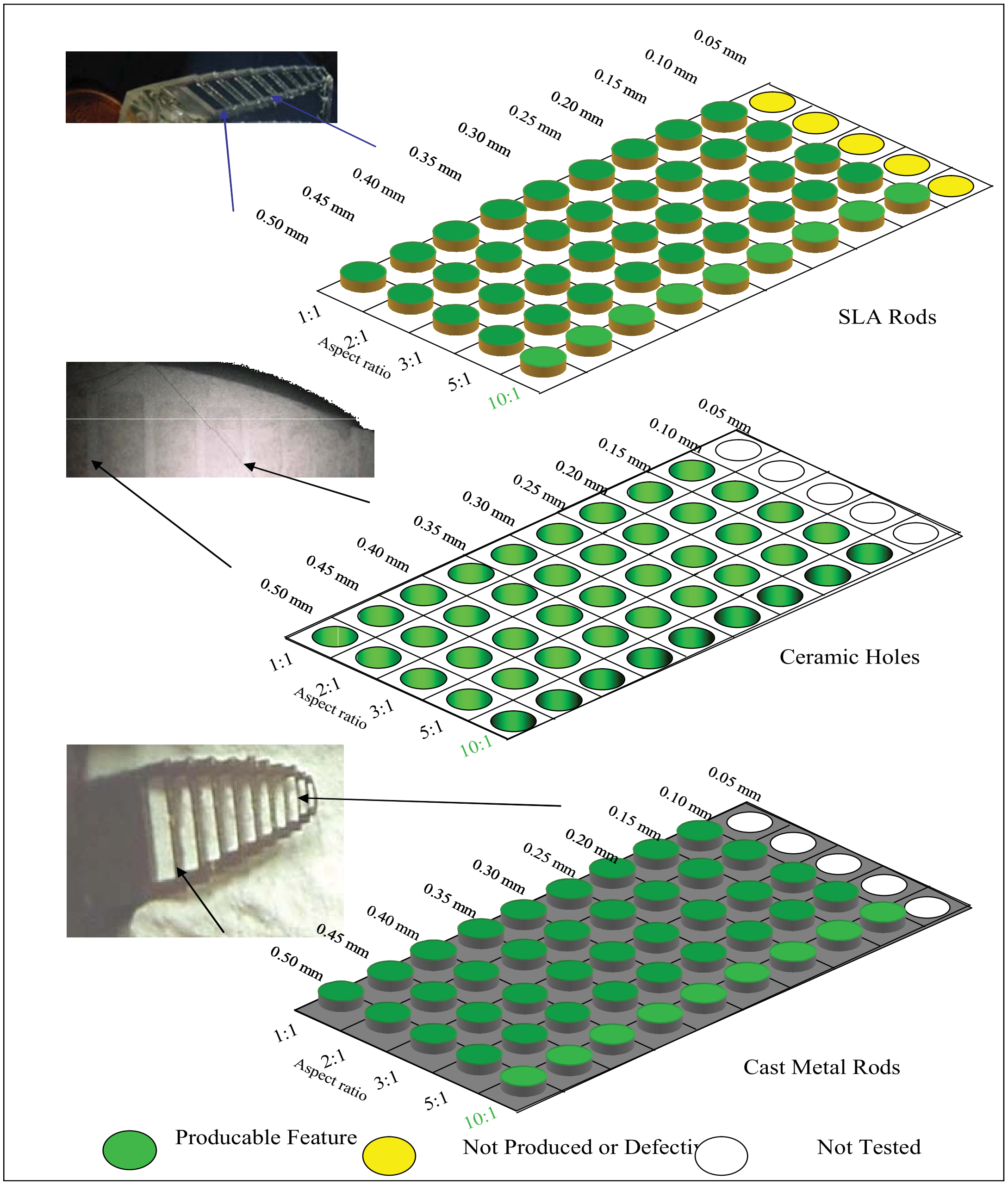
If the step being evaluated is an additive process it is important to verify that all build angles are producable. BMP2+/- are used to verify that the user does not overlook a problematic build angle and to verify the results of BMP1. BMP2+/- are scaled to match the minimal hole and rod diameter revealed with BMP1+/-. If BMP2+/- is unable to build features at a particular angle it is recommended to repeat the flow chart using the new "worst-case" build angle. All features must form to pass the verification. Machine variation from build to build may play a role in BMP2 failure. At least five copies are recommended. If aspect ratio results are a concern from BMP1 aspect ratios on BMP2 can be adjusted.

Additional notes and suggestions:

- Patterns used to evaluate subsequent steps can be built at "best-case" build angle to provide data beyond the "current" capability of SFF resolution.
- Steps may be combined if they are inseparable. Ideally each step is evaluated independently of all other steps.
- If SFF support structure is required on a rod or hole element it is not a feature that can be produced as a lattice element.

3. Example Results

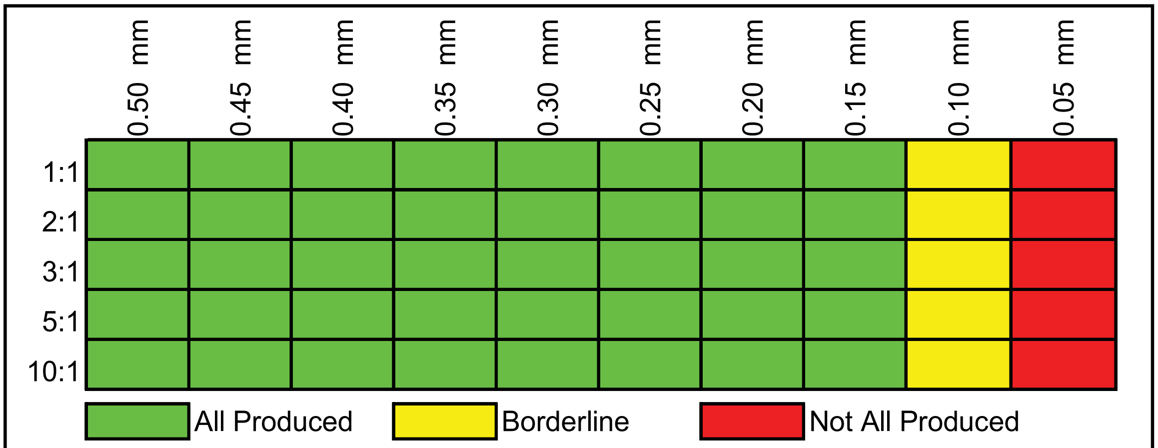
- A graphic is prepared for each process step as shown in graph 2. Those features formed are shown in green. Features that did not form or defective features are shown in yellow. Untested features are shown in white.
- The 3D graphic representation is helpful for communicating the feature form, hole or rod, for any step.



Graph 1. Hybrid Path Results, 1 SFF step, 2 Hybrid Steps

- Using Boolean AND all common feature-size and aspect ratio data points are summed, resulting in an "all produced" or "not all produced" to provide hybrid path capability (Graph 2).
- Borderline features can be shown in yellow to emphasize the edge.
- Features that appear defective should not be counted as "formed"

4.



Graph 2. Combined Hybrid Path Results, Rod Feature

CAUTIONARY MEASURES AND CONSIDERATIONS

- *Build Crash Misinformation* -if small features break free during the SFF process they may damage features during recoats that would otherwise be successfully formed.
- *SFF Z Error* -error due to material being added to down-facing SFF surfaces may be misleading and CAD compensation may close off holes unintentionally.
- *Laser Beam Compensation Error* – Some features may not be included in a slice file due to laser beam compensation while other features may be larger than CAD due to laser beam diameter error.
- *Data-use risk-* When using the resulting data for design input for any application the designer must understand the risk involved and the probability of features forming as expected. For critical aerospace or medical applications sufficient safety factors, based on sound statistical data must be applied.
- *Stair Stepping Error-* Stair-stepping can lead to variations in effective diameter as rods become smaller. Stair-stepping may also present notch sensitive regions not to be overlooked.
- *Other Properties-* The aforementioned approach only addresses geometric capabilities of a process. Additional testing is required to characterize other critical properties.

5. CONCLUSIONS

An approach and benchmark geometries were developed for use in evaluating the "rod" and "hole" capability of SFF and SFF-based hybrid fabrication paths.

This new approach is being used for, but is not limited to, the design of optimized intertwined lattice structures.

This approach may be applicable to evaluating objects on a range of scales from sub-nano to meso-scale.

6. FUTURE RECOMMENDATIONS

A concern not addressed with the six aforementioned benchmark geometries is the "depth" capability of a lattice field produced by a given SFF-based hybrid path. Benchmarking Geometry to capture lattice depth capability, driven by the results of BMP1 and BMP2, should be developed.

A benchmarking procedure and geometries for evaluating slot and wall capabilities of fabrications processes could be developed based on BMP1 by scaling the form in one direction.

7. ACKNOWLEDGMENTS

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