FREEFORM FABRICATION OF STOCHASTIC AND ORDERED CELLULAR STRUCTURES

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Abstract

Cellular materials provide a unique challenge to SFF technology. Such materials have unique properties of low mass, high strength, and good insulation properties. To produce such cellular structures, SFF systems require a designed microstructure with a feature size significantly lower than the resolution of the process. In this paper, we examine means of producing stochastic foams using the instability of a viscous thread and various methods for production of closed celled foams. These techniques allow for the production of foams without the need for pre-described cell structures. Such foams, when made from elastic materials can act as novel actuating materials.

Introduction

Cellular materials are ubiquitous in the modern world. Often they are used because of their low weight and outstanding insulating properties. They have been used as thermal, acoustic, and mechanical isolators. Varying the pore side and material density allows for the manipulation of stiffness, strength and other material properties. Cellular materials fall into two major categories: stochastic, and ordered. (1) Stochastic cellular materials include foams, sponges, and non-woven textiles. These produce an assortment of closed or open cells which do not follow any regular deterministic pattern. Non-woven textiles in particular are used in such varied applications as carpets, filters, surgical gowns, and textured surfaces. Ordered cellular structures consist of geometric patterns such as truss structures, lattices, and honeycombs. (2) Traditional subtractive methods of manufacturing are generally incapable of directly producing such ordered microstructures.

Background: Cellular Structures

SFF of cellular materials has focused on the production of ordered cellular structures. In order to produce stochastic foam, SFF technology required that the highly complex shape be completely specified in the geometry file (STL) prior to fabrication. Few CAD programs are capable of generating such complex shapes. David Rosen of Georgia Tech has developed tools for automatically generating regular mesostructures. (3) However, production of such parts with a designed mesostructure requires the fabrication process to have a resolution much finer than the feature resolution of the mesostructure.

Many applications of ordered cellular microstructure have used geometric processing techniques to create a lattice from an arbitrary geometry. These processes often rely on producing a strand with a width smaller than the width specified in parsing the geometries shape. This creates an open celled structure. In order to produce closed cellular structure, a fugitive material is required, or the shape must have each layer be geometrically identical. Fugitive material allows for each cell to be individually isolated. (4) A regular shape allows for the exterior boundary of the lattice to be sealed. Tissue scaffolds and piezoelectric sensors and actuators have been produced using these techniques. (5)

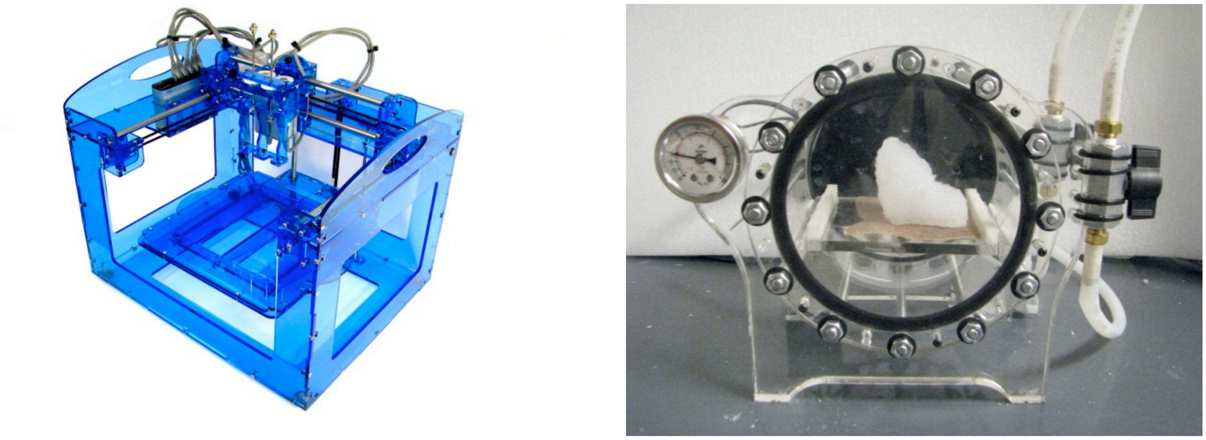
Solid freeform fabrication of actuating materials has relied on electrically driven materials. Piezoelectric actuators which have been fabricated provide small directional displacement. (6). Ionomeric polymer-metal composite actuators have been successfully produced in the past and can be embedded in biocompatible geometries. However they have a directional actuation. (7) These constraints necessitated the development of a material with entrapped air. Such a material could expand and contract approximately isometrically when cycled through external pressures when made of elastic materials.

Background: Viscous Thread Instability

The instability of viscous threads is familiar to anyone who has drizzled honey. The threads buckle near the surface causing a coiling effect. This is known as the liquid rope coiling effect. According to Stephen Morris's paper *The Meandering Instability of a Viscous Thread*, "The moving surface breaks one of the basic symmetries of the "pure" rope coiling problem, and has the effect of unfolding the coiling instability into a rich panoply of distinct bifurcations." (8) These states can include: figure eights, meandering, translated coiling, and double coiling. The patterns are entirely predictable based on the nozzles width, relative speed, and height along with the material's density, viscosity, and surface tension. Inducing these states in a robocasting system allow for the production of stochastic structures. The shapes and properties of the produced materials are deterministic based on the controlled parameters, but the microstructure produced is random. (9)

Methods: Apparatus

In order to perform the experiments, a digital fabricator with adaptable path planning software was needed. A Model 2 Fab@Home Digital Fabricator with a syringe based deposition tool was used due to its ability to deposit a wide variety of materials, including elastic build materials and support materials. (2) FabStudio version 1 beta was used to generate the tool path information. It was selected for its versatility and the ease of modifications to path planning.



(a) (b)

Figure 2: Fab@Home Model 2 digital fabricator (a) and the vacuum chamber (b) used in experiments

In order to demonstrate the ability of materials to actuate a single test geometry was selected. The primary test geometry was a rectangular prism of 20 mm by 20 mm by 10 mm. This small geometry was selected for its ability to be quickly constructed and because volumetric actuation could be easily measured. A pressure chamber which can alternate between positive and negative 29 inches of mercury (98 kPa) from atmospheric pressure was used to actuate the closedcell foams. Using external pressure variations for the testing of the material allows without designing an interface to a pressure source.

Methods: Foamed Materials

Initial attempts focused on the creation of materials which would contain air when extruded. Such materials, when deposited, could turn any geometry directly into a foamed object. In order to entrap the air, liquid silicone was carbonated. Two pressure vessels were connected by a channel. In one vessel reactants of acetic acid and sodium bicarbonate were placed and allowed to react, producing carbon dioxide. In the other vessel a large quantity of silicone was placed. Pressure was allowed to equalize between the chambers until the reactions in the reaction chamber had completed. The pressure was then released and the silicone was allowed to dry in bulk.

Another method involved chemical reactions with the material. Sodium bicarbonate powder was rapidly mixed into liquid silicone. A solution of acetic acid and water was then mixed into the combined silicone/bicarbonate. The solution was mixed vigorously until the reaction had completed. The silicone was allowed to cure in bulk and a foamed structure was produced.

Methods: Lattice Foamed Material

Custom pathing algorithms which generate geometric distributions of air were attempted. These were based on an alternating regular rectangular lattice structure. Initial attempts focused on sealing a region which has been sparsely filled. The primary pather decomposed the geometry into 3 regions: the bottom seal layers, the top seal layers, and the interior layers. The top and bottom regions were pathed using a conventional solid fill pather. The interior region used a custom pather which produced two concentric boundary paths to form a wall which sealed the layers form the exterior, and interior paths which left only one quarter of the space filled. The double wall ensured that a single error in the print process would not connect the interior air to the atmosphere. Dow Corning RTV Sealant 732, clear silicone was used as the build material since it is sufficiently elastic and prints reliably.

This process relied on assumptions that can be made about the rectangular geometry of the prisms. The prism is 2.5-D; each layer had the same geometry as the previous layers. This ensured that the exterior solid boundaries were continuous and unbroken. The sparse filled region remained contained. In order to apply this method to a 3D geometry, the geometry would need to vary slowly, so that the outer boundary changes by no more than one path width inwards or outwards from layer to layer.

Modifying this method allows it to be applied to an arbitrary geometry. If the geometry is sliced by three or more multiples of the materials native path height, it is possible to apply the sealed sparse planning algorithm to the slice. The top and bottom sub-layers are solid filled, and the intermediate sub-layers are sparse filled. (See figures 4 and 5)

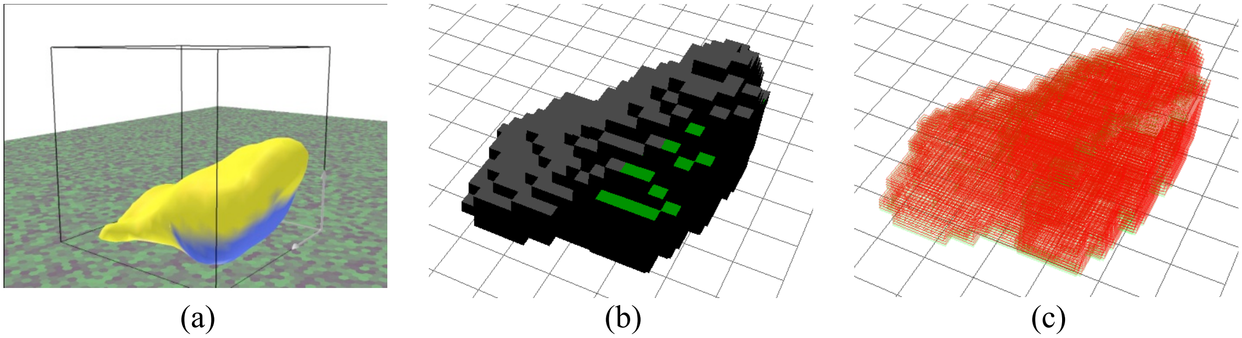


Figure 4: An arbitrary geometry(a) can be sliced into sections which are integer multiples of the build materials native path height(b) which can then by pathed to ensure a closed sparse filled region(a)

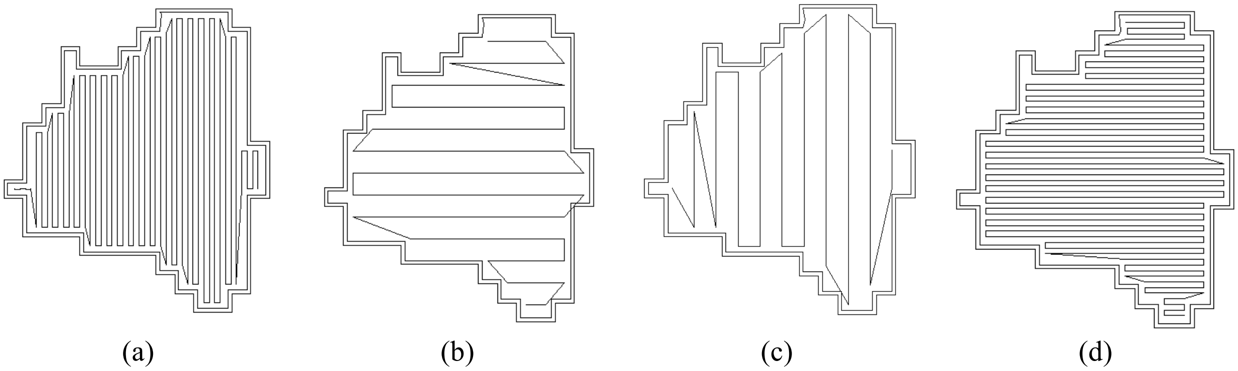


Figure 5: A Single slice of the geometry is divided into sub slices which are then pathed using either a sparse fill or solid fill pather. The solid fill(a)(d) sandwiches sparsely filled layers(b)(c)

Method: Stochastic Deposition

Instability of a viscous fluid flow can be induced by adjusting the flow and pathing characteristics. The values are manually tuned until the silicone enters the translated coiling state. The flow rate of the material is increased beyond its rate for construction of solid objects while the material's deposition nozzle is elevated from the build platform beyond its normal solid construction height. This allows the materials to spiral after the stream from the deposition head hits the build target. The relative height of the nozzle and the flow rate control the radius of the spiral of material. Path speed relative to fluid flow determines the linear spiral density. The density of the paths controls the spiraled material stream's overlap between paths. (9) By using these modified flow values, it is possible to create an object where each layer consists of the translated coiled material. An object made from the coiling strand becomes a complex foam as each successful layer is added.

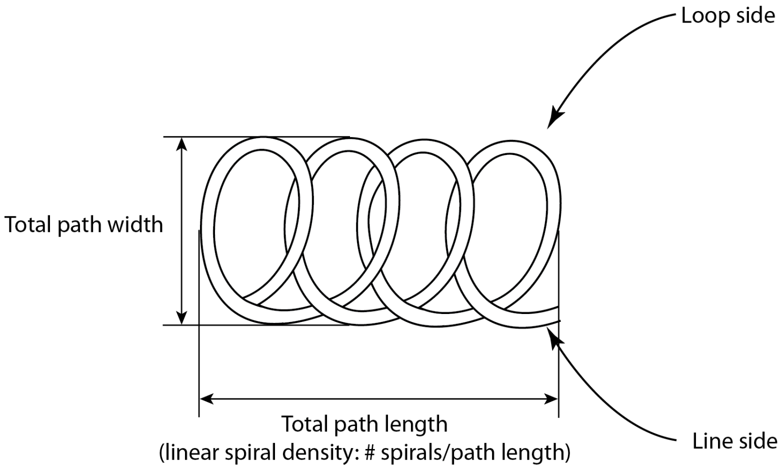


Figure 6: typical regular spirals observed throughout much of the range for each parameter

Results: Foamed Materials

Carbonation of liquid silicone attempts resulted in several large (1mm diameter) bubbles in the surface of the silicone. The majority of the silicone remained unimpregnated with gas. Silicone was successfully foamed using sodium bicarbonate and additional acetic acid. The uncured foam silicone could be extruded through a standard EFD syringe at 80 psi. The foamed silicone took significantly longer than normal to cure. The cured foam silicone was placed in the vacuum chamber and cycled through positive and negative 29 inches of Hg several times. The material expanded significantly during expansion stages, and contracted during positive pressure stages. However the material quickly lost its air content and the performance degraded too rapidly to be used as an actuator.

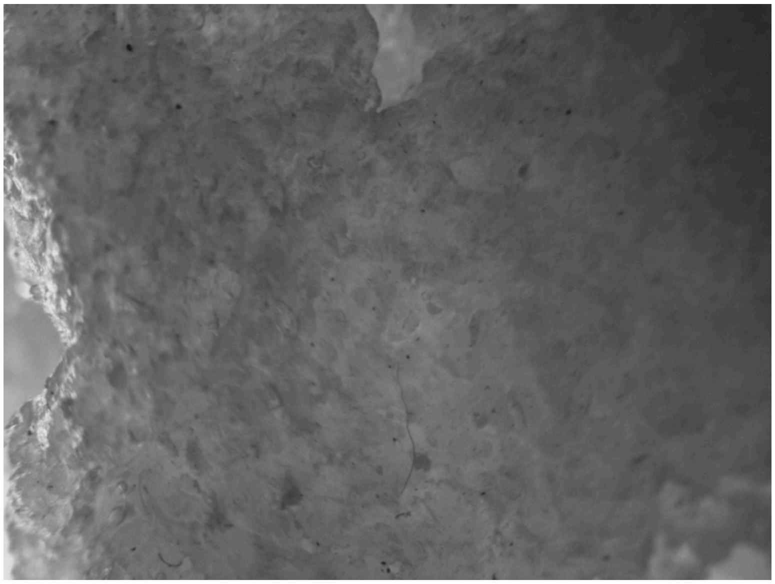


Figure 9: A cross section of the foamed silicone created through sodium bicarbonate reactions shows it has a closed cellular structure.

Results: Lattice Foam production

Failures of the conventional path planner and printing errors necessitated that the final object be tested for leaks. The printed objects were submerged into water and pressure was applied to their surfaces. If air bubbles appeared, the entire object was coated in a thin layer of additional silicone and then allowed to dry. The process was repeated until no bubbles could be observed. The prisms on average required two coatings of silicon after printing. The path planner used generated paths which did not completely fill the top and bottom solid fill layers. These gaps were due to an error in the algorithm which expanded the layers boundaries to create the walls. The test prisms produced using this method placed in the vacuum chamber expanded to when exposed to -29 inches of mercury from atmosphere. Prisms when exposed to +29 inches of mercury from atmosphere.

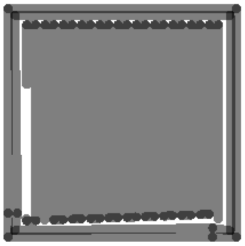
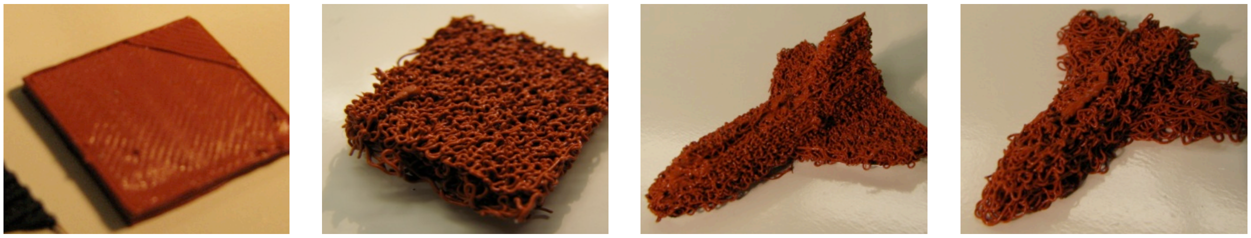


Figure 8: the Path planner deposits material (grey) to build the object but the errors in path planning leave unintended gaps (white) which need to be filled by a bulk coating post processing.

Results: Stochastic Deposition

Translated coiling of the viscous thread produced open celled foams. Changes in the spiral width of the translated coils produced foams of different pore sizes and surface roughness. An arbitrary geometry (space shuttle) was printed using two different spiral widths. The geometry was processed using the modified values of path width and height of the translated coils. The sizes of the pores were of the same order as the resolution of the printing process.



(a) (b) (c) (d)

Figure 9: A material which can be solid printed (a) can be used to create a stochastic foam (b) by using viscous thread instability. By adjusting the properties of the viscous flow, a single geometry could be made into foams of various properties (c) (d).

Discussion:

Previous research in SFF allowed for the direct fabrication of designed ordered cellular structures. Complex cellular features and structures required the pores to be orders of magnitude larger than the process resolution and complex CAD programs to generate the intended geometry (3). Simple lattice cellular structures allowed for pores of the same order as the print process; they could not be used to generate closed cellular structures of arbitrary geometry. The processes used to create the lattice structures required a fugitive support material, or relied on the regularity of the shape. (4)

The geometric processing algorithm used to generate tool paths for FDM machines described earlier shows how a single material can be used to generate shapes with entrapped air. The algorithm overcomes traditional geometric limitations by using a process of generating sub layers of identical boundaries with contain the cellular structure while allowing for the overall shape to vary. Such material distributions can be used to create bulk volumetric actuators.

Volumetric actuators are a novel form of Solid Freeform fabricated actuators. They are the first isometrically expanding additively manufacturable actuator. While the direct deposition of a closed cell foamed elastic material would be the ideal means of creating an external pressure driven volumetric actuator, they are not suitable for the creation of internally driven actuators. Additionally the closed celled materials made from chemical reactions were not as robust as the geometrically planned materials. It should be possible to use the geometric processing methods to create pneumatic actuators that are powered by internal pressure changes.

The deposition of material by means of viscous thread instability allows for the creation of materials of stochastic cellular structure. The pores are inherently of print process order and do not require any additional computation to translate a solid geometry into a stochastic foam of the desired shape. This demonstrates the ability to create a foamed object without the need for descriptions in CAD or complex geometric processing.

The ability to freeform fabricate foams of arbitrary shape but controlled pore size and void fraction could allow for novel application of SFF. Catalytic converters, filters, and any other application of either non-woven threads or foams could not benefit from the novel abilities of SFF. Additionally it is possible to use a single material to create gradations in mechanical properties by varying the print parameters used. (9) Textures could be applied to additively manufactured parts without the need to have the texture features be orders of magnitude larger than the process resolution.

Conclusion:

The techniques described here allow for the fabrication of various cellular structures. A single material can be used to generate closed and open celled regular lattices. It can be used to produce stochastic open celled foams using viscous thread instability. Or it can be directly foamed to create closed cell stochastic foams. These processes enable new applications for solid freeform fabrication without the need for CAD tools or complex algorithms. The closed celled lattice has already demonstrated the ability to create a novel volumetric actuator.

Acknowledgements:

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