Investigating a finite element model for acoustic field-assisted particle patterning – applications in additive manufacturing of polymer composites

Michael Flannery

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Investigating a finite element model for acoustic field-assisted particle patterning – applications in additive manufacturing of polymer composites

by

Michael Flannery

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
Shan Hu, Major Professor
Jaime Juarez
Matthew Frank

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2020

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DEDICATION

This work is dedicated to my wife, Katharine Flannery, whose love and support kept me motivated through this process.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>List</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>iv</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>v</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>vi</td>
</tr>
<tr>
<td>CHAPTER 1. GENERAL INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Manufacturing Composites with Fused Deposition Modeling</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Manufacturing Composites with Powder Bed Fusion Methods</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Manufacturing Composites with Stereolithography</td>
<td>3</td>
</tr>
<tr>
<td>1.4.1 Magnetic Field Assisted Stereolithography</td>
<td>4</td>
</tr>
<tr>
<td>1.4.2 Acoustic Field Assisted Stereolithography</td>
<td>6</td>
</tr>
<tr>
<td>1.4.3 Acoustic Field Assisted Stereolithography with Actuators Perpendicular to Build Plate</td>
<td>8</td>
</tr>
<tr>
<td>1.4.4 Acoustic Field Assisted Stereolithography with Actuators Parallel to Build Plate</td>
<td>9</td>
</tr>
<tr>
<td>1.4.5 Line Spacing Analysis for Acoustic Field Assisted SLA with PZT Actuator Parallel to Build Plate</td>
<td>11</td>
</tr>
<tr>
<td>1.5 Acoustic Field Assisted Direct Ink Writing</td>
<td>12</td>
</tr>
<tr>
<td>1.6 Other Acoustic Field Particle Patterning Considerations</td>
<td>13</td>
</tr>
<tr>
<td>1.7 Manuscript Preview</td>
<td>14</td>
</tr>
<tr>
<td>1.8 Citations</td>
<td>14</td>
</tr>
<tr>
<td>CHAPTER 2. INVESTIGATING A FINITE ELEMENT MODEL FOR ACOUSTIC FIELD ASSISTED PARTICLE PATTERNING – APPLICATIONS IN ADDITIVE MANUFACTURING OF POLYMER COMPOSITES</td>
<td>18</td>
</tr>
<tr>
<td>2.1 Abstract</td>
<td>18</td>
</tr>
<tr>
<td>2.2 Introduction</td>
<td>18</td>
</tr>
<tr>
<td>2.3 Materials and Methods</td>
<td>21</td>
</tr>
<tr>
<td>2.3.1 Particle Patterning Setup</td>
<td>21</td>
</tr>
<tr>
<td>2.3.2 Frequency Domain Finite Element Analysis</td>
<td>22</td>
</tr>
<tr>
<td>2.3.3 Material and Simulation Models</td>
<td>22</td>
</tr>
<tr>
<td>2.3.4 Simulation Setup</td>
<td>24</td>
</tr>
<tr>
<td>2.4 Results and Analysis</td>
<td>25</td>
</tr>
<tr>
<td>2.4.1 Particle Patterning Experiments</td>
<td>25</td>
</tr>
<tr>
<td>2.4.2 FEA Simulations</td>
<td>27</td>
</tr>
<tr>
<td>2.5 Conclusions</td>
<td>29</td>
</tr>
<tr>
<td>2.6 Citations</td>
<td>29</td>
</tr>
<tr>
<td>CHAPTER 3. GENERAL CONCLUSIONS</td>
<td>32</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1.1. Propeller printed using magnetic field assisted SLA, a) Digital image, b) Printed part, c) Printed part detail showing an agglomeration of magnetic particles, d) Detail image of part. (Lu et al.\textsuperscript{16}) .................................................................5

Figure 1.2. Different particle distribution patterns created using magnetic field assisted SLA. Specimens are shown in a loading fixture. (Joyee et al.\textsuperscript{17}) ..................6

Figure 1.3. a) Schematic of a laser beam selectively curing a section of photocurable resin with acoustically aligned particle fillers. b) side view of the resin vat showing the configuration of PZT actuators and the transverse wave created (Llewellyn-Jones et al.\textsuperscript{19}) ......................................................................................8

Figure 1.4. Acoustic field assisted SLA setup used by Lu et al., A) A digital rending of the printer, B) Labeled photograph of the printer, C) Detailed flowchart of the manufacturing process (Lu et al.\textsuperscript{22}) ........................................................................................................10

Figure 1.5. Samples created by Lu et al. shown with the corresponding CAD model and PZT plate configuration (Lu et al.\textsuperscript{22}) .................................................................11

Figure 2.1. Digital rendering of the experimental setup. .................................................................22

Figure 2.2. Spring and dashpot models of 2 different material models used. A- linear elastic (LE) and B- Maxwell form of the standard linear solid (VE) ........................................23

Figure 2.3. Bottom surface of FEA model. The grey block is the model of the PET film. The purple rectangle simulates the active PZT plate and was given a “Prescribed Acceleration” boundary condition ..................................................................................25

Figure 2.4. Particle patterns created by silicon dioxide particles suspended in deionized water distributed on PET film. The film is being vibrated by the white PZT plate. ..................................................................................................................26

Figure 2.5. Surface displacement plot of frequency domain simulations for Maxwell Standard Linear Solid with an Isotropic Loss Factor .................................................................27

Figure 2.6. Plot of frequency vs. line spacing of particle patterning experiments ........................28
I would like to thank my committee chair, Dr. Shan Hu, and my committee members, Dr. Jaime Juarez, and Dr. Matthew Frank. I would also like to thank my friends and colleagues who enriched my experience at Iowa State. Lastly, I would like to thank my lab mate Dr. Xiaohui Tang for his assistance in the laboratory.
ABSTRACT

As additive manufacturing (AM) grows as a viable means to manufacture not only prototypes, but also end use production parts, the desire to produce composite materials using AM has grown. Such a machine would combine the unique benefits of AM with the unique benefits of composites. Although many successful AM setups that produce composites have been developed and successfully demonstrated, the way in which the filler materials are arranged within the matrix is an active area of research. This thesis reviews applicable literature pertaining to what different methods have so far been developed to create particle-matrix composites using additive manufacturing with an emphasis on how these methods align filler particles. Chapter two is a proposed manuscript that explores one particular method of arranging particles using acoustic fields. It also shows work performed in an effort to develop an FEA model that accurately predicts the shape of such particle patterns given the configuration of the actuators creating the acoustic field.
CHAPTER 1. GENERAL INTRODUCTION

1.1 Motivation

Additive manufacturing (AM), which is by some considered to be part of a touted third industrial revolution\(^1\), has now become an integral part of today’s product development and manufacturing environment. In its early days AM largely served as a tool for rapid prototyping and a way to test parts for fit, form and function. The advantage being that it afforded a way to create a small number of prototypes before committing to the large upfront tooling costs required by many conventional manufacturing processes. However, AM is now increasingly being used to create final run production parts\(^2-4\). For example, GE Aviation has begun manufacturing the fuel nozzle of its \textit{Leap} engine using a metal-based powder bed fusion process\(^3\). Outside of the Aerospace industry, AM offers many benefits to the manufacturing of biomedical devices and components. The ability to create unique and complex geometries out of a variety of materials opens the door to the manufacturing of patient-tailored surgical implants and prosthetic devices\(^4\).

As AM becomes a more viable manufacturing method in industry, efforts to create composite materials using AM have grown\(^5\). Because composite materials are becoming more commonplace in many industries\(^6\), the desire to manufacture them using AM is a logical one. While current means of creating composite materials using AM currently exist, there are many challenges faced and areas of possible improvement\(^5\). If robust and viable techniques for manufacturing composites with AM can be developed, the unique benefits of AM could be combined with the unique benefits of composite materials in a way that could greatly benefit many industries.
1.2 Manufacturing Composites with Fused Deposition Modeling

One way of creating composites using additive manufacturing uses fused deposition modeling (FDM) to create fiber reinforced polymers\(^7\text{--}^{10}\). Traditional FDM printing is done by extruding a thermoplastic polymer filament out of a heated nozzle onto a build platform, a previous part layer or a piece of scaffold material. Typically, only one kind of material is extruded at a time. To create a fiber reinforced composite, fibers are added to the polymer filament during the extrusion process. One common method is to add short pieces of carbon, Kevlar or glass fibers. These fibers are usually on the submillimeter length scale. Improvements over traditional FDM printing include higher tensile strength, crack resistance, shear strength, and impact resistance\(^7\text{,}^8\). Drawbacks of this method include a potential decrease in inter-layer adhesion strength. This is due to the fiber segments increasing the viscosity of the extruded material. The addition of short fibers also can clog the extrusion nozzle. This creates challenges when it comes to designing a viable printer\(^9\).

Instead of using short lengths of fiber, some efforts have been made to create continuous fiber reinforced composites using FDM\(^9\text{,}^{10}\). Similar to the previous method described, this involves introducing the filament filler into the extrusion nozzle with the thermoplastic polymer. However, in this case the filament is a continuous strand. This has an order of magnitude improvement over the short fiber reinforced composites in tensile strength, but it suffers from geometric constraints\(^9\). Specifically, because the fiber filament is continuous, the print path cannot have as small of a radius of curvature. This results in layers having voids that may not be present when using short fibers. Both described methods utilizing FDM are limited in overall fiber orientation. Because the fibers are extruded through the nozzle with the polymer filament, the fibers are oriented in the print direction\(^9\).
1.3 Manufacturing Composites with Powder Bed Fusion Methods

Another popular type of AM, known as powder bed fusion (PBF), uses high intensity laser light to fuse together powder feedstock layer by layer. One method of creating composites using PBF is to simply mix multiple materials together in the feedstock\textsuperscript{11,13}. Depending on the materials chosen, this results in a composite that has more desirable properties than that of a single-material PBF created part\textsuperscript{13}. Although, in most cases the resulting composite has material properties that are inferior to those of traditionally manufactured particle-matrix composites\textsuperscript{11}. One method developed by Liu et al.\textsuperscript{12} utilized a single metal powder to sinter parts with a relatively high porosity and then infused the piece with liquid metal of another type. In this way PBF along with post-processing techniques were used to create composite materials with desirable material properties\textsuperscript{12}. One limitation of these methods is that the mixing of the different powdered materials creates a composite with a homogenous distribution.

A different method developed by Chung et al.\textsuperscript{13} created particle-matrix composites of glass beads suspended in polymer. By varying the loading fraction different material properties could be achieved. For example, a higher loading fraction of glass beads resulted in a stiffer but more brittle part. Although each individual layer was created using a single loading fraction and a homogenously mixed powder, each layer could have its own loading fraction. By varying the loading fraction layer-by-layer a 1D functionally grated compliant material was created. Due to the layer-by-layer nature, the directionality of the grating was limited to 1D\textsuperscript{13}.

1.4 Manufacturing Composites with Stereolithography

Stereolithography (SLA) is another popular AM method. In SLA printing a high intensity light is used to cure one layer of a photosensitive liquid polymer. To build the next layer the already cured section is either lower further into the liquid vat allowing another layer of liquid to flow over top, or it is raised upwards out of the vat allowing the next layer of liquid polymer to
flow underneath the part. Similar to how some attempts have been made to create composites with PBF, one relatively simple way to create a composite using SLA is to simply mix the filler material into the liquid stock. Such a setup was used in a study performed by Zhang et al.\textsuperscript{14} where carbon nanotubes (CNT’s) were homogenously mixed with a photosensitive polymer resin. The built part was found to have radiation absorbing characteristics. The level of absorption increased with the loading fraction of CNT’s\textsuperscript{14}.

Instead of distributing filler materials homogenously with random orientation, some attempts have been made to orient the filler material. One such attempt was made by Sano et al.\textsuperscript{15} using a fiberglass fabric weave. The weave was placed into the liquid polymer vat before curing. In this way the direction of the fiber orientation could be controlled with respect to the overall part. This method was found to greatly increase the tensile strength of the printed part\textsuperscript{15}.

However, because the fabric fiber was placed and oriented by hand, attempting to automate this method would be difficult. This study also investigated the effect that glass powder and randomly oriented short glass fibers had on tensile strength. Both fillers were found to increase overall tensile strength, but no attempt was made to distribute them inhomogenously.

\subsection*{1.4.1 Magnetic Field Assisted Stereolithography}

Different ways of creating composite materials using SLA with inhomogenously distributed filler particles have recently been developed. One way developed by Lu et al.\textsuperscript{16} uses a magnetic field. Similar to other methods, filler particles are first homogenously mixed into photosensitive liquid polymer. In this particular case particles were used that were sensitive to magnetic fields. Once the mixture was poured into the production vat, a magnetic field was used to concentrate particles into specific areas. Once a desirable distribution was created, the layer was cured. As a test, this method was successfully used to create a propeller that could be driven using a magnetic field.
An analysis of the mechanical properties of specimens created using magnetic field assisted SLA was performed by Joyee et al.\textsuperscript{17}. The specimens were prepared in much the same way as the previously described specimen, but different particle patterns were created. Shown in figure 1.2, iron oxide particles were distributed in 4 different ways. The first way was simply a homogenous mixture. The second, third and fourth ways were created by aligning the particles in linear chains with different orientations. All particle distribution methods were found to increase the stiffness of the material. Additionally, of the different particle configurations the S1-0 orientation was found to have the highest tensile strength\textsuperscript{17}. A major drawback of using this method is that the particles have to be sensitive to magnetic fields. This limits the number of materials that can be used.
1.4.2 Acoustic Field Assisted Stereolithography

Acoustic fields have also been used to manipulate particles within fluids\(^{18}\) and would be well suited to assist particle patterning within SLA. Many groups have worked with just such a setup\(^{19-23}\). Using acoustic fields to pattern particles in SLA offers advantages, the main one being that filler particles need not be sensitive to magnetic fields. This opens the door to a much greater diversity of filler particles both metallic and nonmetallic. The mechanisms by which acoustic fields can manipulate particles within a fluid can be explained by acoustophoresis principles, two of which are the acoustic radiation force and acoustic streaming\(^{24}\). When an acoustic wave is present within a fluid, both principles are at work and compete against one another to affect the motion of a particle. The acoustic radiation force is created by acoustic pressure gradients within the fluid and is defined by the following equation\(^{22}\):

\[
F_r = \frac{2\pi V_p E_{ac}}{\lambda} \Phi \sin \left( \frac{4\pi x}{\lambda} \right) \tag{1}
\]
where $V_p$ is the particle volume and $E_{ac}$ is the acoustic energy density given in the following equation:

$$E_{ac} = \frac{p_a^2 \beta_f}{4}$$

where $p_a$ is the acoustic pressure and $\beta_f$ is the compressibility of the fluid. In equation number 1, $\Phi$ is the acoustic contrast factor given as:

$$\Phi = \frac{5 \rho_p - 2 \rho_f}{2 \rho_p + \rho_f} \frac{\beta_p}{\beta_f}$$

where $\rho_p$ and $\rho_f$ is the density of the particle and fluid respectively and $\beta_p$ is the compressibility of the particle.

Acoustic streaming is a phenomenon that occurs due to fluid motion induced by the acoustic field. In some cases, this fluid motion has more effect on the motion and position of particles than the acoustic radiation force. The force exerted on a particle from acoustic streaming is defined in the following equation:

$$F_s = 6\pi \mu a \Psi v_a^2$$

where $\mu$ is the fluid viscosity, $a$ is particle radius, $\Psi$ is a geometry dependent streaming factor and $v_a$ is the wave amplitude.

In order to determine which effect is dominant and controlling the motion of particles suspended in a liquid subjected to an acoustic field, an Acoustic Strouhal Number (ASN) has been proposed. This quantity is non dimensional and is defined as:

$$ASN = \frac{8 \rho_f V_p f \Phi}{9 \mu a}$$
where \( V_p \) is particle volume, \( f \) is frequency, and \( a \) is the particle radius. If the ASN is greater than 1, the acoustic radiation force is dominant. If the ASN is less than one, acoustic streaming is thought to be the dominant driver of particle motion.

1.4.3 Acoustic Field Assisted Stereolithography with Actuators Perpendicular to Build Plate

Some acoustic field assisted SLA setups have utilized an acoustic field generated by PZT plates whose orientation is perpendicular to the build plate, one of which is shown in figure 1.3.

![Figure 1.3](image.png)

Figure 1.3. a) Schematic of a laser beam selectively curing a section of photocurable resin with acoustically aligned particle fillers. b) side view of the resin vat showing the configuration of PZT actuators and the transverse wave created (Llewellyn-Jones et al. 19)

In these setups, the acoustic wave creates pressure nodes and anti-nodes. Depending on the acoustic contrast factor, the filler particles will be drawn to either the nodes or anti-nodes. If the acoustic contrast factor (\( \Phi \)) is positive, particles will accumulate at the nodes. If \( \Phi \) is negative, particles will accumulate at the anti-nodes. The particle spacing in this sort of a setup is well understood and is equal to \( \lambda / 2 \). Calculating and predicting the particle spacing is relatively
simple once the geometry of the tank is known. Wavelength ($\lambda$) is determined by the following equation$^{19}$:

$$c = f\lambda$$  \hspace{1cm} (6)

where $c$ is the speed of sound through the medium. Although this setup has been shown to be a viable means to manufacture composite materials, it is only capable of producing parts one layer thick.

To move past this limitation a setup was developed by Greenhall et al$^{28}$ that utilized a resin vat with a clear plastic bottom which allowed the light from a projector to cure a layer from below. Above the vat the build platform was suspended with the ability to move in the z-direction. This z-stage working in tandem with the projector from below was able to cure multiple layers. Additionally, this setup utilized as many as 8 PZT actuators in order to increase the diversity of possible patterns. Because multiple layers and multiple patterns were possible, differentiation in particle patterns in the z-direction was accomplished. Thus, structures could be created with 3D controllable anisotropy. However, with actuators situated perpendicular to the build platform, the PZT plates sit above the bottom of the resin vat in both setups discussed. This could impede the printing of parts with larger or more complex geometry.

1.4.4 Acoustic Field Assisted Stereolithography with Actuators Parallel to Build Plate

Other acoustic field assisted SLA setups have utilized PZT actuators that are situated parallel to the build platform$^{22,23}$. One advantage of this setup is that the part can extend beyond the footprint of the PZT plate without interfering with it. A 3D printer with this sort of a configuration was utilized by Lu et al. and is shown in figure 1.4. Similar to previous methods described, a homogenous mixture of liquid polymer resin and filler particles is distributed into the vat. However, in this setup the bottom of the vat is made of a thin plastic film with PZT
plates adhered to the bottom surface of the film. To create a particle pattern, one or more of the PZT plates is actuated which vibrates the film. After a pattern is created, the Z-stage moves downward slowly into the vat. Then, a high intensity light is projected up from below the plastic film. This light cures one layer of the part onto the existing part. The Z-stage is then moved back up and the process repeats itself. Figure 1.4 shows this setup and process in detail. Figure 1.5 shows specimens that were created using this manufacturing method. By varying the combinations of which PZT plates are actuated, and using projection masks, a variety of particle patterns were created. Additionally, by varying the pattern in between layers, the particle pattern could also be varied in the Z-direction. All different test cases had a vibration frequency of 43kHz.

Figure 1.4. Acoustic field assisted SLA setup used by Lu et al., A) A digital rendering of the printer, B) Labeled photograph of the printer, C) Detailed flowchart of the manufacturing process (Lu et al.22)
In the previously described setup, the line spacing does not follow the $\lambda/2$ convention. This can be shown by assuming it does follow the $\lambda/2$ spacing and following out the rest of the calculation to see if the rest of the parameters are reasonable. In “Test Case 1” from figure 1.5, the line spacing is approximately 1mm. Thus, the corresponding wavelength ($\lambda$) would be approximately 2mm. Knowing that the frequency is 43kHz, equation 6 can be used to calculate the proposed speed of sound through the medium. This calculation yields a speed of sound through the liquid resin of approximately 86m/s which is orders of magnitude different from the actual speed of sound through the resin (2230m/s). This means that the particles are not being driven by a transverse wave generated by the PZT plates. One other potential mechanism driving
the particle patterns is the surface deformation of the plastic film separating the PZT plate from the liquid resin.

The following manuscript theorizes that the film is acting a sort of Chladni plate. A Chladni plate is a vibrating thin plate whose surface creates areas of high cyclical deformation known as anti-nodes, and areas of no deformation known as nodes. If loose particles are placed upon a Chladni plate, they accumulate at the nodes\textsuperscript{26}. While patterns created are more complex than those created in a chamber subjected to a transverse standing wave, they can still be simulated using FEA software\textsuperscript{27}. If the particle patterning method utilized in the work performed by Lu et al is to be implemented in an industrial manufacturing setting, a computer simulation that could predict particle patterns given different frequencies and PZT plate arrangements would save hours of laboratory experiments.

1.5 Acoustic Field Assisted Direct Ink Writing

Direct ink writing (DIW) is another means of additive manufacturing where a high viscosity liquid resin is extruded onto a surface and then subsequently cured. If proper care is taken when selecting the resin material and during extrusion, the filament can span small gaps over unsupported segments. Thus, DIW can create parts many layers thick with complex geometry.\textsuperscript{29} Similar to methods developed to create composite materials in FDM, homogeneously mixing particles into the liquid polymer prior to extrusion is possible and has been explored.

To create anisotropic particle distributions using DIW, Friedrich et al\textsuperscript{30} developed an extrusion nozzle that used an acoustic field to concentrate particles in the middle of the polymer stream. The acoustic field was created by a PZT plate adhered to the rectangular extrusion channel. This setup was successfully demonstrated and created particle distributions within deposited layers with a high degree of anisotropy. While an effective proof-of-concept, DIW in general suffers from drawbacks. Because of how DIW is performed, the technology is limited in
terms of part size. Specific aspects of this setup also present limitations. For example, a high viscosity fluid is needed to maintain structural integrity after extrusion but before curing. However, a high viscosity fluid makes acoustic field assisted particle patterning more difficult. To resolve this issue Friedrich et al used a liquid polymer that became less viscous while under high shear stresses in the extrusion channel, and then more viscous while under little shear stress after deposition. The need for such specialized chemistry presents challenges in material selection. In the specific work cited, the curing was heat-initiated and required 90 minutes. Lastly, because particles were concentrated into the middle of the extrusion stream, the directionality of particle patterning is limited to the print direction.

1.6 Other Acoustic Field Particle Patterning Considerations

Outside of applications involving additive manufacturing, particle patterning using acoustic fields has been extensively studied.31-34 Raeymaekers et al34 studied specifically the ability to pattern nanoscale particles. One effort in particular arranged diamond particles with a diameter of 5nm suspended in water using a PZT plate generated acoustic field. Rectangular plates situated perpendicular to the solution vat were used to create parallel lines of particles. A cylindrical PZT plate was used to create patterns of concentric circles. Particle patters were preserved by the evaporation of the water. Although not utilized in a manufacturing process, this work demonstrated using different configurations of PZT plates to create different particle patterns. It also demonstrated patterning nanoscale particles using acoustic fields.

Raeymaekers et al34 also explored some of the fundamental forces at work when attempting to control the motion of small particles suspended in fluid. In addition to the previously discussed acoustic radiation force and the effects of acoustic streaming, particle suspensions subjected to an acoustic field are also effected by Brownian motion and Bjerknes force.34 Brownian motion is present regardless of whether or not an acoustic field is being used,
and becomes more of a factor as particle size becomes smaller. It competes with the acoustic radiation force and could cause low pattern quality. Bjerknes force causes particles to attract to one another and form agglomerations. When considering the effects of acoustic streaming and Brownian motion, the presence of Bjerknes force induced particle activity could be advantageous in patterning. This is because as agglomerations form, the effective diameter of particles within the solution increases. An increased diameter decreases the effects of Brownian motion and acoustic streaming, and increases the effect of the acoustic radiation force. 24,34

1.7 Manuscript Preview

The following proposed manuscript uses the particle patterning setup used in the work performed by Lu et al. shown in figure 1.4 to explore the effect that frequency has on particle patterns and characterize the patterns. It then develops and tests different simulation models to try and create a model that corresponds with experimental results.

1.8 Citations


CHAPTER 2. INVESTIGATING A FINITE ELEMENT MODEL FOR ACOUSTIC FIELD ASSISTED PARTICLE PATTERNING – APPLICATIONS IN ADDITIVE MANUFACTURING OF POLYMER COMPOSITES

Modified from a manuscript to be submitted to Finite Elements in Analysis and Design

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2.1 Abstract

This work explores particle patterns created when a homogenous solution of particles suspended in a liquid is subjected to an acoustic field. The acoustic field setup is based on one that has been successfully used to create particle-matrix composites with stereolithography additive manufacturing. During the manufacturing process the acoustic field is used to pattern the filler particles in a controlled and intentional design. This work explores the effect that frequency has on the particle patterns. Additionally, an FEA simulation model is developed that shows good agreement with laboratory experiments.

2.2 Introduction

Additive manufacturing (AM) technologies have become an integral part today’s product development and manufacturing environments. Increasingly, AM is being used to create final parts and products instead of being used solely for rapid prototyping and in limited use scenarios. [1] Certain aspects specific to AM, such as no tooling costs, make it advantageous in the aerospace, biomedical, and other industries. [1,2] As its use as a viable manufacturing method has grown so has the desire to create composite materials using AM. In this effort, methods for making polymer composites containing fiber reinforcements using fused deposition modeling (FDM) have been developed. However, such methods suffer from limitations in terms of loading fraction and fiber orientation. [3,4] Specifically, due to the extrusion process the fiber segments
orient themselves in the print direction. For certain applications this may be advantageous, but it
does not allow for other orientations. Methods for manufacturing particle-polymer matrix
composites have also been developed for use in FDM, stereolithography (SLA), and selective
laser sintering (SLS). [4,5] These methods rely upon using feedstock made of particles
homogenously mixed with the respective polymer base material. However, this homogenous
mixing does not allow for local control of particle distribution. Consequently, the ability to make
material properties directional, which would be advantageous for certain applications, is limited.

More Recently, work has been done to achieve inhomogeneous distribution of particles
within these polymer composites. One method uses a magnetic field to arrange solid particles in
a tank of liquid SLA feedstock. [6,7] Once the particles are arranged in the desired pattern, a
layer of photosensitive feedstock is cured capturing the pattern. Because a magnetic field is used
to arrange the particles, the particles must be responsive to a magnetic field. This limits the
choices of particles that can be used. To move past this limitation, methods utilizing acoustic
fields have been developed. [8-10, 13] Certain early attempts at this [8, 13] utilize an acoustic
field generated by piezoelectric actuators (PZT plates) situated perpendicular to the build
platform. In this setup a standing wave is present within the liquid SLA feedstock creating
regularly spaced pressure nodes and anti-nodes. Due to differences in density and speed of sound
between the liquid polymer and the solid particles (acoustic contrast factor), the particles migrate
towards the nodes or anti-nodes. The resulting agglomerations of solid particles occur regularly
at a spacing of $\lambda/2$ where $\lambda$ is the wavelength of the standing wave present in the liquid polymer
[8, 13]. This concept is well documented and understood in the field of acoustophoresis [8, 13,
14]. When using this sort of setup one must only know the speed of sound through the medium,
in this case the liquid polymer, and the distance between the PZT plates to be able to be able to
identify frequencies that will create a standing wave. Consequently, the spacing between particle agglomeration can also be easily predicted with some degree of certainty. This is demonstrated in the 3D printing setup used by Llewellyn-Jones et al. [8].

A different setup developed by Lu et al [9,10] utilizes PZT plates situated parallel to the build platform. The pattern that the particles create is dependent on plate shape, spacing, configuration, and vibration frequency. The spacing of the line patterns does not follow the $\lambda/2$ formation demonstrated in different setups. It is the assertion of this paper that the reason the line spacing does not follow this common convention is because the build platform is acting as a sort of Chladni plate. Chladni plates were first studied extensively by Ernst Chladni [15]. Previous experiments with Chladni plates have shown the ability to consistently and predictively arrange particles of various sizes into specific patterns [11], and even control the motion of particles [12]. Similar to the concept of using standing transverse waves in a fluid media to control the location of particles, Chladni plates rely on wave nodes and anti-nodes to move particles into anisotropic distributions. However, due to the underlying physics controlling the motion of vibrating plates and membranes, the spacing and overall shape of these particle distributions is more difficult to predict. This is especially true in the setup utilized by Lu et al. [9,10] due to the complex boundary conditions. Because of this, a high-fidelity analytical model is needed to accurately predict what the particle distributions will look like. If constructed properly, such a model could be used to simulate many different plate configurations and frequencies to quickly identify what particle distribution patterns are possible. This work attempts to gather more experimental data on what particle distribution patterns are possible and investigate potential computational models that could be used to predict particle patterns.
2.3 Materials and Methods

2.3.1 Particle Patterning Setup

To gather data on a range of particle pattern configurations, the setup shown in figure 2.1 was used. A sheet of PET film was placed over a base plate and held in place with adhesive. The adhesive was applied in a way that secured all 4 outer edges of the film, and left a square with dimensions \( w = 67 \text{mm}, l = 67 \text{mm} \) free to vibrate. A PZT plate was then situated between the base plate and the film and attached to the film with adhesive. To aid in pattern visualization, a piece of black paper was slipped in between the base plate and the PET film. The medium used to create patterns was silicon dioxide homogenously suspended in deionized water at a weight fraction of 2.5%. To mix the solution a Fisher Scientific stir plate was used to spin a stir rod in a beaker at 300RPM for at least 5 minutes. This solution was then spread over the PET film. The PZT plate was excited with a sinusoidal wave generated by a function generator and fed through an amplifier at 20V for a period of between 5 and 10 seconds. This occurred over a range of different frequencies. In an attempt to create consistent and reliable patterns, the setup was simplified and contained only one rectangular PZT plate. This reduced the number of boundary conditions and reduced potential variabilities induced when attaching multiple PZT plates. The base plate was made from VeraWhite plastic manufactured by Stratasys. The PET film was DuraLar manufactured by Grafix Plastics and had a thickness of 75\( \mu \)m. The PZT plate was model SMPL20W15T1R111 manufactured by Steiner & Martins, Inc. and had dimensions of 20x15x1mm. The adhesive used was 3M Scotch Brand double sided tape. The function generator was a Tektronic AFG1022 and the amplifier was a Krohn-Hite 7602M.
2.3.2 Frequency Domain Finite Element Analysis

A main factor driving the design of the model was the desire to simplify it compared to previous attempts [9]. Specifically, the simulation focused on the PET film which acted as a vibrating surface when excited by the PZT plates. An equation that describes the motion of a vibrating thin plate is the two dimensional wave equation:

\[
\frac{1}{c^2} \frac{\partial^2 U(x, y, t)}{\partial t^2} = \frac{\partial^2 U(x, y, t)}{\partial x^2} + \frac{\partial^2 U(x, y, t)}{\partial y^2}
\]  

(6)

Where \( U(x, y, t) \) is displacement in the z-direction, and \( c \) is wave velocity [16].

2.3.3 Material and Simulation Models

Close attention was paid to the material model used for the PET film. Multiple different constitutive relationships were used and compared with one another in terms of how well they reflected experimental results. The first material model used was linear elastic (LE). The 1-D representation of which, shown in figure 2.2A, follows Hooke’s law [17]:

\[
\sigma = E\varepsilon
\]  

(7)
Where $\sigma$ is stress, $\varepsilon$ is strain, and $E$ is Young’s modulus. A linear elastic material model, while useful in many situations, ignores the viscoelastic nature of polymers. For this reason, the second material model used was the Maxwell form of the standard linear solid (VE), shown in figure 2.2B. This is made of a linear elastic unit in parallel with a Maxwell unit. The 1-D representation of which is [17]:

$$\sigma + \frac{\eta_1}{E_1} \dot{\sigma} = E_0 \varepsilon + \frac{\eta_1 (E_0 + E_1)}{E_1} \dot{\varepsilon}$$

(8)

Where $\eta$ is the viscosity associated with the Maxwell unit. To create two more simulation models, a damping attribute was added to the material domain in the form of an isotropic loss factor. When this is added, the FEA solver includes a damping matrix which is defined as:

$$C = \frac{\eta K}{\omega}$$

(9)

Where $K$ is the damping matrix, $\eta$ is the loss factor and $\omega$ is the frequency. This damping attribute was combined with the two material models to create two additional simulation models LE-D and VE-D.

Figure 2.2. Spring and dashpot models of 2 different material models used. A- linear elastic (LE) and B- Maxwell form of the standard linear solid (VE)
2.3.4 Simulation Setup

The FEA model was done using COMSOL Multiphysics 5.4. The PET film was modeled using a block with dimensions $l = 67\text{mm}$, $w = 67\text{mm}$, $h = 0.075\text{mm}$ (figure 2.3). This domain was assigned various material models during simulations. To simulate the effect of the PZT plates, the bottom surface of the PET film was partitioned with rectangles of dimension $l = 20\text{mm}$, $w = 15\text{mm}$. Although in this work only one PZT plate was utilized, the silhouette of 4 PZT plates was included in the model for dimensional reference. For all material models the following boundary conditions applied: The outer edge of the PET film was set as a “Fixed Constraint”. The top surface was set as a “Free” boundary. Except for the area representing the single active PZT plate, the bottom surface of the film was set as a “Free” boundary. To simulate the vibration of the flat PZT plate, one rectangular boundary on the bottom surface of the film was given a “Prescribed Acceleration” in the $z$-direction of $1\text{m/s}^2$. During the frequency domain simulations, this prescribed acceleration acted as the PZT plate vibrating in the $z$-direction at a certain frequency. All simulations were created using the “Solid Mechanics” physics. All studies had the type “Frequency Domain”.

For the LE simulations the domain representing the PET film was assigned the material model “Linear Elastic Material”. The value for the Young’s Modulus of 4.9GPa was provided by the manufacturer. For VE, the PET film was assigned “Linear Elastic Material” to which the attribute “Viscoelasticity” was added. Within “Viscoelasticity” the “Standard Linear Solid” material model was selected. For the viscoelastic parameters, a shear Modulus of 13GPa and a viscosity of 335.96GPa-s was chosen [18]. LE-D was modeled by starting with the “Linear Elastic Material” and adding the attribute “Damping”. Within damping “Isotropic Loss Factor” was chosen as the damping type. The isotropic loss factor chosen was 0.2. To create VE-D, damping was added to the VE material model.
2.4 Results and Analysis

2.4.1 Particle Patterning Experiments

Previous works that have used a similar setup [9,10] have focused on the effects that plate shape and placement have on particle patterns. In this work the effect of frequency is investigated. To accomplish this every 4,000th frequency between 40kHz and 140kHz was tested for whether a discernable pattern was created. If no discernable pattern was created the film was cleaned, the function generator was set to the next frequency, and the film was rewetted with the particle-laden solution. If a discernable pattern was created, the function generator would be manually tuned until the pattern was clearly discernable. In this way it was found that patterns of parallel lines emanating from the PZT plate were present across narrow ranges of frequencies. In between these narrow frequency ranges were relatively large gaps where the parallel lines became disjointed, blurred or no discernable pattern was visible. Images of these patterns are shown in figure 2.4. To characterize the different particle patterns, the average line spacing was measured. As can be seen in figure 2.4, some lines have breaks and inconsistencies can be seen.
This may be due to slight warpage of the plastic film or adhesive which is a known source of error.

Figure 2.4. Particle patterns created by silicon dioxide particles suspended in deionized water distributed on PET film. The film is being vibrated by the white PZT plate.
2.4.2 FEA Simulations

Similar to the particle patterning experiments, FEA simulations were performed by sweeping each material model through different frequencies. At each frequency, a surface plot of the top surface of the PET film was generated (figure 2.5). These plots demonstrate how the
wave generated by the PZT plate propagates through the film. The science behind Chladni plates [11, 12] dictates that particles accumulate near nodes. These nodes are shown on the plots as areas of no deformation colored white. The different simulation models were found to mimic the real-world results to varying degrees of success. The LE model created some surface deformation patterns that matched the overall shape and frequency of the experimental results, but the line spacing was too narrow. Furthermore, there were many frequencies identified during particle patterning experiments that could not be replicated using the LE model. Similarly, the VE model could not replicate every frequency, but the spacing was found to be in line with experimental results. Both models that employed damping (LE-D, VE-D) created patterns that matched the experimental results at every frequency that was found to create a discernable pattern. However,

![Frequency vs. Line Spacing for Different Simulation Models](image)

**Figure 2.6.** Plot of frequency vs. line spacing of particle patterning experiments
the line spacing in the model that included viscoelasticity (VE-D) matched much more closely with experimental results than the model without (LE-D). A plot comparing line spacing between computer simulations and particle patterning experiments is shown in figure 2.6. The surface deformation plot of the VE-D model is shown in figure 2.5. The frequencies plotted correspond with frequencies that were found to show a discernable pattern in the particle patterning experiments. As can be seen, there is a great deal of correlation between the experimental and simulation results.

2.5 Conclusions

More particle distributions patterns were successfully generated and categorized. All consisted of parallel lines radiating from the PZT plate. Line spacing decreased as frequency increased. While it is clear that particle spacing depends on frequency, it is evident that the relationship is not as simple as $\lambda/2$. When attempting to replicate experimental results using FEA analysis, it was learned that the material model needs to include viscoelasticity. When this is included line spacing corresponds closely with experimental results. Additionally, damping needs to be included. Taking damping into consideration will bring the overall pattern more in line with experimental results. Future work for both experimental and simulation will involve more complex setups to build a more robust and predictive computational model.

2.6 Citations


CHAPTER 3. GENERAL CONCLUSIONS

This thesis reviewed applicable literature pertaining to various methods of producing composites using additive manufacturing with a focus on how filler particles were aligned. It discussed the advantages of using acoustic fields as a means to intentionally pattern particles during the manufacturing of particle-matrix composites with stereolithography (SLA). The manuscript showed the work that I had performed both in laboratory experiments and in computer FEA simulations in an effort to better understand how acoustic fields could be used to pattern particles. Particle patterns were successfully demonstrated and characterized, and an FEA simulation that demonstrated good agreement with the experiments was developed. This work could be applied to the manufacturing of composites using additive manufacturing.