Silicone Whipping Additive Manufacturing (SWAM) :

Technology and Application in Automotive Manufacturing

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Motivation for Additive Manufacturing

- Accelerating Product Development → Prototype
- Reducing Tooling Investment
- Increasing Production Flexibility
- Offering Customized Product
- Enabling Co-creation
- Optimizing Products Expenses
- Time Management
# Challenges of 3D Printing Elastomers

<table>
<thead>
<tr>
<th>CHALLENGES</th>
<th>INFORMATIONAL GAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inherent Properties of Elastomers</td>
<td>Need of Unique Processing under PAM.</td>
</tr>
<tr>
<td>Printer Design</td>
<td>Need of Simple Structure</td>
</tr>
<tr>
<td>Elastomers Processability</td>
<td>Need to develop proper Printing Technique.</td>
</tr>
<tr>
<td>Printability</td>
<td>Need to optimize printing parameters.</td>
</tr>
<tr>
<td>Inferiority in Final Product &gt; Surface Roughness</td>
<td>Need Strategies &gt; Other Applications.</td>
</tr>
</tbody>
</table>
Research Motivation

Develop SWAM Technology

- Understand materials
- Understand process
- Design properties
  - Seat cushion
  - Soft tissue
Automotive Applications


Soft Robotics Applications


Cushion Application

http://www.adevotech.com/innovation.html

Tissue Replica

http://www.adevotech.com/innovation.html
SWAM : Silicone Whipping Additive Manufacturing
Concept

Custom 3D Model

Gcode Generation via Slicing

Printing Parameters
Created by: Gurkamal Saggu

V: Print Speed
Q: Flow Rate
d: Nozzle Diameter
h: Gap Distance

Final Components
Created by: Gurkamal Saggu
Part 1: Selection Of Silicone For Paste Printing


Part 3: Application Of SWAM To Prototype Automotive Cushion
Part 1: Selection Of Silicone For Paste Printing

**Aim**: To Select Durable, Biocompatible and Flexible Elastomeric Components for Printing.

**Methodology**:

- **Parameters Optimal Values**
  - Layer Height: 0.3 mm
  - Infill: 100%
  - Print Speed: 7.5 mm/s
  - Nozzle Diameter: 0.84 mm
  - Flow Rate: 125%

Various Sealants

Printed Dog Bone (Model)
Part 1: Selection Of Silicone For Paste Printing

Aim: To Select Durable, Biocompatible and Flexible Elastomeric Components for Printing.

Observation:
- High Curing Silicones > Defects (Elasticity and Modulating Pressure)
- Slow Curing Silicones > Defects (Limits Heights, Bridging and Overhangs)
- Loaded Silicones > Advantage (Good Elasticity and Dried Faster)

Print Smoothly !!
Part 1: Selection Of Silicone For Paste Printing

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Print Smoothly !!

1. Aluminum
2. Almond
3. Clear
Part 1: Selection Of Silicone For Paste Printing

**Aim**: To Select Durable, Biocompatible and Flexible Elastomeric Components for Printing.

**Result**:

- **Aluminum**
  - Caused ‘Smearing’ during Printing.
  - Less air pockets > Inc. Modulus.
  - Less Ideal appearance.

- **Almond**
  - More elasticity in wet phase.
  - Limits Print Speed.

- **Clear**
  - Printed same as Almond
  - Measuring True Density
  - Better Option for Producing Elastomeric Components
Part 1: Selection Of Silicone For Paste Printing

Conclusion:

- Selected DAP 100% Silicone Window, Door & Siding Sealants.
- Selected best option of Elastomeric component based on the Printability.
- Studied mechanical properties to choose best Durable and Flexible Components.
- Providing technical means of comparison among several options.
- Less Cost Material.

Literature Review:

- Piling up of Viscous liquid onto surface:
  - Liquid Rope Coiling Effect.

- Coined by George Barnes (1958)
  - Frequency of Coiling = fn (Height, Velocity)

- Modes: Viscous, Gravitational, Inertial & Inertia-Gravitational.

- Neil Ribe (2016):
  - Frequency of Coiling = fn (Q, H, d)

Buckling of Silicone
http://softmatter.seas.harvard.edu/index.php/Fluid_rope_trick_investigated

Literature Review:

<table>
<thead>
<tr>
<th>Model</th>
<th>Add-On</th>
<th>Heated Build Material</th>
<th>Build Material Vol. (mL)</th>
<th>Nozzle Diameter (mm)</th>
<th>Gap Distance (mm)</th>
<th>Nozzle Speed (mm/s)</th>
<th>Flow Rate (mL/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscous Thread Instability, VTI (2016)</td>
<td>No</td>
<td>No</td>
<td>60</td>
<td>0.41</td>
<td>3-5</td>
<td>10-20</td>
<td>N/A</td>
</tr>
<tr>
<td>AM by Liquid Rope Coiling (2017)</td>
<td>Yes</td>
<td>No</td>
<td>60</td>
<td>0.41-1.19</td>
<td>6-51</td>
<td>16-1</td>
<td>0.12-1.04</td>
</tr>
</tbody>
</table>

- **VTI :-**
  -- Only focus on the fabrication of alternating loops to form foam.

- **LRC :-**
  -- Developed systematic strategy by liquid rope coiling to create foam.

  However, there is still lack of knowledge about the amount of deposition depending on variable printing parameters. How would it effect the properties of foam. ???

**Aim**: Demonstrating Line Printing Characteristic.

**Methodology**:

<table>
<thead>
<tr>
<th>Printing Parameters</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Diameter (mm)</td>
<td>0.41</td>
<td>1.19</td>
</tr>
<tr>
<td>Gap Distance (mm)</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>Nozzle Speed (mm/s)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Flow Rate (ml/min)</td>
<td>0.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

$2^K - \text{Factorial Experiments}$

$(2^4 \times 3) + 12 \text{ (CP)} = 60 \text{ Runs}$
Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling’

“Line Printing”

Methodology:

- Fiber Diameter
- Break Loops Count
- Line Width
- Deposition Height

Images:
- Fiber Diameter
- Break Loops Count
- Break
- Line Width
- Deposition Height
<table>
<thead>
<tr>
<th>S.No</th>
<th>Single Overlaps</th>
<th>Multiple Overlaps</th>
<th>Features of Filament</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Straight/ Zigzag.</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>X</td>
<td>Straight &amp; Consistent Overlapping.</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>X</td>
<td>Straight, Clustered and Double Looping.</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>-</td>
<td>Distant, Straight/ Reversed Overlapping.</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>2X</td>
<td>Consistent, Clear Multiple Overlapping.</td>
</tr>
<tr>
<td>6</td>
<td>2X</td>
<td>X</td>
<td>Consistent or Nested Multiple Overlapping</td>
</tr>
</tbody>
</table>

1  
2  
3  
4  
5  
6  


Conclusion:

- Optimized Printing Parameters.
- Demonstrated new termed techniques: “Line Printing”
- Illustrated the characteristic and measurement of Line Printing.
- Detailed results obtained through statistical Analysis: Matched with Parameters relationships obtained by previous authors.
- Studied Liquid Rope Coiling Effect with respective to Printing parameters.
Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling':
“Line Printing”

Empirical Relationship:

\[
\frac{\text{Flow Rate (Q)}}{\text{Print Speed (V)}} = \text{Condition for Coiling !!}
\]

Boundary Conditions 1
- Flow Rate (Q) = near 0
- Print Speed (V) = finite

No Looping Occurs

Boundary Conditions 2
- Flow Rate (Q) = finite
- Print Speed (V) = near 0

Large number of Looping Occurs

Diagram:
- V: Print Speed
- Q: Flow Rate
- d: Nozzle Diameter
- h: Gap Distance

- **Stream Velocity, \(v\) (cm/s):** Velocity according to the extruder, also called initial velocity (\(V_i\)). [Barnes, 1958]

- **Average Velocity, \(<V>\) (mm/s):** Velocity with the effect of gravity, also [Gurkamal, 2020]
Calculation of $v = V_i$.
Consider Nozzle Stream Flow (No Gravitational Effect)

\[ v = (V_i) \] \[ (\text{Barnes, 1958}) \]

\[ <V> \ (\text{mm/s} \ [\text{Gurkamal, 2020}]) \]

\[ d = \text{Diameter of Nozzle (mm)} \]

\[ Q = \text{Adjusted Flow Rate (mm}^3/\text{s}) \]

\[ V_i = Q/A \quad ........... (1) \]

\[ v = (V_i) \]  [Barnes, 1958]

\[ \langle V \rangle = \frac{V_i}{\text{diameter of nozzle (mm)}} \]  [Gurkamal, 2020]

Consider the Middle Stream Flow (Gravitational Effect)

\[ V_f^2 = V_i^2 + 2ah, \]

\[ \langle V \rangle^2 = v^2 + 2gh, \]

\[ \langle V \rangle = \sqrt{v^2 + 2gh} \]  \[\ldots (2)\]

2\textsuperscript{nd} Empirical Relationship: Avg stream Velocity & Print Speed

\[
\frac{\text{Avg. Velocity } (\langle V \rangle)}{\text{Print Speed } (V)} = \text{Condition for Coiling!!}
\]

**Boundary Conditions 1**
- Avg. Velocity \(\langle V \rangle = 0\)
- Print Speed \(V = \infty\)

No Looping Occurs

**Boundary Conditions 2**
- Avg. Velocity \(\langle V \rangle = \infty\)
- Print Speed \(V = 0\)

Infinite number of Looping Occurs

Infinite number of Looping Occurs

\[v = (V_i)\] [Barnes, 1958]

\[<V> \text{ (mm/s)}\] [Gurkamal, 2020]

Main Conclusion

- Formation of Loops.
- Disappearance of Single Overlaps.
- Occurrence of Multiple Overlapping.
- Spreading of Filament Deposition.

Boundary Conditions 1
- Flow Rate \( (Q) = 0 \)
- Avg. Velocity \((uV)\) = 0
- Print Speed \((V)\) = Inf.

Boundary Conditions 2
- Flow Rate \((Q)\) = Inf
- Avg. Velocity \((uV)\) = Inf
- Print Speed \((V)\) = 0
Part 3: Application Of Swam To Prototype Automotive Cushion

Literature Review:

**Silicone**

✓ Can last for up to 20 years

✓ Non-flammable, Does not release toxic fumes when ignited.

✗ Release of unpleasant odor when cured (Acetic Acid).

\[
\begin{align*}
\text{Me} & \quad \text{H}_2\text{O} & \quad \text{Me} \\
\text{OH} & \quad \text{O-Si-OH} \quad \text{OAc} & \quad \text{O-Si-O} \\
\text{OAc} & \quad \text{O-Si-OH} + \text{AcO} & \quad \text{O-Si-O} \\
\text{OAc} & \quad \text{O-Si-O} & \quad \text{OAc}
\end{align*}
\]

Both can be used as cushioning material in the Automotive Industry.

**Polyurethane**

✗ Only lasts for 5-10 years

✗ Readily catches fire, releases toxic fumes when ignited

✓ Does not release an odor when processed

\[
\begin{align*}
\text{O} & \quad \text{C} \quad \text{N} & \quad \text{N} \quad \text{C} \quad \text{O} + \text{HO} \quad \text{C} \quad \text{C} \quad \text{OH} \\
\text{H} & \quad \text{H} & \quad \text{H} & \quad \text{H} & \quad \text{H} & \quad \text{H} & \quad \text{H} & \quad \text{H} & \quad \text{H} & \quad \text{H}
\end{align*}
\]
Part 3: Application Of Swam To Prototype Automotive Cushion

**Aim**: Printing Variable Density Cushion with Variable Firmness

**Methodology**:

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Nozzle Diameter (mm)</th>
<th>Gap Distance (mm)</th>
<th>Flow Rate (ml/min)</th>
<th>Print Speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block A</td>
<td>0.84</td>
<td>50</td>
<td>0.8</td>
<td>10</td>
</tr>
<tr>
<td>Block B</td>
<td>0.41</td>
<td>75</td>
<td>0.4</td>
<td>10</td>
</tr>
<tr>
<td>Block C</td>
<td>0.41</td>
<td>25</td>
<td>0.8</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Density of Specimen (g/cc)</th>
<th>Average Height (mm)</th>
<th>Max. Force Deflection @ 50% (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block A</td>
<td>0.501</td>
<td>57.69</td>
<td>319.8096</td>
</tr>
<tr>
<td>Block B</td>
<td>0.297</td>
<td>51.01</td>
<td>87.9310</td>
</tr>
<tr>
<td>Block C</td>
<td>0.315</td>
<td>51.04</td>
<td>158.7312</td>
</tr>
</tbody>
</table>
Part 3: Application Of Swam To Prototype Automotive Cushion

Result:

- Graph: Load (N) v/s Time (min)
  \[ L = f(n) (t) \]

- Force applied up to 50% of Specimen Height: Standard ASTM test.

- \[ L_A > 2L_C > 3.5L_B \]

- All Blocks reached to their max. Load at same time with variable Density and Firmness.

- Controlled variation in Firmness has been achieved.
Graph: Firmness (N) v/s Density (g/cc).

Firmness measured up to 50% of Specimen Height: Standard ASTM test.

\[ F_A > 2F_C > 3.5F_B \]

Not Direct Relationship between two quantities.

Block B has lowest density because of less deposition (Low Q & Low d), Whereas Block A has the highest because of more deposition (High value parameters)
Part 3: Application Of Swam To Prototype Automotive Cushion

Result:

- Graph: Stress (KPa) v/s Strain (%).
- Compressed up to the Maximum Load.
- No Break in the specimen occurred.
- Compared and obtained better output than VTI technology (by J.I. Lipton), PU form automotive seat cushions (by W.N Patten).
- Porous structure due to less & thin interconnectedness between layers leads Block B to achieve maximum Strain of 97.5% followed by Block A and C (95% & 92% resp.).

![Graph showing Stress vs Strain for Blocks A, B, and C]

Block A: 0.501 g/cc; 95%
Block B: 0.297 g/cc; 97.5%
Block C: 0.315 g/cc; 92%
Part 3: Application Of Swam To Prototype Automotive Cushion

Conclusion:

- Developed Prototype for Automotive Cushioning through Printing Parameters.
- Focused on the interconnectedness between layers to achieve strength through Line Printing characteristic of overlapping.
- Fabricated and Controlled ‘Variable Density’ & ‘Variable Firmness’ for Cushioning.
Main Conclusions

- Introduction of Simple Designed installed setup for printing silicone called, SWAM.
- Developed proper optimized technique for printing different type of Foam Structures, Line Printing.
- Demonstrated the effects of printing parameters over the properties of Final Specimen using Line Printing.
- Fabricated Durable, Light weight and Flexible elastomeric components for Automotive Application, Cushioning.
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