Silicone Whipping Additive Manufacturing (SWAM) :

Technology and Application in Automotive Manufacturing

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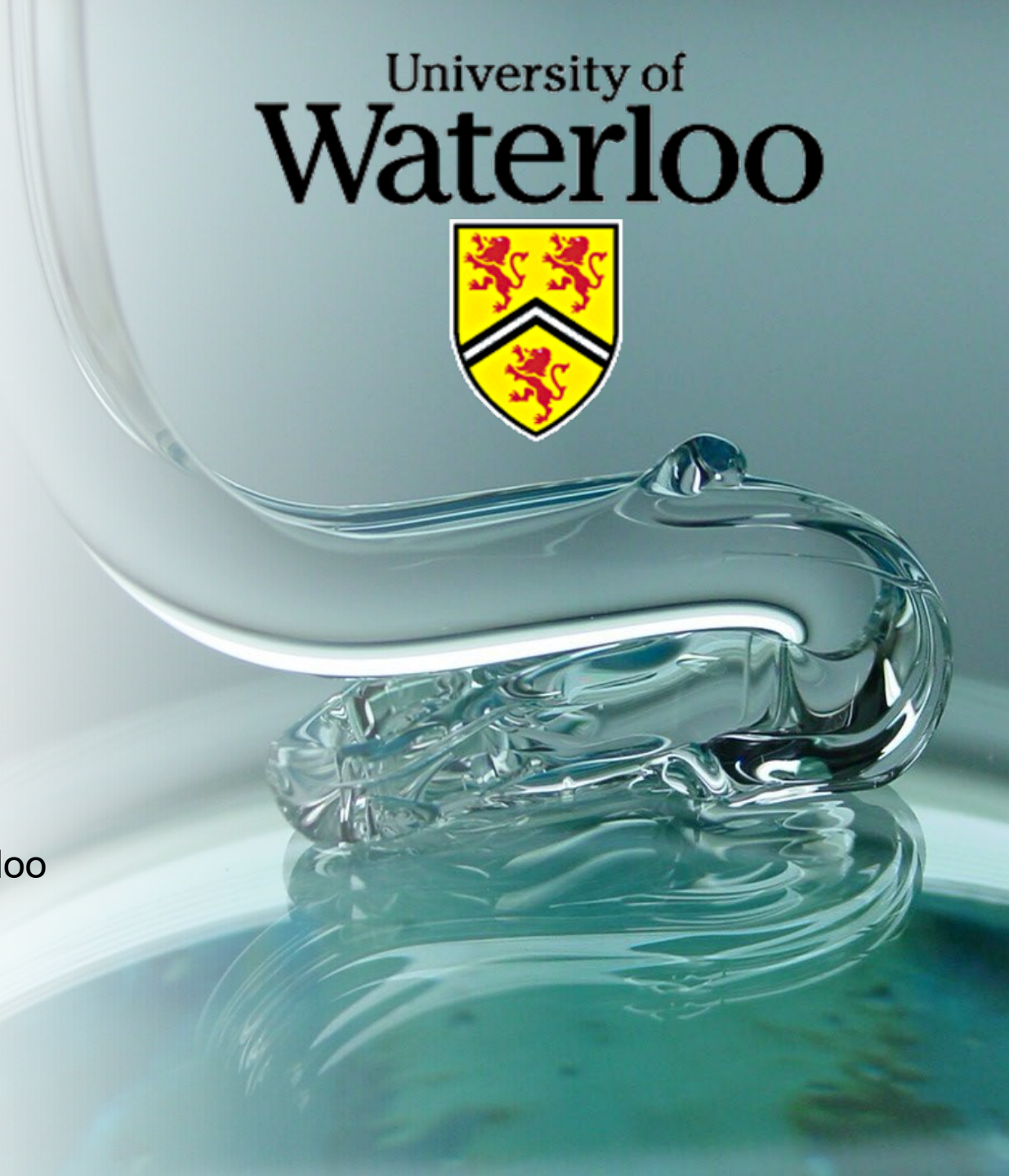

Contents

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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

CHALLENGES	INFORMATIONAL GAP
Inherent Properties of Elastomers	Need of Unique Processing under PAM.
Printer Design	Need of Simple Structure
Elastomers Processability	Need to develop proper Printing Technique.
Printability	Need to optimize printing parameters.
Inferiority in Final Product > Surface Roughness	Need Strategies > Other Applications.

Research Motivation

Develop SWAM Technology

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

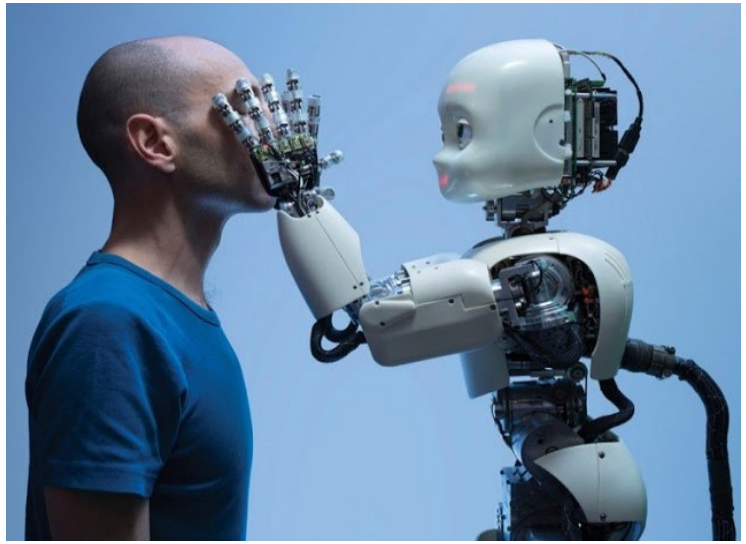
Pictured by : Gurkamal Saggu

Automotive Applications

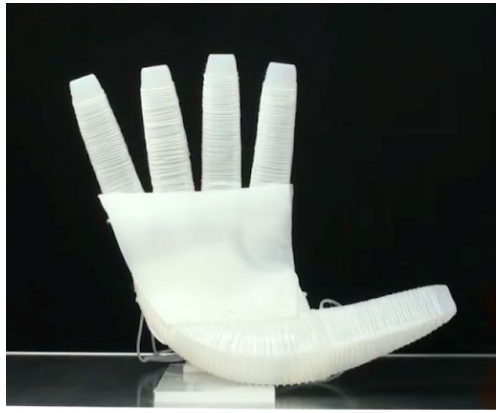
https://www.synopsys.com/verification/solutions/automotive/prototyping-in-automotive.html

Cushion Application

Soft Robotics Applications



https://www.doncaprio.com/robotics-trends-to-watch-out-for-in-2019/

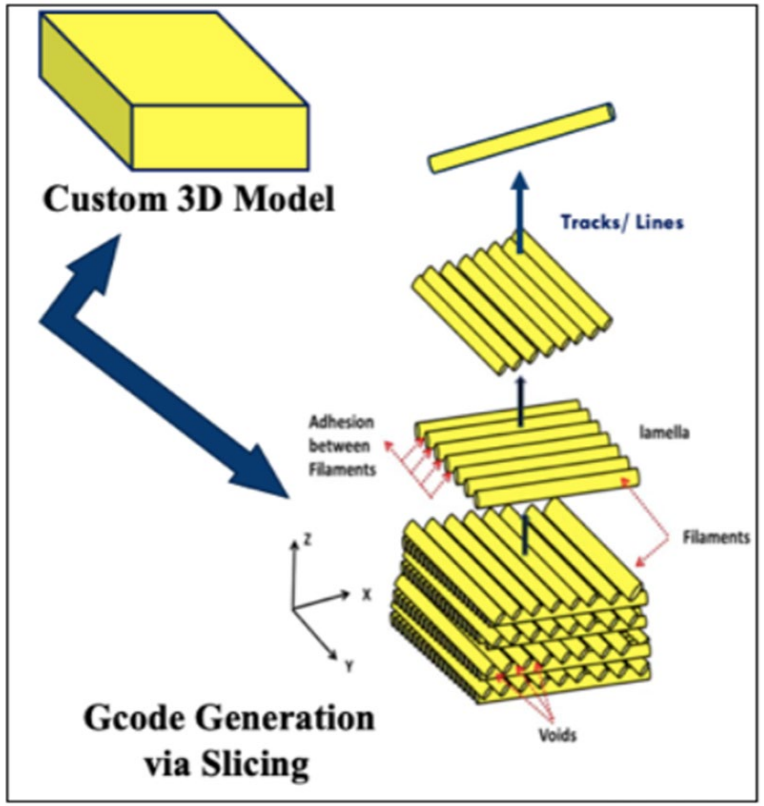


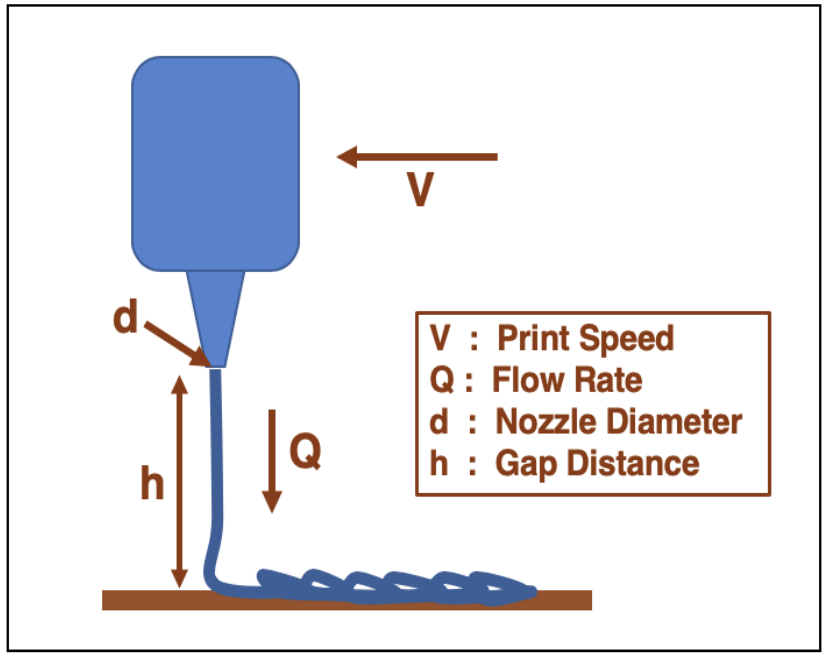
Tissue Replica

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

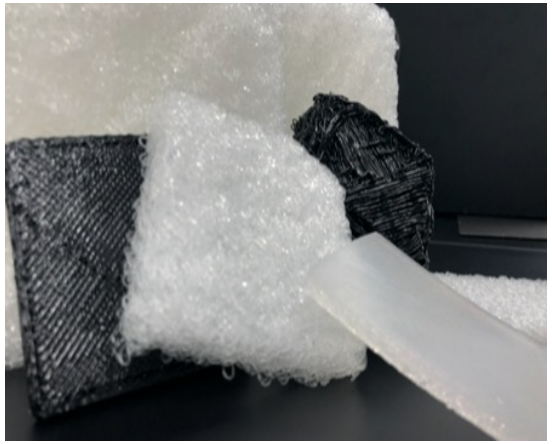
SWAM : Silicone Whipping Additive Manufacturing

Concept





Printing Parameters
Created by : Gurkamal Saggu



Final Components
Created by : Gurkamal Saggu

Part 1: Selection Of Silicone For Paste Printing

Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling : “Line Printing”

Part 3: Application Of SWAM To Prototype Automotive Cushion

Part 1: Selection Of Silicone For Paste Printing

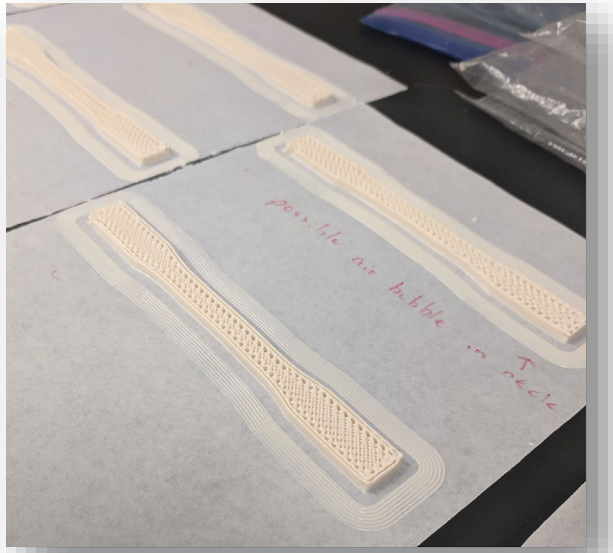
Aim : To Select Durable, Biocompatible and Flexible Elastomeric Components for Printing.

Methodology :

Various Sealants

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

Printing Parameters



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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- ✓ Loaded Silicones > Advantage
  (Good Elasticity and Dried Faster)

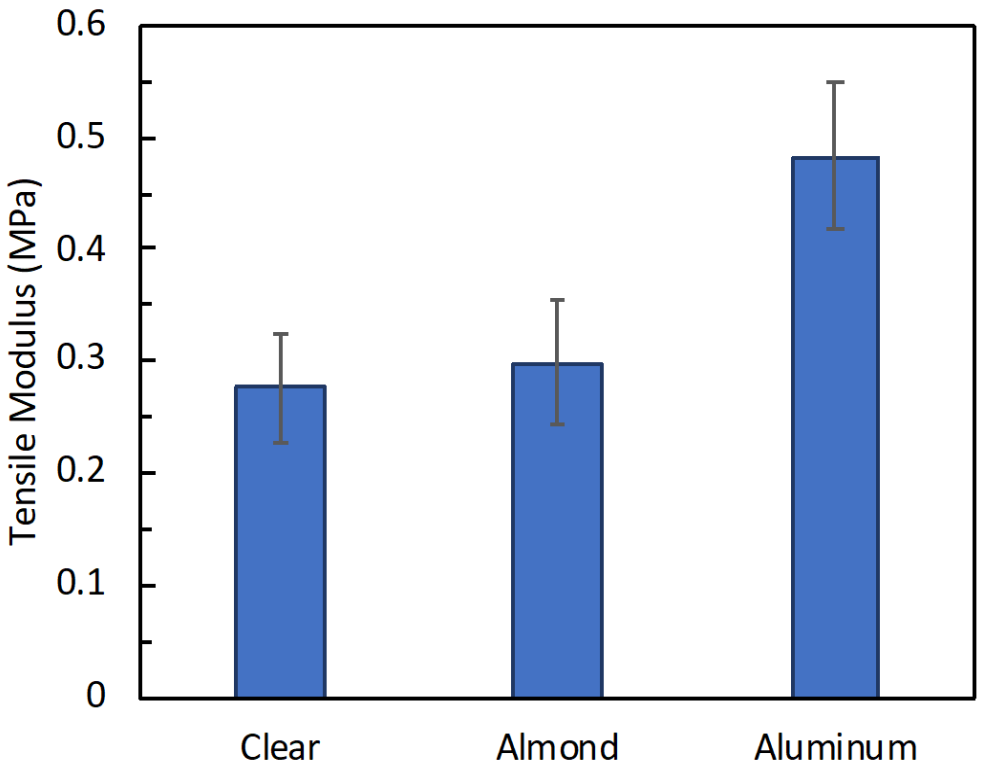
1. **Aluminum**
2. **Almond**
3. **Clear**

Print Smoothly !!

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 :

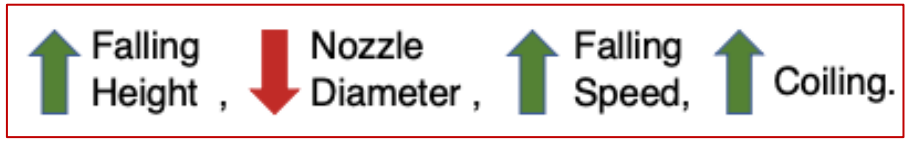
- Selected DAP 100% Silicone Window, Door & Siding Sealants.
- Selected best option of Elastomeric component based on the Printability.
- Studied mechanical properties to choose best Durable and Flexible Components.
- Providing technical means of comparison among several options.
- Less Cost Material.

Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling : “Line Printing”

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

Part 2: Effect Of Printing Parameters On 'Liquid Rope Coiling : "Line Printing"

Literature Review :

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

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

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

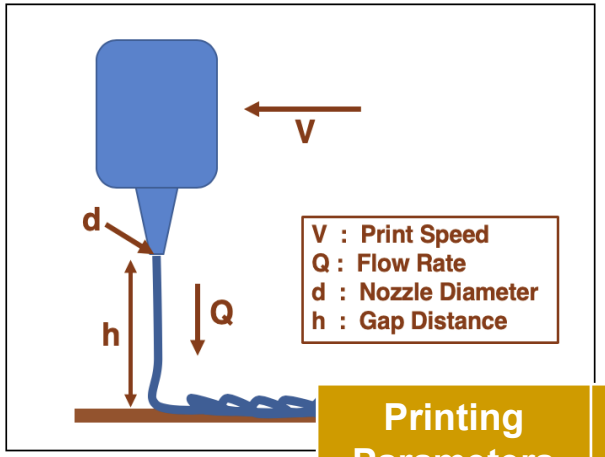
However , there is still lack of knowledge about the amount of deposition depending on variable printing parameters. How would it effect the properties of foam. ???

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

Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling : “Line Printing”

Aim : Demonstrating Line Printing Characteristic.

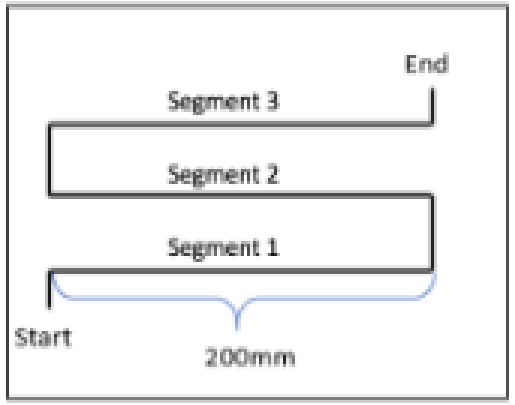
Methodology :

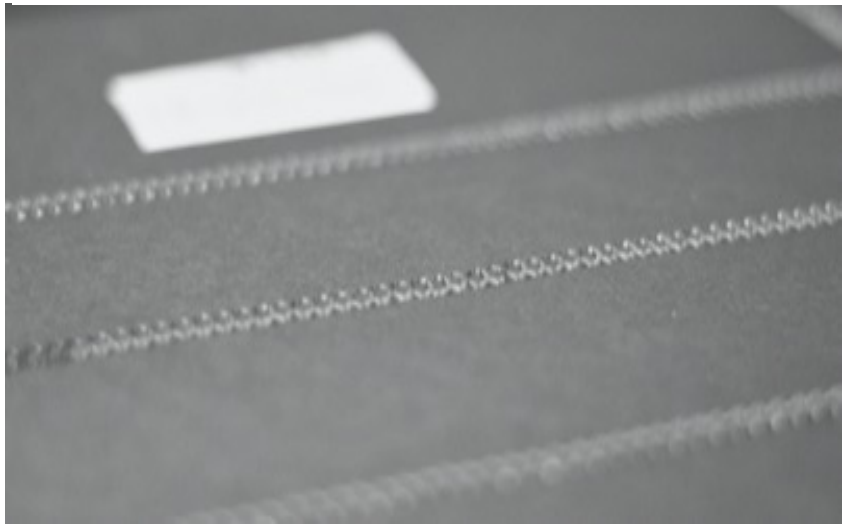


2^K - Factorial Experiments
$(2^4 \times 3) + 12$ (CP) = 60 Runs

Printing Parameters	Low	High
Nozzle Diameter (mm)	0.41	1.19
Gap Distance (mm)	25	75
Nozzle Speed (mm/s)	5	10
Flow Rate (ml/min)	0.4	0.8

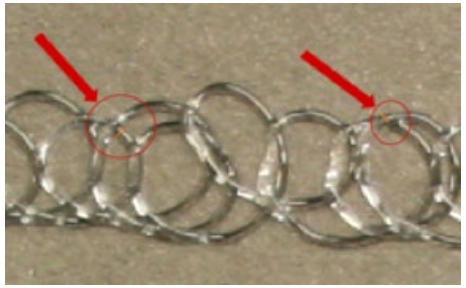
Line Printing Technique using GCode



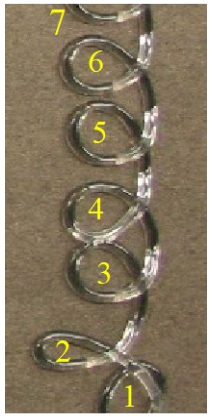


Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling : “Line Printing”

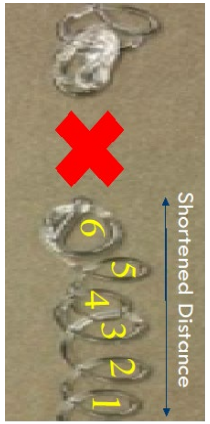
Methodology :



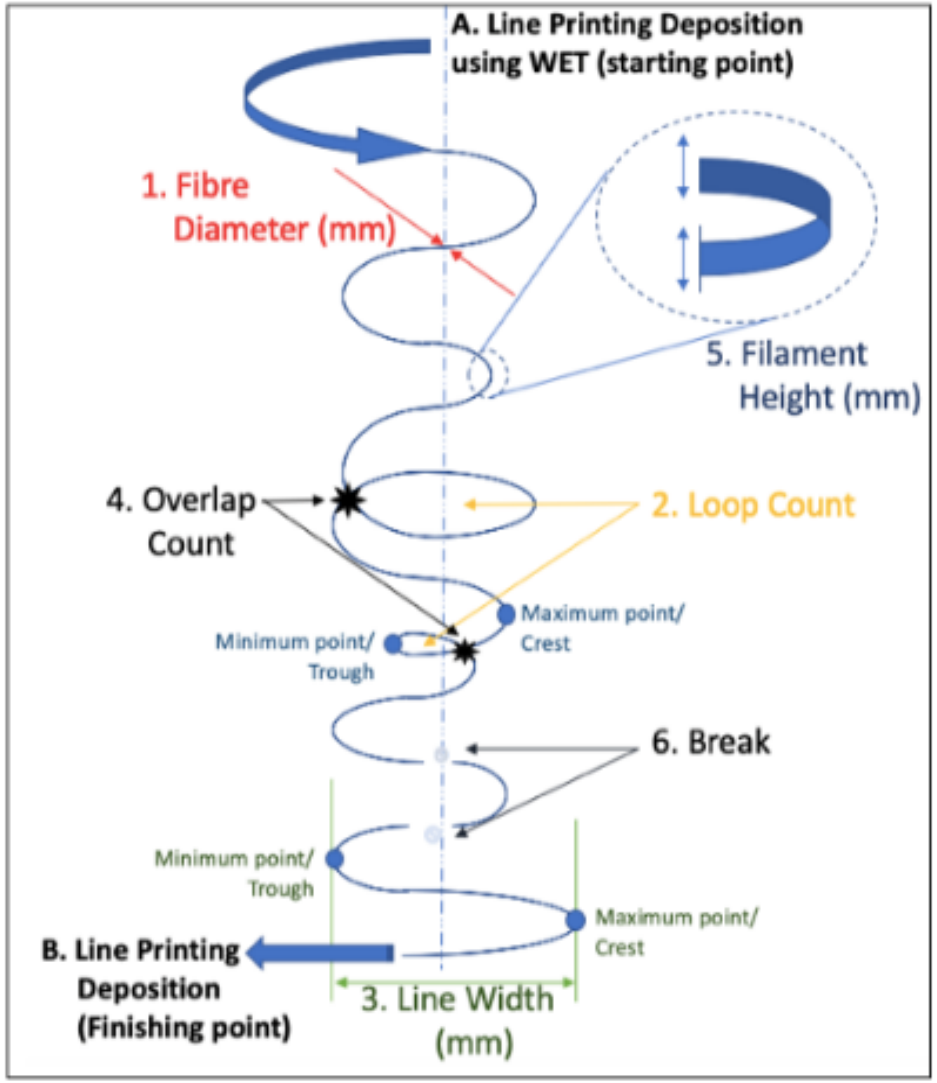
Fiber Diameter

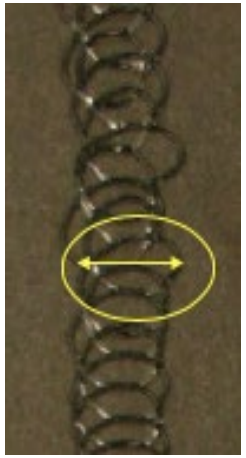


Loops Count

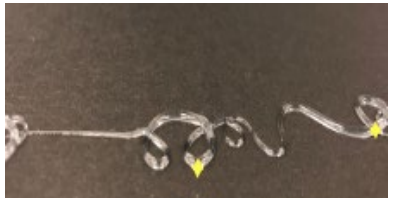


Break



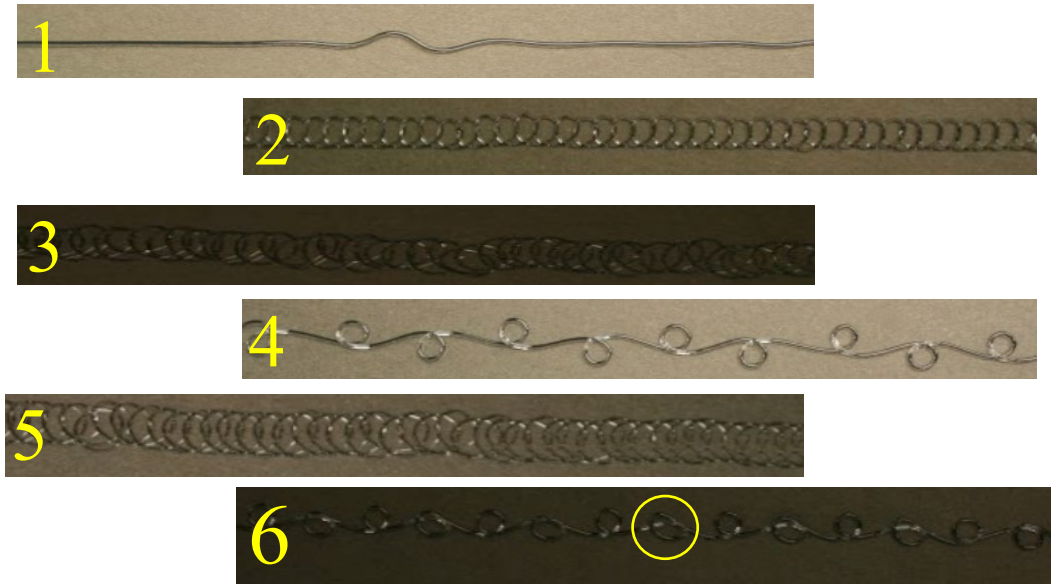


Line Width



Deposition Height

S.No	Single Overlaps	Multiple Overlaps	Features of Filament
1	-	-	Straight/ Zigzag.
2	X	X	Straight & Consistent Overlapping.
3	-	X	Straight, Clustered and Double Looping.
4	X	-	Distant, Straight/ Reversed Overlapping.
5	X	2X	Consistent, Clear Multiple Overlapping.
6	2X	X	Consistent or Nested Multiple Overlapping



Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling : “Line Printing”

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

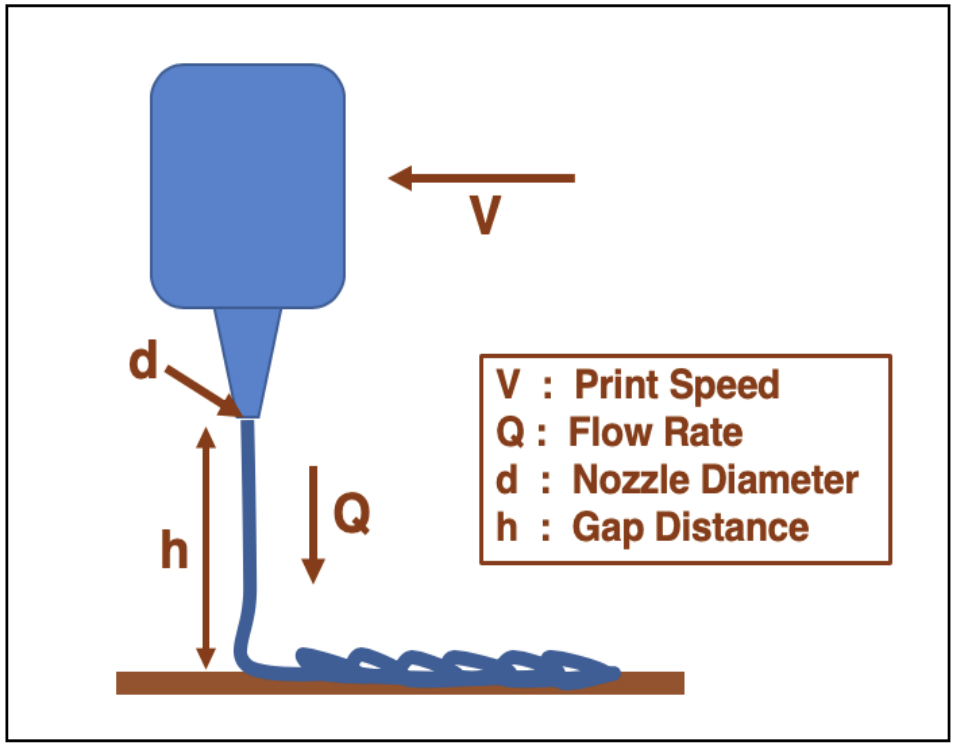
- Flow Rate (Q) = near 0
  Print Speed (V) = finite

No Looping Occurs

Boundary Conditions 2

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

Large number of Looping Occurs



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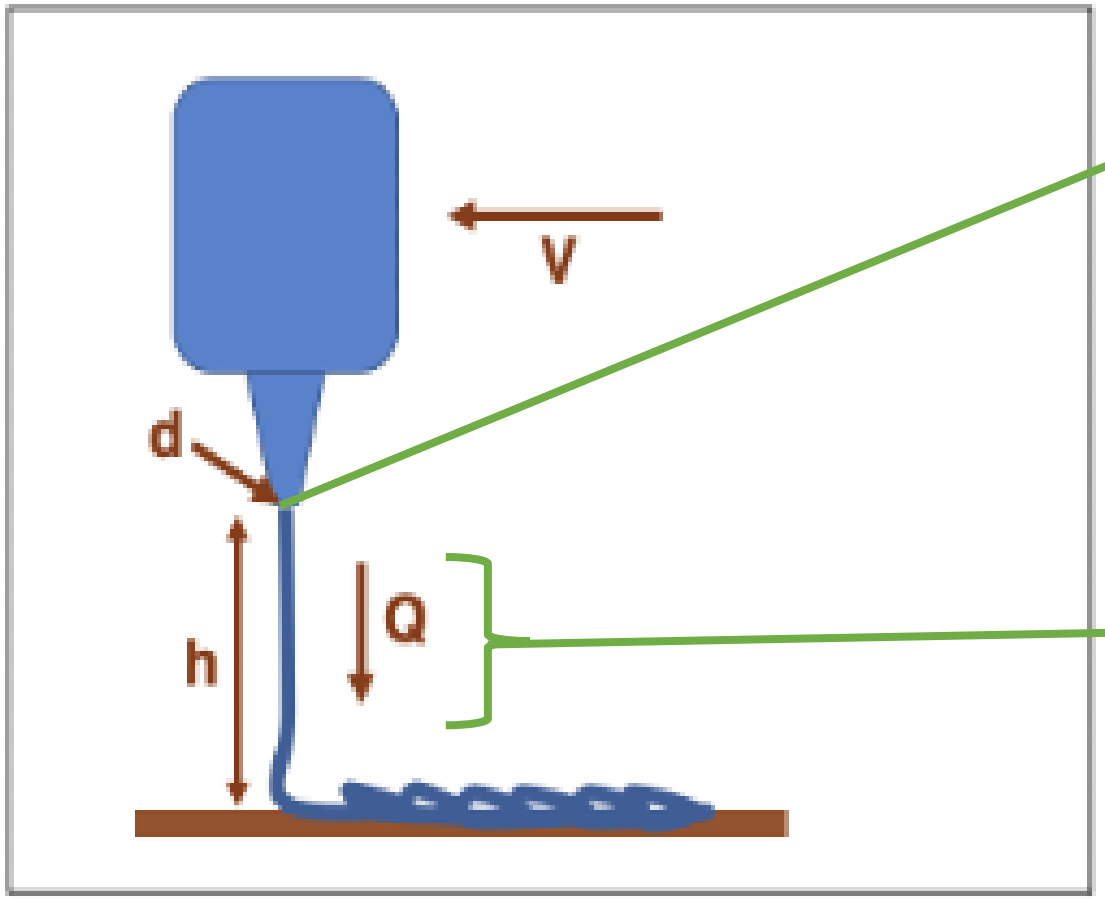
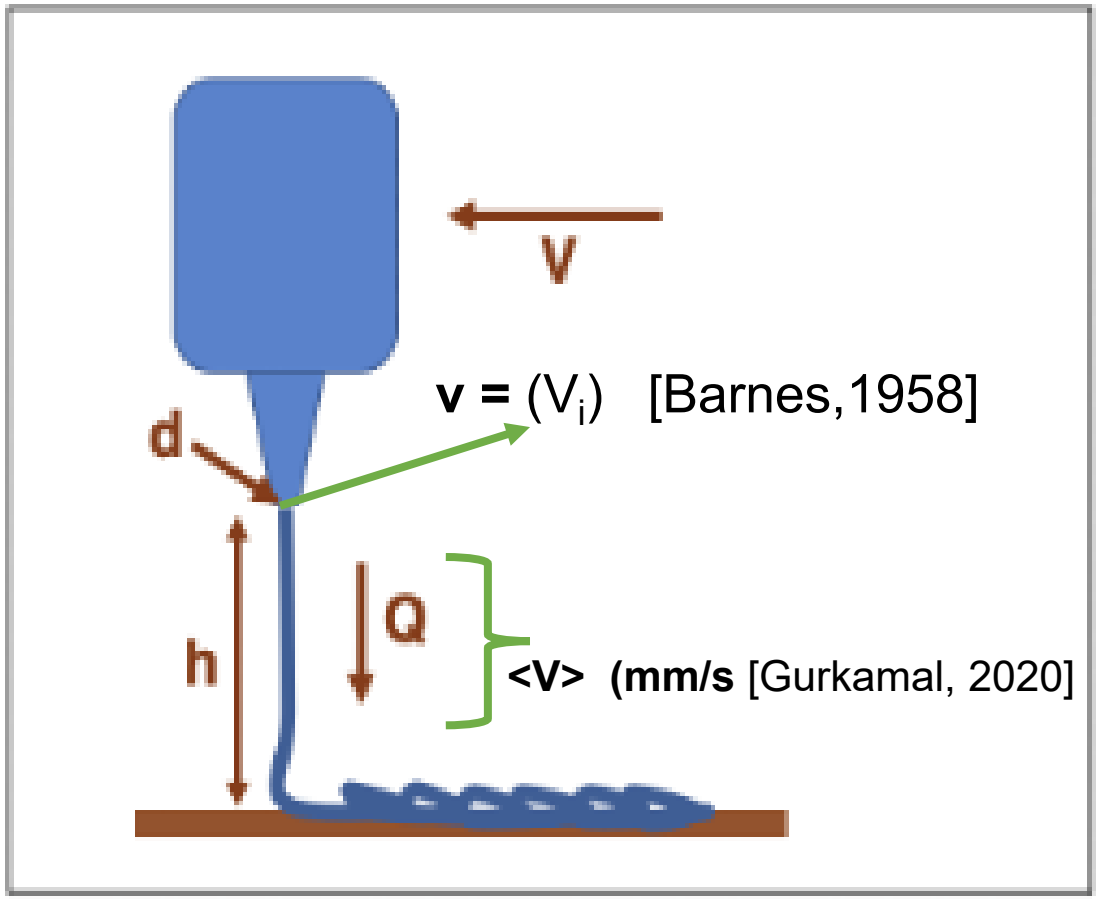


- **Stream Velocity, v (cm/s)** :- Velocity according to the extruder , also called initial velocity (V_i). [Barnes,1958]

Average Velocity, <V> (mm/s) :- Velocity with the effect of gravity, also [Gurkamal, 2020]

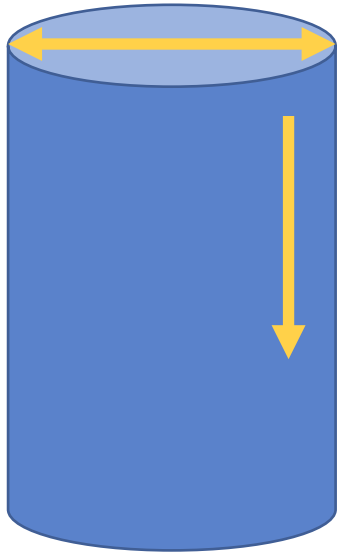
Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling : “Line Printing”



Calculation of v = V_i .

Consider Nozzle Stream Flow (~~No Gravitational Effect~~)

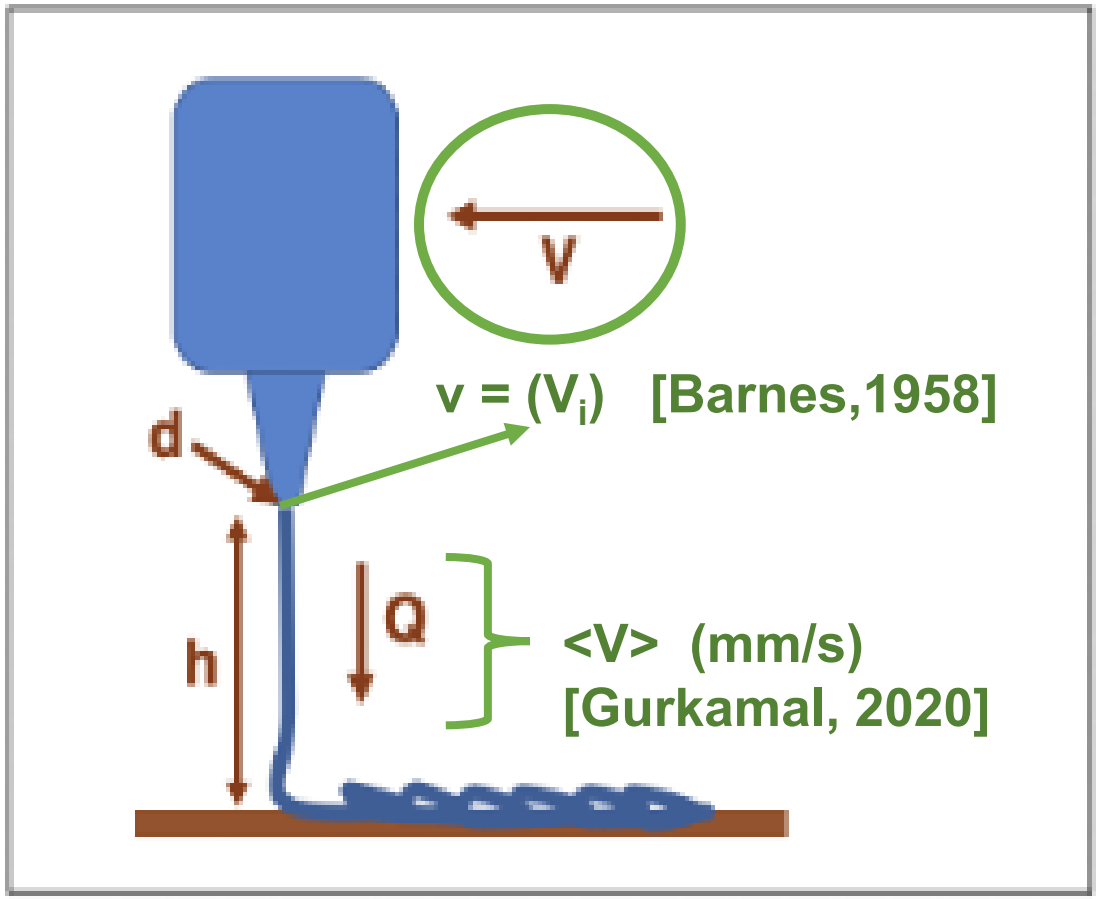
d = Diameter of Nozzle (mm)



Q = Adjusted Flow Rate (mm^3/s)

$$V_i = Q/A \quad \text{..... (1)}$$

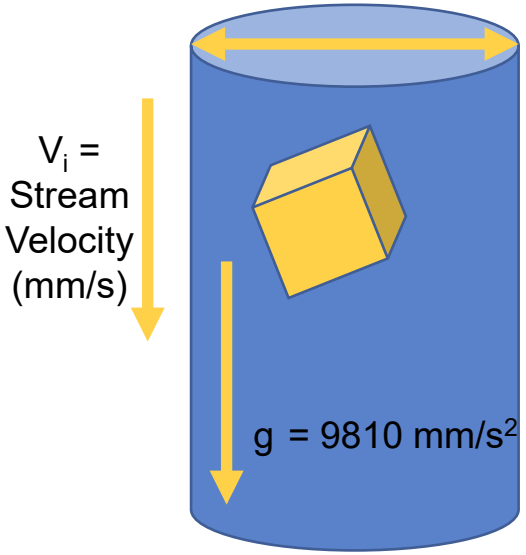
Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling : “Line Printing”



Calculation of <V> ,

Consider the Middle Stream Flow (Gravitational Effect)

d = Diameter of Nozzle (mm)



Using Free Falling Object Equation,

$$V_f^2 = V_i^2 + 2ah,$$

$$\langle V\rangle^2 = v^2 + 2gh,$$

$$\langle V\rangle = \sqrt{v^2 + 2gh} \quad \text{..... (2)}$$

Part 2: Effect Of Printing Parameters On 'Liquid Rope Coiling : "Line Printing"

2nd **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

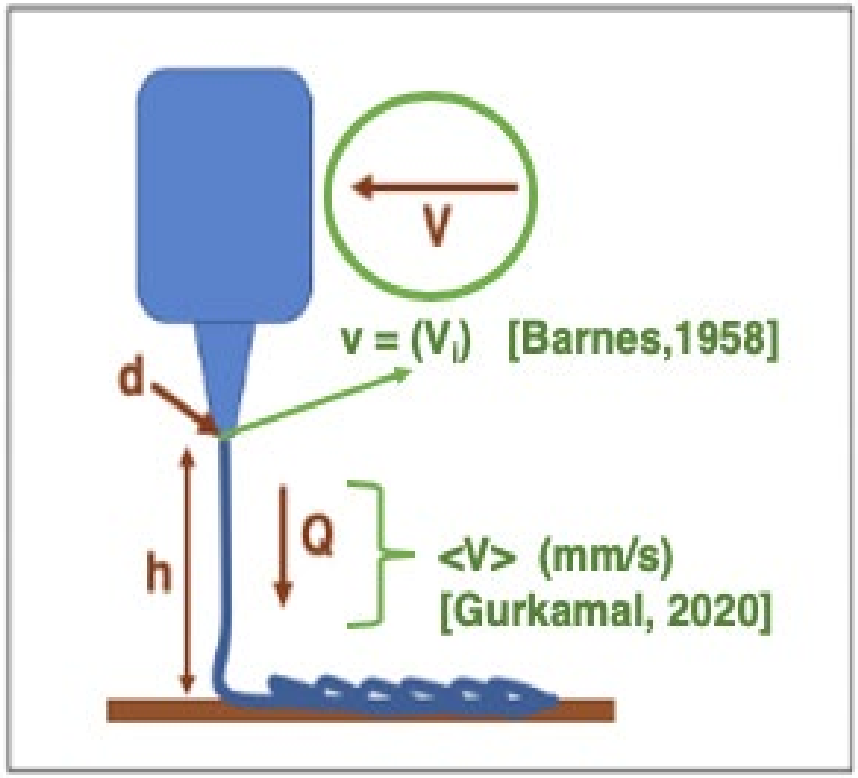
- Avg. Velocity (<V>) = 0
  Print Speed (V) = Inf.

No Looping Occurs

Boundary Conditions 2

- Avg. Velocity (<V>)= Inf.
  Print Speed (V) = 0

Infinite number of Looping Occurs



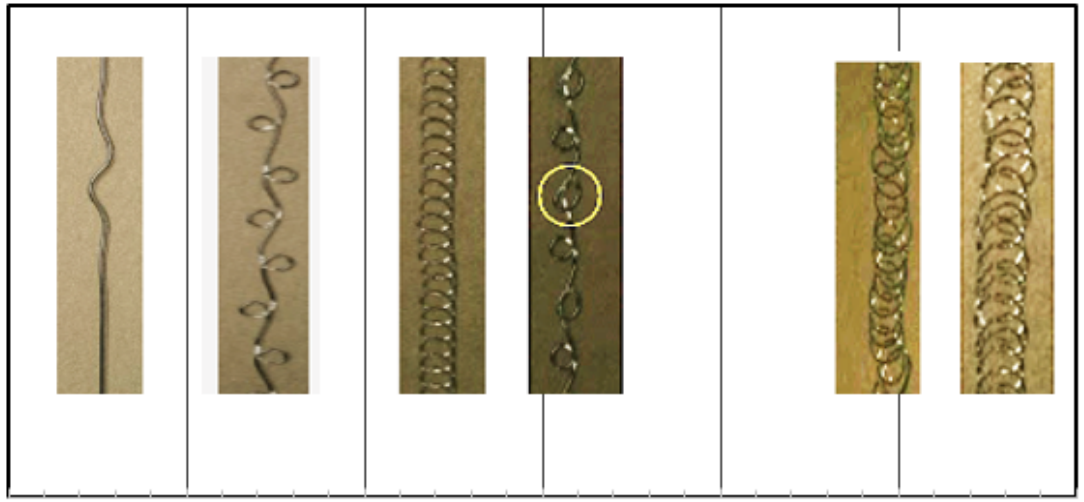
Part 2: Effect Of Printing Parameters On ‘Liquid Rope Coiling : “Line Printing”

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 (<V>) = 0

Print Speed (V) = Inf.



0.0 0.5 1.0 1.5 2.0 2.5 3.0

Flow Rate / Print Speed (mm^2)

0.0 50.0 100.0 150.0 200.0 250.0 300.0

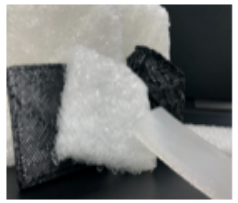
Avg. Velocity / Print Speed

Boundary Conditions 2
- Flow Rate (Q) = inf
- Avg. Velocity (<V>) = inf

Print Speed (V) = 0

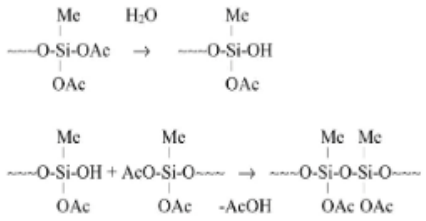
Part 3: Application Of Swam To Prototype Automotive Cushion

Literature Review :



Silicone

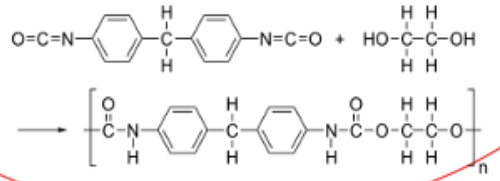
- ✓ Can last for up to 20 years
- ✓ Non-flammable, Does not release toxic fumes when ignited.
- ✖ Release of unpleasant odor when cured (Acetic Acid) .



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



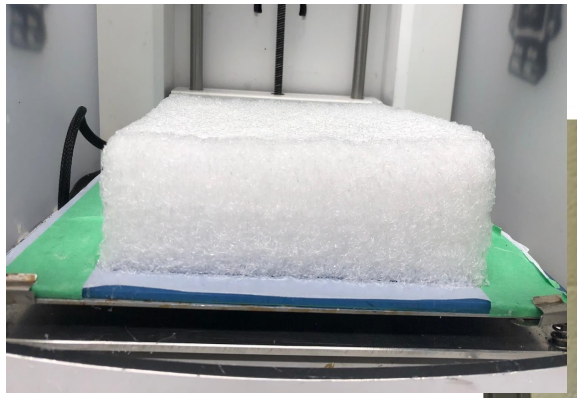
Part 3: Application Of Swam To Prototype Automotive Cushion

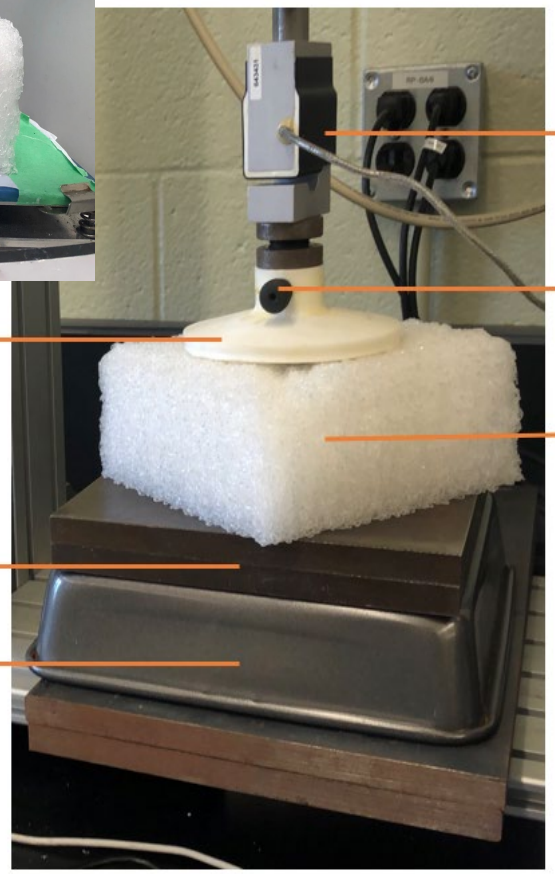
Aim : Printing Variable Density Cushion with Variable Firmness

Methodology :

Specimen	Nozzle Diameter (mm)	Gap Distance (mm)	Flow Rate (ml/min)	Print Speed (mm/s)
Block A	0.84	50	0.8	10
Block B	0.41	75	0.4	10
Block C	0.41	25	0.8	5

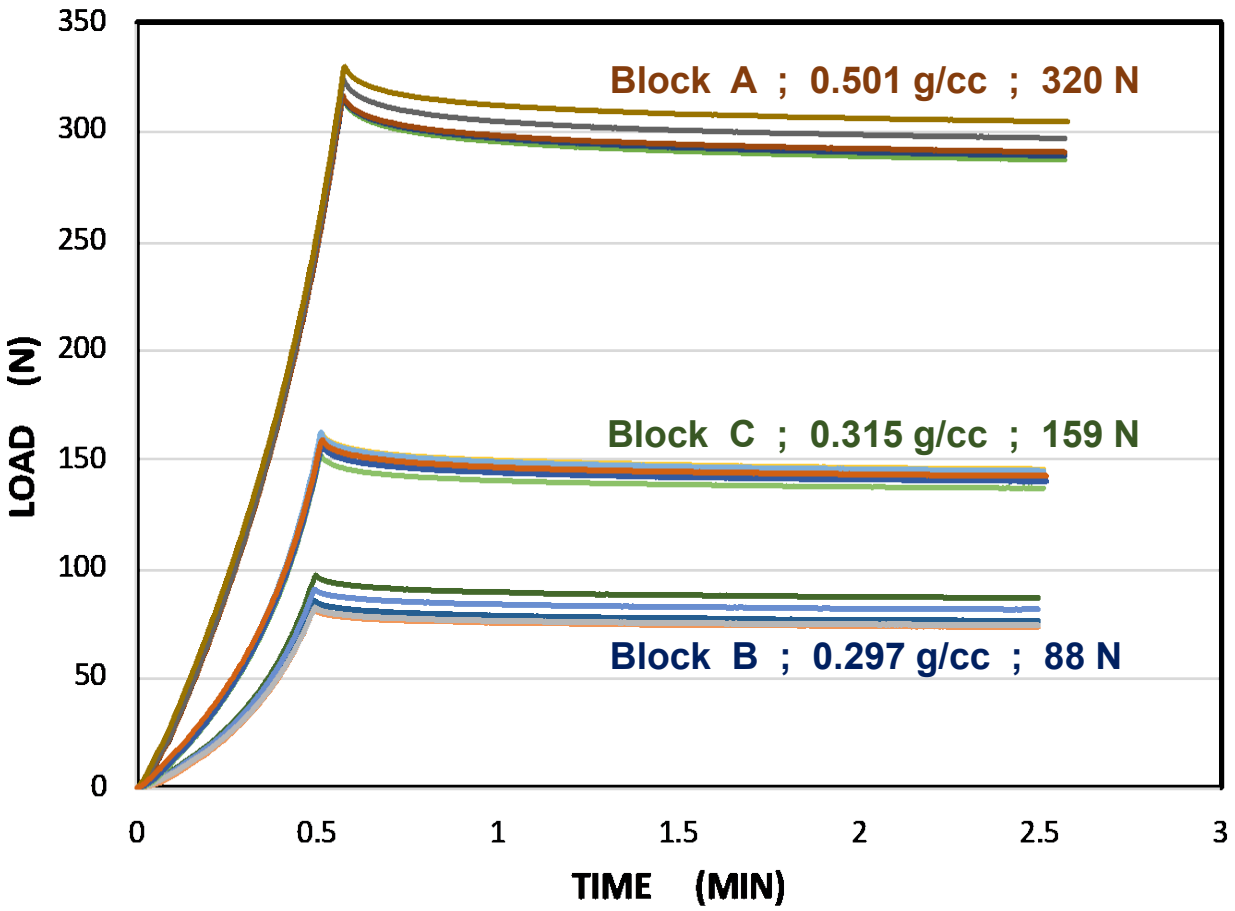
Specimen	Density of Specimen (g/cc)	Average Height (mm)	Max. Force Deflection @ 50% (N)
Block A	0.501	57.69	319.8096
Block B	0.297	51.01	87.9310
Block C	0.315	51.04	158.7312





Part 3: Application Of Swam To Prototype Automotive Cushion

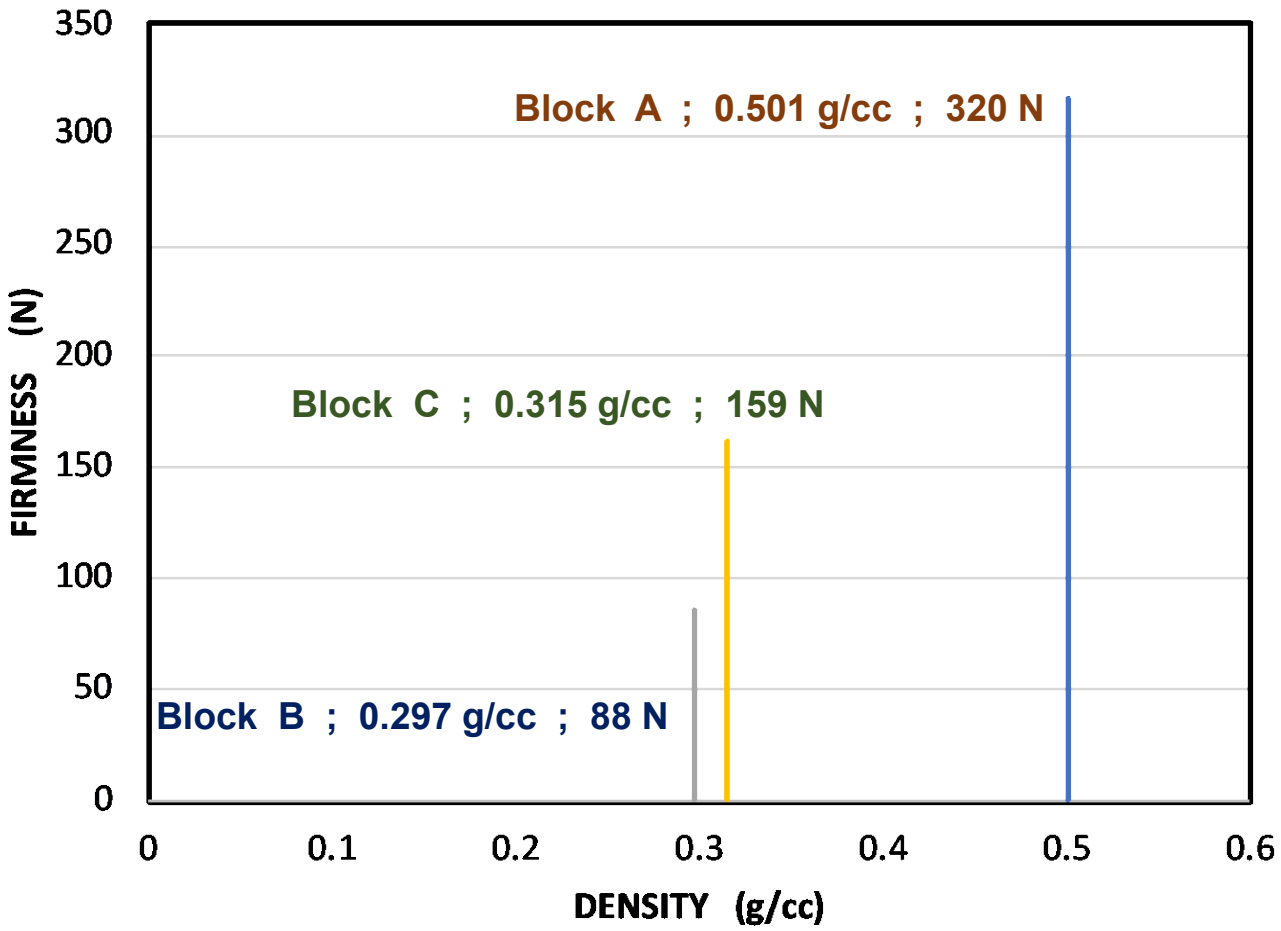
Result :



- Graph : Load (N) v/s Time (min)
  L = fn (t)
- Force applied up to 50% of Specimen Height : Standard ASTM test.
- $L_A > 2 L_C > 3.5 L_B$
- All Blocks reached to their max. Load at same time with variable Density and Firmness.
- Controlled variation in Firmness has been achieved.

Part 3: Application Of Swam To Prototype Automotive Cushion

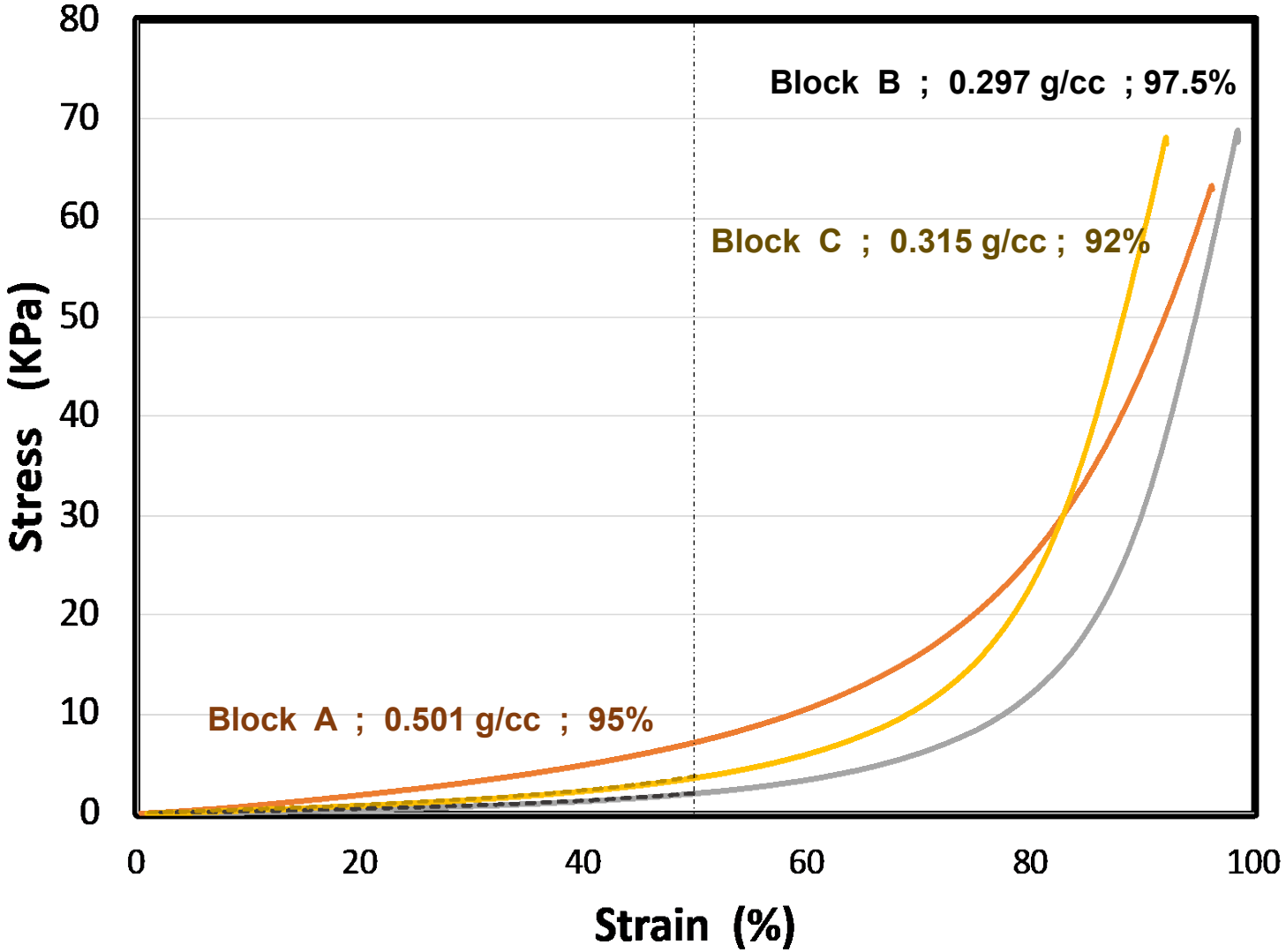
Result :



- 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.)

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 overs the properties of Final Specimen suing Line Printing.
- Fabricated Durable, Light weight and Flexible elastomeric components for Automotive Application, Cushioning.

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