Project 2

MEEN 687: Additive and Subtractive Processes in Custom Manufacturing

Group: Team 2	
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“An Aggie does not lie, cheat, or steal, or tolerate those who do.”

Part I: Extrusion Rate

Part a

Given:

Material: Dragon Skin 10 Silicone Resin
Needle ID: 1.55 mm
Needle OD: 2.10 mm
Needle size: 14 gauge
Needle length: 20 mm
Density, ρ: 1.400282874 g/mm^3
Time, t: 60 s

Table1 : Results of extrusion rate study

Pressure (psig)	Mass (g) in 60 s				
	1	2	3	4	5
30	1.47	1.2	1.28	1.28	1.41
40	7.02	7.31	7.26	8.4	8.49
50	12.48	11.68	10.84	10.4	10.48
60	13.83	13.64	13.93	13.55	13.66
70	14.5	14.54	16.36	15.88	16.05

Solution:

$$Q = \frac{m}{t^{*}\rho}$$

$$V = \frac{Q}{A}$$

Experimental Velocity (mm/s)						
Pressure (psig)	1	2	3	4	5	Average Velocity (mm/s)
30	9.27	7.57	8.07	8.07	8.89	8.38
40	44.28	46.11	45.79	52.99	53.55	48.55
50	78.72	73.68	68.38	65.60	66.11	70.50
60	87.24	86.04	87.87	85.47	86.16	86.56
70	91.46	91.72	103.20	100.17	101.24	97.56

Part b

$$\Delta P = Q\frac{128\eta L}{\pi d^4}$$

$$Q = \frac{\pi \Delta P R^4}{8\eta L} = \frac{\pi \Delta P D^4}{128\eta L}$$

$$Q = AV$$

$$V = \frac{\Delta P d^2}{32\eta L}$$

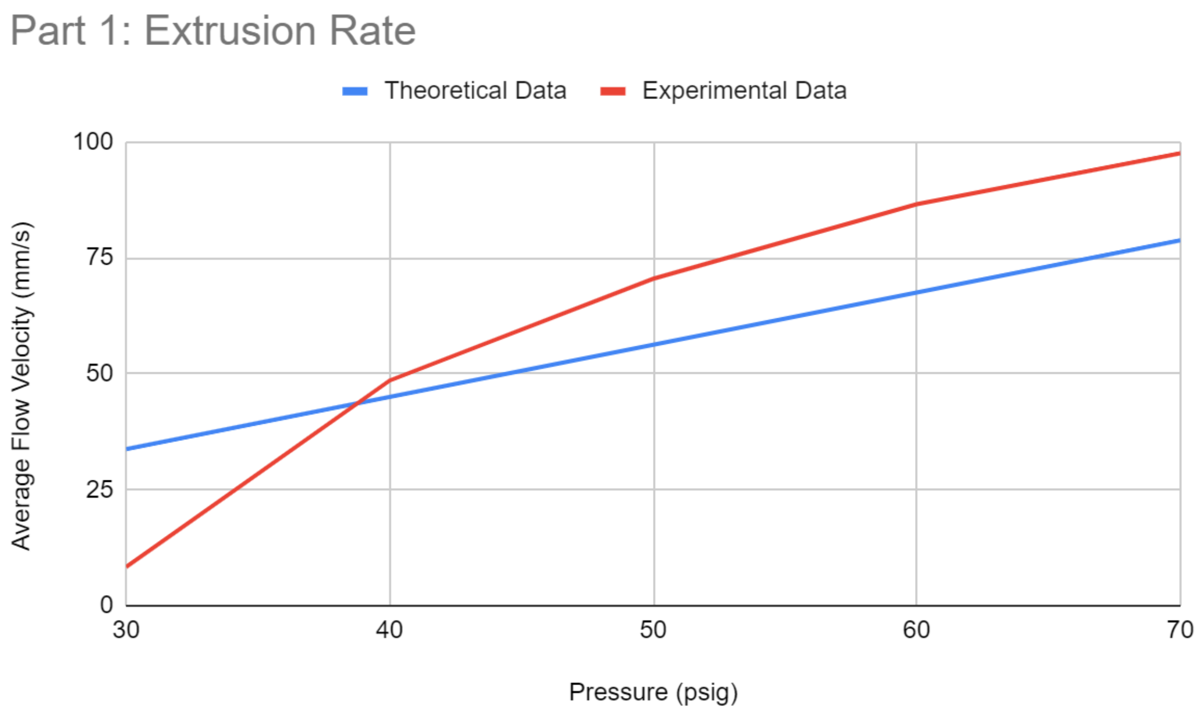

Figure 1: Flow velocity versus Pressure

Part c

A possible reason for the discrepancy between the theoretical and experimental data is because the theoretical equation does not take into account gravity (weight of the printing material) which adds a vertical force that increases the pressure within the printing apparatus (the needle).

Perhaps the biggest reason for the discrepancy, though, is the fact that Dragon Skin 10 is a non-Newtonian material (where the theoretical model assumes Newtonian). This means that the material's viscosity will decrease with increased strain rate. In this experimental setup, the main driving force behind strain rate is pressure. As the pressure increases, the fluid becomes less viscous and can flow more easily, thus increasing its flow velocity. This can be seen in the graph, where the experimental flow velocity quickly overtakes the theoretical one as pressure increases.

Part II: Printing Quality

Part a & b

Calculations

L_W: Width of printing line

d_f: Needle Inner Diameter

V_s: Flow Velocity

P_s: Printing Velocity

$$Volume_{syringe} = Volume_{Printed\ Material}$$

$$A_{needle} * Flow\ Velocity * t = A_{Printed\ Material} * Printing\ Speed * t$$

$$\frac{\pi}{4} d_{Filament}^{\ \ 2} * V_S = \frac{\pi}{4} L_w^{\ 2} * P_S$$

$$L_w = \sqrt{d_f^{\ 2} (\frac{V_s}{P_s})}$$

Table 3 : Results of extrusion rate study

Pressure (psig)	Printing Speed (mm/s)	Experimental Width (mm)
40	28	2.724
40	44.7	2.754
40	53.1	2.284
40	58.7	2.422
40	64.3	2.496
40	69.9	2.158
40	83.9	1.9

Table 4 : Results of extrusion rate study

Velocity (mm/s)	Theoretical Width (mm)
45.01423234	1.965294354
45.01423234	1.555438559
45.01423234	1.427116284
45.01423234	1.357336637
45.01423234	1.296884011
45.01423234	1.243850068
45.01423234	1.135339223

Table 5 : Results of extrusion rate study

Dynamic Viscosity	0.000023 (N/mm^2)*s		
Needle length	20 mm		
Pressure	40 psig	275800	Pa
		0.2758	N/mm^2

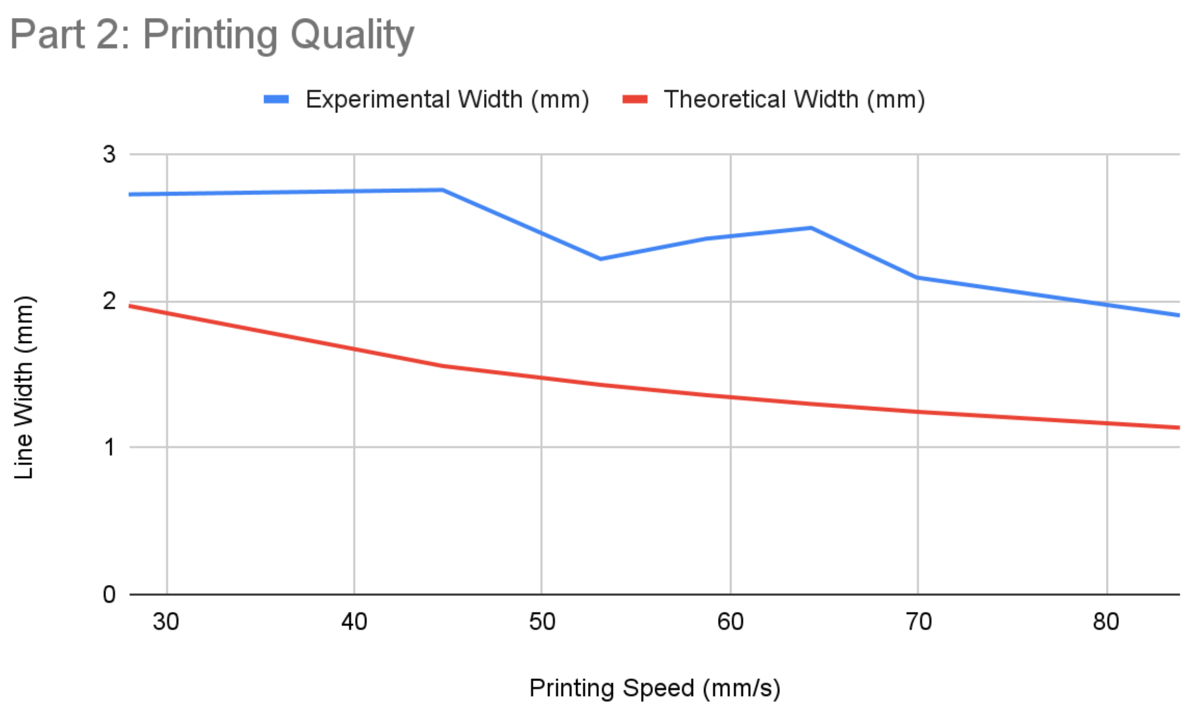

Figure 2: Width (of printed line) versus Printing Velocity

<u>Part c</u>

The discrepancies seen in this experiment might have a number of causes. Perhaps the most important one, as mentioned in Part 1C, is that Dragon Skin 10 Fast is a non-Newtonian fluid and therefore exhibits shear thinning. Since flow velocity here is kept constant, the resin's viscosity will not change (and viscosity is not even a variable involved in the calculation of print width).

However, its viscosity will affect other material properties and print results. For example, being less viscous than expected at higher flow velocities (such as the one here) may lower the adhesion and surface tension on the print bed, resulting in wider prints than expected. It may also lower the cohesion of layers, causing the print to sink down and widen out. This is reinforced by the discrepancy in the data.

Part III: System Design

As opposed to traditional additive manufacturing materials like ABS or PLA, the printability of Dragon Skin 10 Fast is severely affected by its viscosity, curing time, and adhesion (which are all related). To explore this in depth, it is necessary to understand the chemistry behind 3D printing of soft, liquid polymers like Dragon Skin.

This branch of additive manufacturing is known as direct ink writing. For silicone rubbers like Dragon Skin, a mixture of the polymer, a crosslinking agent, and a solvent is held in a syringe and extruded through a fine nozzle or needle to be deposited on the print bed as a continuous line. Additional layers are deposited onto previous ones to produce the desired 3D shape. By itself, the silicone rubber would collapse into an amorphous blob. This is because it is non-reactive to itself, meaning that subsequent layers are unable to chemically bond to each other.

In solid form, silicone rubbers are made up of repeating chains of Si-O-Si bonds, resulting in rubber's characteristic flexible, elastic form. To achieve this solid structure, the Si-O-Si chains must be crosslinked, or held together by covalent bonds in a three-dimensional network. For the purposes of printing liquid, uncrosslinked silicone rubber, this is where the crosslinking agent comes into play. This vital component contains reactive functional groups that produce new covalent bonds and link the polymer chains together. To initiate this reaction, heat, light or a catalyst must be used. It is worth noting that using a crosslinking agent with a higher concentration of reactive functional groups will result in a tougher, stiffer rubber, while one with a lower concentration will result in a softer, more elastic rubber. Interlayer adhesion (and therefore material strength) is determined largely by the degree to which the rubber is crosslinked.

Another critical component in the mixture is the solvent, a volatile organic compound that diffuses the crosslinking agent throughout the polymer mixture and facilitates uniform crosslinking. For the purposes of 3D printing, it also lowers the viscosity of the material and allows it to flow more easily through the nozzle. The solvent ultimately evaporates after the mixture is deposited. Similar to the crosslinking agent, the choice of solvent influences the final product. A more volatile solvent produces a faster crosslinking reaction, reducing the cure time for the rubber to solidify but yielding a less solid final product. In contrast, a less volatile solvent increases the cure time, but allows a slower, more complete crosslinking reaction resulting in a solid, rubbery structure with higher strength and stiffness. [1]

With this chemical framework, how can our custom setup be designed to optimize for 3D printing Dragon Skin 10 Fast? As its name implies, this is the fast-curing variant of the silicone rubber, so a highly volatile solvent must be used. To produce an acceptable rubber product, a crosslinking agent with a high concentration of reactive functional groups must also be employed. In order to catalyze the crosslinking reaction, the extruded material must be held at 100° C at a minimum for the curing process [2]. If Dragon Skin 10 Fast must be used, its interlayer adhesion will never be as good as its slower-curing variants (due to a lesser degree of crosslinking). To mitigate this, the printing speed should be kept low (to whichever point it remains feasible for rapid prototyping) to allow for a uniform, more complete crosslinking reaction.

Contributions

All team members participated in all aspects of the project. We all worked through the project together to familiarize ourselves with the process and concepts. Carlos and Victor took care of the write up & calculations for parts 1, while Luis and Diego focused on the write up & calculations for part 2. As a team, we all worked on the aggregating and collecting the literature review to expand out system design suggestions for part 3.

A. References

"Predicting interracial layer adhesion strength in 3D printable silicone" by Walker, Lingle, Trixler, Wallin, Healy, Menguc, Davidson [1]

https://www.sciencedirect.com/science/article/abs/pii/S2214860421004784

"Calculating the temperature and degree of cross-linking for liquid silicone rubber processing in injection molding" by Weiber, Walz, Schmid, Mayer, Deckert [2]

https://aiche.onlinelibrary.wiley.com/doi/10.1002/amp2.10072#:~:text=Since%20cross%2Dlinking%20takes%20place,the%20kinetic%20modeling%20of%20LSR.