Polymer Extrusion

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Table of Contents

Abstract

In this experiment, the extrusion of high-density polyethylene and cycolac was explored using a single screw extruder with a long (125mm) and small diameter (3.125mm) die. The die & extruder characteristics , which can be defined by the relationship between the wall shear rate and shear stress, was created to describe the apparatus. For polyethylene, the extruder was discovered to have the expected non-Newtonian behavior. While, the cycolac didn't show the expected trend. The viscosity of polyethylene was shown to decrease with increase shear rate. This was due to the non-Newtonian behavior of the fluid. A phenomenon known as shear thinning is the cause of this trend. In addition, the mass flow rate was discovered to increase linearly with increasing screw speed, which was varied from 5-30 rpm. The extrudate swell was also measured against shear rate. The data showed that as shear rate increased the extrudate swell also increased. Lastly, the differential scanning calorimetry (DSC) was used to determine the crystallinity of polyethylene and cycolac. The DSC confirmed the semi-crystalline and amorphous nature of polyethylene and cycolac respectively. The DSC resulted in a 27.7% and 29.2% crystallized polyethylene for the 5 and 10 RPM respectively with a 170 °C melting temperature and a recrystallization temperature of 25 °C. Reheating resulting in a crystallinity increase to 29.9% and 30.6% respectively, this, corresponds to a greater organization of polymer chains after the polymer was allowed to recrystallize.

Introduction

Polymer extrusion is an important industrial process, used when a continuous production of uniform profile is required. A myriad of products are gotten from polymer extrusion. These products are derived by melting thermoplastics and extruding it through a die. The shape of the die determines the shape of the polymer product.

Thermoplastics are commonly used raw materials for polymer extrusion, which include polyethylene, polypropylene, polystyrene, PVC, nylon and polycarbonate. These thermoplastic materials are used in polymer extrusion because they become soft and melt when heated and turn solid when cooled. In return, these materials can form a plethora of products varying from liners and foil to tubing, wiring, and even plastic bags. Sheet extrusion, tubing extrusion, and blown film extrusion are specific types of polymer extrusion processes that are optimized to produce these products [1].

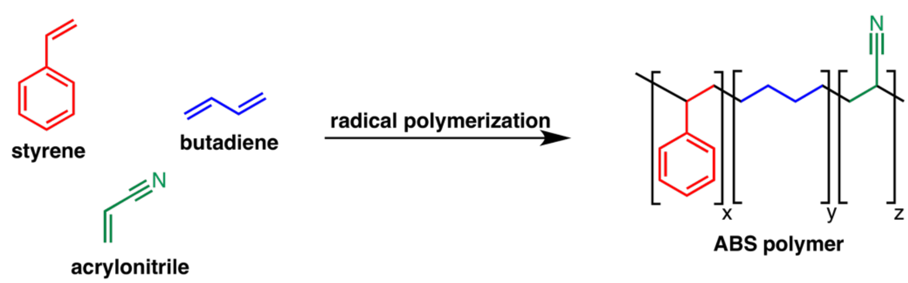

Figure 1: Chemical structure of ABS.

[2]

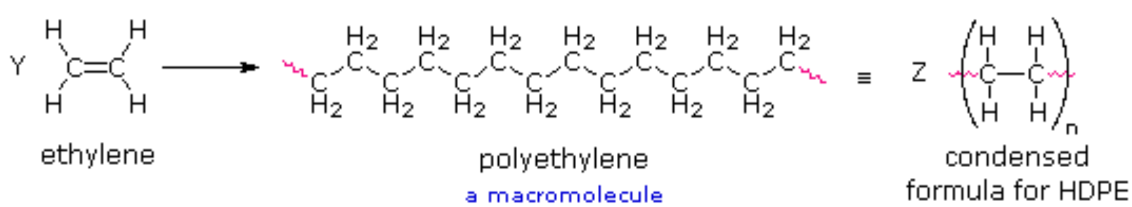

Figure 2:Chemical structure of HDPE

[3]

In this experiment, a single screw extruder was used to extrude Cycolac (ABS) and Marlex 5502BN (HDPE). The research goals for this experiment were to characterize a small circular die while extruding ABS and HDPE through it.

Background

The polymers used in the lab were Marlex brand high-density polyethylene (HDPE) and Cycolac brand acrylonitrile butadiene styrene (ABS). HDPE is a very durable material with excellent stiffness and is widely used from plastic water bottles to pipeline. This polymer has a density of 0.964 g/cm^3 and a melting temperature between 90$°C$ - 140 $°C$ [6]. ABS is resistant to much higher temperatures and gets mechanically stronger over time with high impact strength and stiffness. This polymer has a melting temperature between 190 $°C$. - 250 $°C$ [7]. When heated above the melting point the polymer turns to a liquid which then allows a screw to push it through a die. Once exited the die it is cooled and the polymer chains reform resulting in what is called the extrudate. HDPE is characterised to be a semi-crystalline polymer, while ABS on the other hand, is amorphous.

Shear viscosity of a fluid is the resistance to deformation from stress or resistance to flow [4]. For a Newtonian fluid, shear viscosity is defined as the shear stress divided by the shear rate as described in (1).

$$\boldsymbol{\mu} = (\boldsymbol{\tau}/\gamma) \ (1)$$

where η is the viscosity of the fluid, τ is the shear stress on the fluid, and ɣ is the shear rate applied to the fluid [4]. A unique property about polymeric liquids is the more shear rate is increased the more it deviates from the ideal shear viscosity. For this reason, some polymers must be modelled as non-Newtonian fluids [4]. This introduces a new variable n which shows the deviation of the fluid from Newtonian behaviour. Therefore, when n=1, the fluid is Newtonian, when n>1 the fluid has dilatant behavior, and when n<1, in the case of polymers, the fluid has pseudoplastic behaviour. Dilatant behavior can be characterized by a decrease in viscosity while the shear rate is increasing. Pseudoplastic behaviour can be characterized by an increase in viscosity while the shear rate is increasing. The shear viscosity and shear stress of a non-Newtonian fluid can be described with (2) and (3).[5].

$$\boldsymbol{\mu} = m\gamma^{n-1} \quad (2)$$

$$\tau = m\gamma^{n} \quad (3)$$

For a circular die, as used in the experiment, there are characteristic equations that can be used to calculate shear rate and the shear stress. The relationship between shear rate to radius of pressure drop across the die, ΔP, the length of die, L, and the diameter of the die, D by (4). The relationship of the shear rate to the volumetric flow rate, Q, and the radius of the die, R, by (5).[5].

$$\tau = D\Delta P/4L \quad (4)$$

$$\gamma = 4Q/\boldsymbol{\pi}R^3 \quad (5)$$

These can then be plugged into (1) and the viscosity of the polymeric melt can be calculated.

This, however, is assuming the polymer acts as a Newtonian fluid which it does not. For this reason, the Rabinowitsch correction is need. In the Rabinowitsch correction constant pressure drop is assumed through the die. [5] .Here there is the apparent shear rate, which is the shear rate of a Newtonian fluid, or (5), there is also a corrected shear stress given by (6), which relates apparent shear rate to the unit less correlation b, given by equation (7).

$$\gamma_W = (3+4/b) * \gamma_A \quad (6)$$

$$b = d(\log \gamma_A) / d(\log \tau) \quad (7)$$

This then calls for a new viscosity of the non-newtonian fluid relating the corrected shear stress to the shear rate given by (8).

$$\mu = \tau / \gamma_W \quad (8)$$

With polymer extrusion, there is something known as extrudate swell where after the extrudate exits the end of the die, its diameter increases to bigger than that of the die. This results from residual stress in the polymer as it travels through the extruder. The difference in temperature between the hot polymer exiting the polymer and the outside temperature can affect how much it swells. The extrudate swell related to the extrudate cross sectional area divided by the die cross sectional area is given by (9) [4].

$$Extrudate\ Swell = \frac{Extrudate\ Cross\ Sectional\ Area}{Die\ Cross\ Sectional\ Area} \quad (9)$$

Experimental Procedure

Before the lab session, two trays with polymer were placed in the oven to remove moisture. Zone temperatures were specified in the TRF submitted for every session. For HDPE the benchmark temperature profile was 70ºC, 90ºC, 130ºC, 170ºC, 170ºC for zones 1-3,5,6 respectively. We changed temperatures for zones 2,3,5,6, but zone 1 remained at 70^{o}C as it is below melting point of HDPE and solid polymer in zone 1 pushes on the liquid further in the extruder. Similarly, while performing experiments on cycolac (ABS), we consistently kept zone 1 at 180^{o}C. The extruder was cleaned by the TAs prior to loading polymer in the hopper.

Heated polymer was transferred from the tray into the hopper. Safety gloves were used to avoid skin burns. After extruder zones reached their respective temperatures, the machine was turned on and extruder speed was set to the desired value. We obtained samples at 5, 7, 10, 15, 20, 25, 30 RPM. Conveyor belt speed was set to match the speed of the extrudate by adjusting the dial and visual inspection in order to avoid thinning.

Three samples were taken for each RPM-temperature profile set. Samples were weighed on a scale and their mass was divided by time it took to produce samples to obtain mass flow rate. The diameter of the samples was measured via calipers and divided by the diameter of the circular die to obtain the swell ratio.

To perform DSC crystallinity testing, samples had to be made by punching out 8-12 mg of the desired extrudate using a leather hole puncher while using gloves. The samples were then placed into an aluminum pan with a lid crimped over it. The sample was then placed in the machine in its respective spot and then the machine was turned on. To ensure the sample completely melted in the DSC trials, the machine got to about 10 degrees below the selected temperature, so temperatures about 40-50 degrees above melting point. Taking this into account, for HDPE the temperature was set to start at 20^{o}C go up to 170^{o}C at 20^{o}C/min, then go from 170^{o}C to 25^{o}C at 10^{o}C/min, and finally go from 25^{o}C back up to 170^{o}C at 20^{o}C/min. For cycolac the temperature was set to start at 20^{o}C go up to 315^{o}C at 20^{o}C/min, then it goes down to 25^{o}C at 10^{o}C/min, and finally back up to 315^{o}C at 20^{o}C/min. The DSC testing was performed twice in order to let the polymer recrystallize on its own. This was performed in order to see the true crystallinity of the polymer due to the fact that when the polymer is first extruded it may cool too quickly thus preventing it from crystallizing properly.

Results and Discussion

Crystallinity

The crystallinity of polyethylene marlex 5502 and cycolac(ABS) was investigated. From the literature, it has been stated that polyethylene is a semi-crystalline polymer with a possible range of 25%-85% crystallinity (citation). While, Cycolac has been stated to be an amorphous polymer (citation). As can be seen on table 1, the polyethylene shows that it is a semi-crystalline polymer. In addition, as can be seen the second heating crystallinity is higher that the first, showing the real crystallinity of polymer. Lastly, as can be seen the increase in RPM and in addition torque doesn't affect the crystallinity. In table 1, cycolac can be seen to have an extremely low crystallinity. Therefore, showcasing its amorphous properties.

Table 1: Percent crystallinity of polymers at different temperature profiles and RPMs

Polymer tested	Temperature profile	RPM	First heating crystallinity	Second heating crystallinity
Polyethylene	70/120/150/180/200	5	27.7%	29.5%
Polyethylene	70/120/150/180/200	10	29.2%	30.6%
Cyclonac	180/200/220/250/260	5	3.1%	3.2%

Shear Stress vs. Shear Rate

The die characteristics can be analyzed by a shear stress and shear rate graph. In figure 3, it can be seen that as the shear rate increases the shear stress also increases. As can be seen from figure 3, for polyethylene the relationship of shear stress to shear rate isn't linear. This can be attributed to its non-Newtonian characteristics. This figure indicates that the polyethylene is undergoing "shear thinning" due to its non-Newtonian characteristics. From the figure 3, it can be seen that at increasing temperature the effect of increase shear rate doesn't increase the level of shear stress. This is intuitive because at increase die temperature the fluid will be more easily

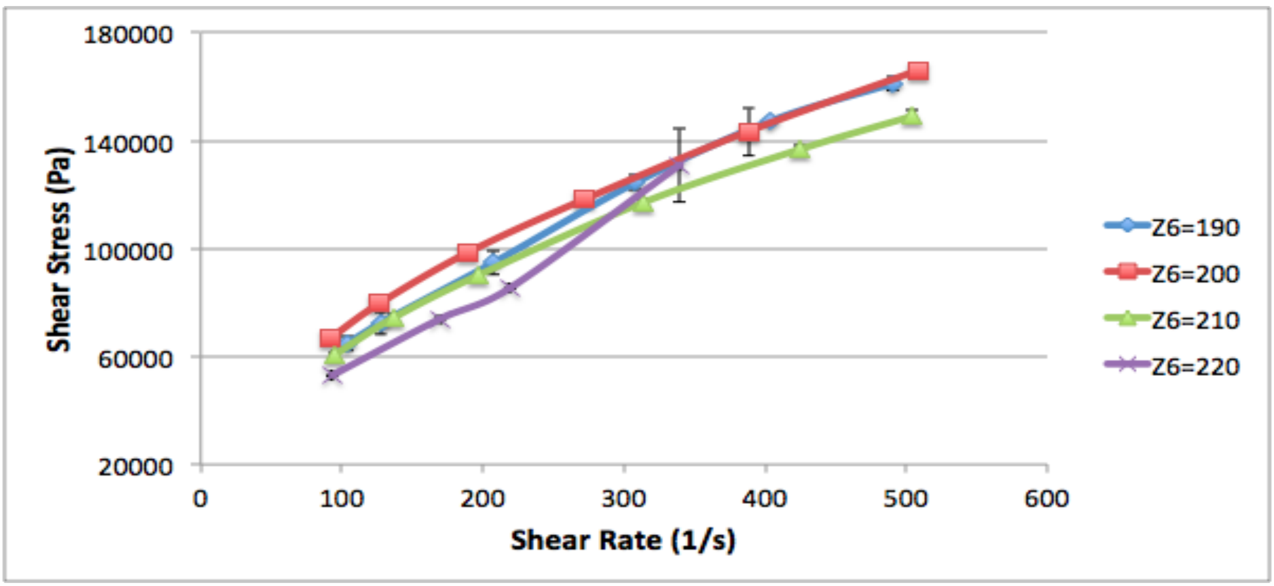

Figure 3: Shear rate vs Shear Stress graph of Polyethylene with zone temperatures :Z1: 70℃, Z2: 100℃, Z3: 140℃, Z5: 180℃ and only zone 6 was varied.

extruded at each shear rate thus inducing less stress. However, figure 4 doesn't show the same for cycolac. This is primarily due to the lack of sufficient data points collected during the course of the experiment.

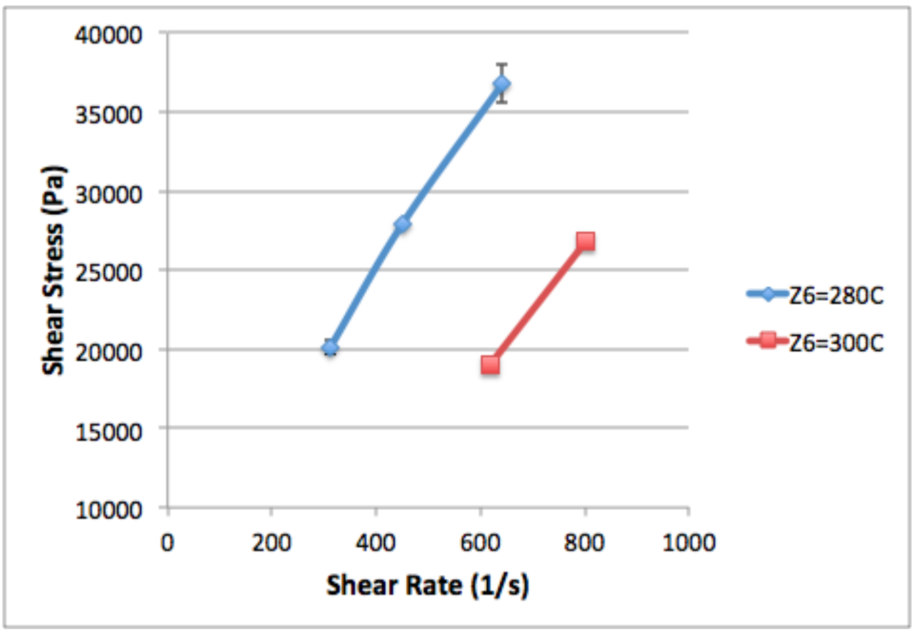

Figure 4: Shear rate vs Shear Stress graph of cycolac with temperature profile Z1: 180°C, Z2: 210°C, Z3: 230°C, Z5: 260°C, with only zone 6 being varied.

<u>Viscosity vs. Shear Rate</u>

For the small circular die the effect of viscosity with increasing shear rate was identified. In figure 5, you can see that as shear rate increases, viscosity decreases for all temperature profiles of polyethylene. This doesn't only align with the expected trend from the literature [8]. This also aligns with the trend from the theory that indicates that a non-Newtonian fluid viscosity decreases with increasing shear rate. This is an effect of "shear thinning" which is to be expected since polyethylene melt is a pseudo plastic fluid.

Cycolac, shown in figure 6, however has conflicting trends with one experimental trial having a positive slope while the other displaying the opposite. This is probably the result of a small experimental screw speed range when extruding the cycolac which prevented the establishment of a concrete trend. With cycolac only trials between 10-20 rpm were experimented with and if this range were widened, then the shear thinning would also be apparent with cycolac.

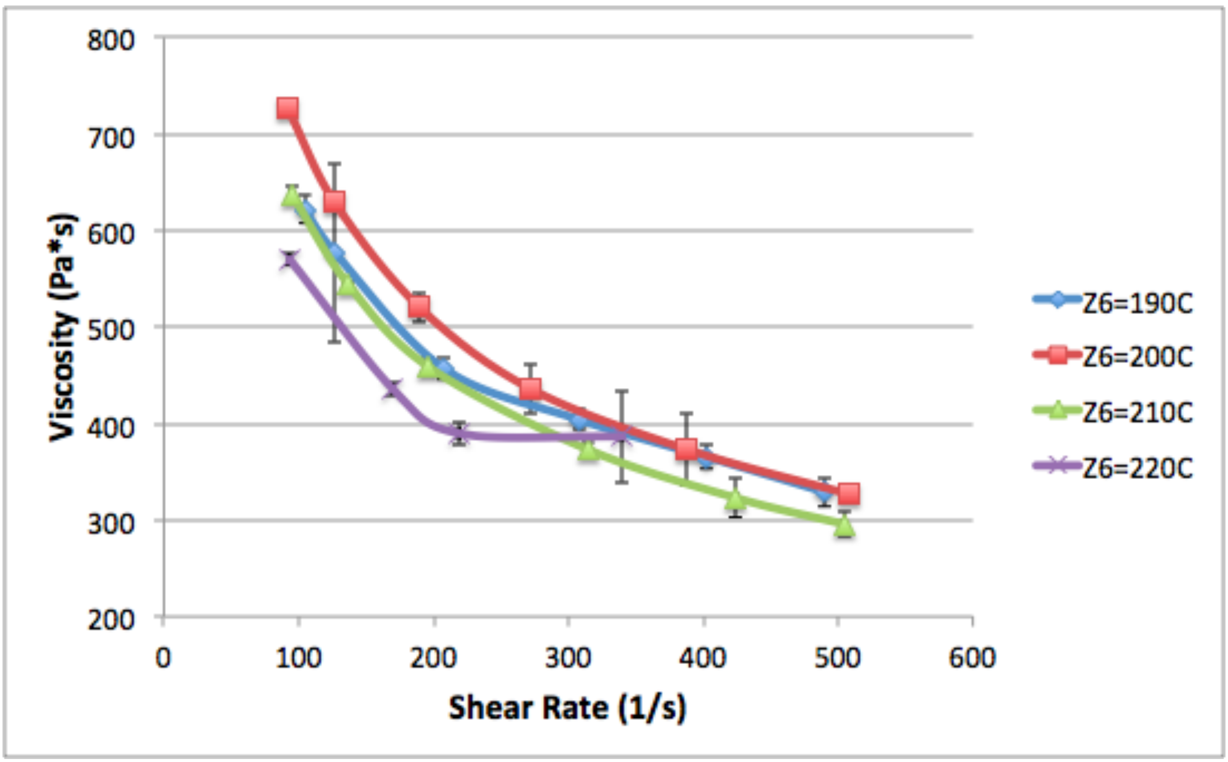

Figure 5: Viscosity vs Shear rate graph of Polyethylene for the following temperature profile: Z1: 70℃, Z2: 100℃, Z3: 140℃, Z5: 180℃, & zone 6 varied

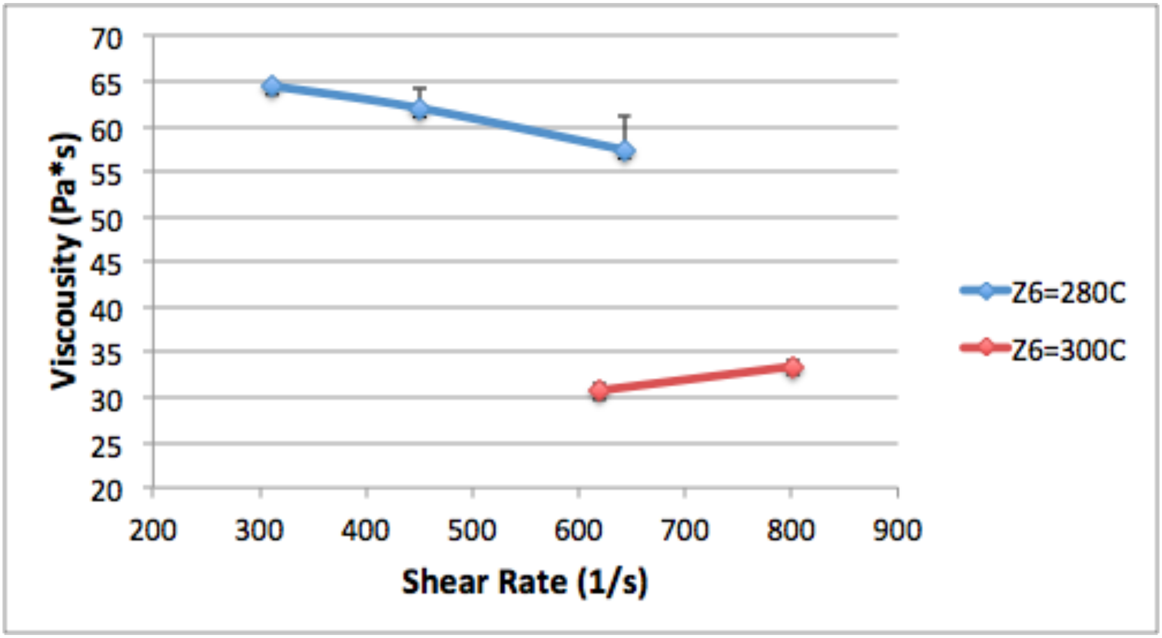

Figure 6: Viscosity vs Shear rate of cycolac for the following temperature profiles Z1: 180oC, Z2: 210oC, Z3: 230oC, Z5: 260oC and Z6 being varied

<u>Mass flowrate vs Screw Speed</u>

As can be seen in figure 7, the mass flowrate increases with increasing screw. This is as a result of more material being able to be pushed out due to the increased screw speed. In addition, even though there may be some slight overlap; it can be seen that at increasing temperatures for the same screw speeds there are higher mass flow rates. This is as a result of decreased viscosity that is expected to decrease, meaning more material can be pushed forward with a single screw turn. The results shown in figure 7, align with the results gotten in the literature; that with increasing screw speed the mass flowrate should increase [8].

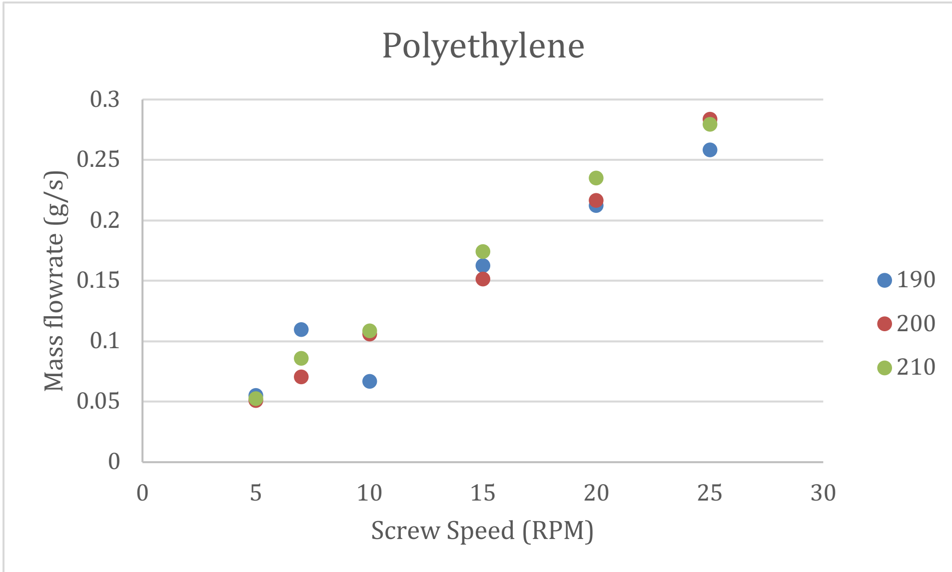

Figure 7: Mass flowrate vs Screw speed for the following temperature profiles : for the following temperature profile: Z1: 70℃, Z2: 100℃, Z3: 140℃, Z5: 180℃, & zone 6 varied

<u>Extrudate swell</u>

The extrudate swell was measured to determine the ratio between the extrudate exiting the apparatus and the diameter of the long die, 3.125 mm. As shown on figure 8, the extrudate ratio showed a trend of increasing ratio with increasing shear rate. This can be result of the shear thinning effect as the shear rate increasing, the viscosity decreases, allowing for the polymer to expand more.

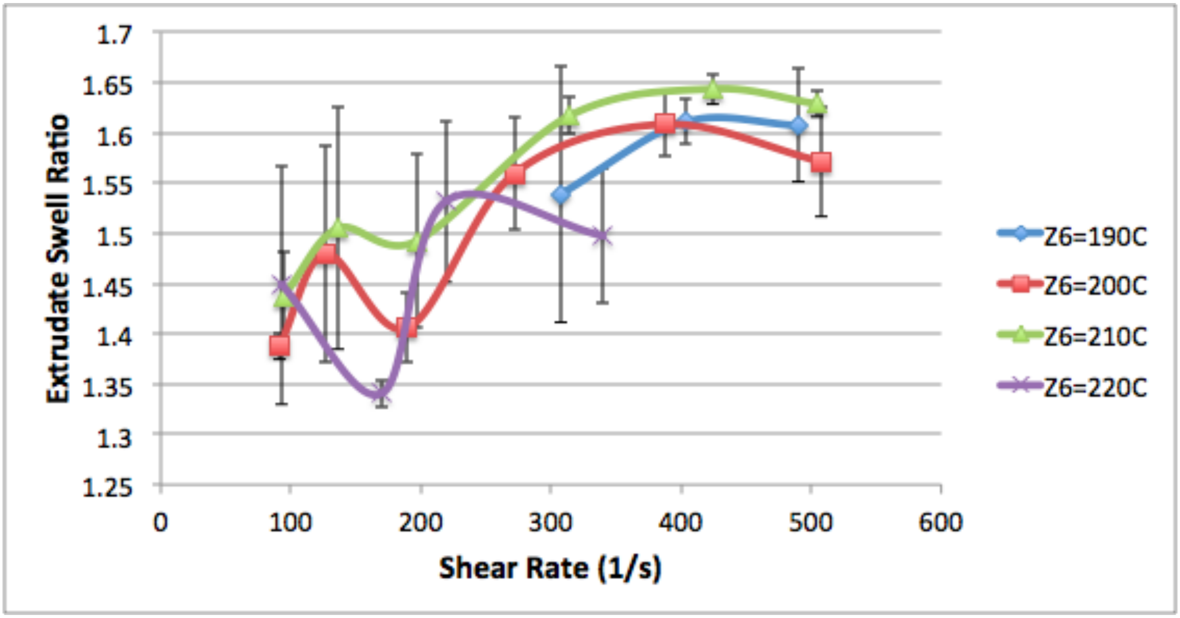

Figure 8: Extrudate swell ratio vs Shear rate for polyethylene for the following temperature profile: Z1: 70℃, Z2: 100℃, Z3: 140℃, Z5: 180℃, & zone 6 varied

Conclusion and Recommendations

The high-density polyethylene marlex 5502 BN and the cycolac resin were successfully extruded from the Haake Rheo Drive using seven increasing extruder heating zone profiles under six increasing screw speed values to evaluate fluid flow and material properties of the processed polymer. The polymers resins used were both analyzed after extrusion to discover their crystallinity with the aid of a differential scanning calorimetry (DSC). The DSC confirmed the semi-crystalline and amorphous nature of polyethylene and cycolac respectively. The DSC resulted in a 27.7% and 29.2% crystallized polyethylene for the 5 and 10 RPM respectively with a 170 °C melting temperature and a recrystallization temperature of 25 °C. Reheating resulting in a crystallinity increase to 29.9% and 30.6% respectively, this, corresponds to a greater organization of polymer chains after the polymer was allowed to recrystallize. The mass flow and thermodynamic data were gathered during the extrusion of samples to generate a shear rate vs shear stress profile. From the figure 3, it can be seen that at increasing temperature the effect of increase shear rate doesn't increase the level of shear stress. For polyethylene, the extruder was shown to have the expected non-Newtonian behavior. While, the cycolac didn't show the expected trend. The viscosity of polyethylene was shown to decrease with increase shear rate. This was due to the non-Newtonian behavior of the fluid. A phenomenon known as shear thinning is the cause of this trend. In addition, the mass flow rate was discovered to increase linearly with increasing screw speed, which was varied from 5-30 rpm. The extrudate swell was also measured against shear rate. The data showed that as shear rate increased the extrudate swell also increased.

I would recommend to future groups to focus their research primarily on cycolac. During this round, the data gotten coincided with what was expected for polyethylene and in addition aligned with what other groups got. However, without sufficient amount of data to be able to make decent graphs, no useful information could be gotten for to characterize the single screw extruder for cycolac.

Word Count - 2450

Notation

ẏ = shear rate (s-1)
η = viscosity (Pa*s)
τ= shear stress (Pa)
L= length of die (m)
R= radius or die(m)
ρ= density (g/cm3)
Q = volumetric flowrate (m^3/s)
ΔP = pressure drop (Pa)
m=consistency index (Pa*sn)
n=deviation from Newtonian behavior

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Appendix

A. Sample Calculations

1. Extrudate Swell

$$Extrudate\ swell = \frac{Diameter\ of\ Polymer}{Diameter\ of\ die}$$

2. Shear Stress

For a capillary die:

$$\tau_w = \frac{R}{2}\left(\frac{\Delta P}{L}\right)$$

Example: R = 0.0022m, L = 0.03m, ΔP = 260psig

$$\tau_w = \frac{0.0022}{2} * 260psig * \frac{6894.76\ Pa}{psig} * \frac{1}{0.03} = 65730\ Pa$$

3. **Apparent Shear Rate**

For a capillary die:

$$\dot{\gamma_a} = \frac{4Q}{\pi R^3}$$

Example: Q = 1.33x10^{-7} m^3/s, R = 0.0022m

$$\gamma_a = \frac{4 * 1.33x10^{-7}}{3.14 * 0.0022^3} = 15.9\ s^{-1}$$

4. **Non-Newtonian Shear Rate**

For a capillary die:

$$\gamma_w = \frac{3n + \dot{1}}{4n}\left(\frac{4Q}{\pi R^3}\right) = \frac{3n+1}{4n}\dot{\gamma_a}$$

Example: n = 0.7, γ_a = 16s^{-1}

$$\gamma_w = \left(\frac{3(0.7) + 1}{4(0.7)}\right)(16)\ =\ 17.714 s^{-1}$$

5. **Viscosity**

$$\eta = \frac{\tau_w}{\dot{\gamma_w}}$$

Example: τ_w =65730 Pa , γ_w = 17.7s^{-1}

$$\eta = (\frac{65730}{17.7})\ = 3700\ Pa * s$$

B. Data Analysis

Excel was used to calculate all values and create all graphs

C. Raw Data

Experimentat Day #1 (01/30/2018)

Temperature Profile Trial #1

Z1	Z2	Z3	Z5	Z6
70	90	130	170	170

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)
3180	2622	5	1.732	60
2870	2800	5	1.837	60
3130	4000	5	2.113	60
6240	8656	10	6.826	60
5556	6601	10	5.643	60
5510	5547	10	5.543	60
4560	6706	7	4.316	60
4340	5888	7	4.05	60
4130	4939	7	3.618	60

Experimentat Day #1 (01/30/2018)

Temperature Profile Trial #2

Z1	Z2	Z3	Z5	Z6
70	100	140	180	180

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)
3260	4530	5	3.302	60
3200	4383	5	2.98	60
3120	4163	5	3.047	60
4700	5049	10	6.428	60
4540	4567	10	5.931	60

4650	5699	10	6.59	60	
3380	4415	7	3.778	60	
3700	4672	7	3.975	60	
3340	3644	7	3.215	60	

Experimental Day #1 (01/30/2018)

Temperature Profile Trial #3

Z1	Z2	Z3	Z5	Z6
70	100	140	180	190

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter
2940	5940	5	3.122	60	
3000	6638	5	3.334	60	
3170	6517	5	3.443	60	
4250	5972	10	6.163	60	
4390	6522	10	6.7	60	
4660	6701	10	6.865	60	
3310	4881	7	3.729	60	
3250	4362	7	4.637	60	
3600	7403	7	3.706	60	
5950	7166	15	1.673	10	4.92
5730	6610	15	1.641	10	4.67
5720	6365	15	1.556	10	4.84
6820	7871	20	2.172	10	5.1
6910	7961	20	2.163	10	4.96
6840	7434	20	2.042	10	5.04
7640	7526	25	2.601	10	5.2
7450	7056	25	2.461	10	4.85
7430	7344	25	2.695	10	5.02

Experimental Day #2 (02/01/2018)
Polymer: Polyethylene Marlex 5502
Temperature Profile Trial #1

Z1	Z2	Z3	Z5	Z6
70	120	150	180	200

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)
3850	4243	5	3.243	60
3710	4290	5	3.359	60
3600	4326	5	3.318	60
4070	2654	10	5.235	60
3800	2654	10	4.536	60
3860	3401	10	5.297	60
3260	3020	7	3.729	60
3200	3051	7	3.778	60
3380	3663	7	4.136	60

Temperature Profile Trial #2

Z1	Z2	Z3	Z5	Z6
70	140	160	200	220

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
3680	4896	10	6.23	60	
3490	4065	10	6.091	60	
3500	4034	10	5.821	60	
2370	3785	5	3.207	60	3.9
2310	3605	5	2.914	60	
2370	3788	5	3.182	60	
2370	3203	7	3.452	60	
2640	3957	7	4.129	60	4.2
2810	4285	7	4.109	60	4.3

Temperature Profile Trial #3

Z1	Z2	Z3	Z5	Z6

70	140	160	200	240

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
1810	1688	14	1.767	30	3.9
2570	2121	14	2.556	30	4.6
2960	2764	14	2.812	30	4.5
2480	1870	10	2.073	30	4
2400	1324	10	2.125	30	4.3
2493	1700	10	1.893	30	4

Experimental Day #3 (02/07/2018)
Polymer: Cycolac

Temperature Profile Trial #1

Z1	Z2	Z3	Z5	Z6
180	200	220	250	260

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
630	679	5	2.868	60	2.6
620	648	5	2.852	60	2.5
610	670	5	2.865	60	2.4
1470	1552	10	8.123	63	3.3
1450	1578	10	3.696	30	3.1
1470	1594	10	4.288	30	3.2
1070	1327	7	2.897	30	3.1
1120	1374	7	2.931	30	3.1
1070	1374	7	2.75	30	3
1930	1724	15	1.876	10	3.55
1940	1744	15	2.004	10	3.56
1950	1724	15	1.844	10	3.61
2170	1990	20	2.28	10	3.15
2170	1938	20	2.819	10	3.05

2190	2042	20	2.772	10	3.12
2590	2345	25	3.363	10	3.18
2590	2314	25	3.453	10	3.17
2570	2397	25	3.273	10	3.27
2810	2607	30	3.966	10	3.07
2800	2559	30	3.855	10	3.16

Temperature Profile Trial #2

Z1	Z2	Z3	Z5	Z6
180	200	220	250	280

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
370	784	5	1.661	30	2.6
350	773	5	1.53	30	2.6
420	873	5	1.75	33	2.6
1010	1411	10	3.896	30	3
990	1536	10	5.309	40	2.2
1020	1599	10	4.49	30	2.3
770	1270	7	3.14	31	2.4
700	846	7	2.803	30	2.4
670	742	7	2.658	30	2.3

Temperature Profile Trial #3

Z1	Z2	Z3	Z5	Z6
180	210	230	260	280

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
940	1359	10	4.115	30	
970	1515	10	4.237	30	
980	1557	10	4.272	30	
1330	1912	15	4.232	20	
1330	1818	15	4.003	20	
1320	1766	15	4.332	22	

1710	2174	20	3.058	10	3
1800	2010	20	2.94	10	2.9
1700	1901	20	2.668	10	3.1

Temperature Profile Trial #4

Z1	Z2	Z3	Z5	Z6
180	210	230	260	300

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
900	1219	15	2.14	10	3.29
910	1447	15	2.133	10	3
930	1510	15	2.117	10	3.02
1270	2006	20	2.698	10	3.03
1260	1959	20	2.765	10	2.96
1290	1918	20	2.812	10	3.08

Experimental Day #4 (02/13/2018)
Polymer: Polyethylene

Z1	Z2	Z3	Z5	Z6
70	100	140	180	200

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
3100	5374	5	1.51	30	4.3
3080	5479	5	1.524	30	4.33
3190	5401	5	1.571	30	4.38
3760	5502	7	2.153	30	4.25
3720	5432	7	2.107	30	4.9
3710	5594	7	2.11	30	4.72
4550	7005	10	3.066	30	4.27
4580	6821	10	3.269	30	4.46
4690	7124	10	3.193	30	4.45
5560	6503	15	1.503	10	5.07

5500	6576	15	1.617	10	4.74
5490	6696	15	1.432	10	4.81
7020	8446	20	2.538	10	4.96
6820	7302	20	2.033	10	5.14
6220	6153	20	1.926	10	4.98
7610	7641	25	2.74	10	5.08
7820	8375	25	2.872	10	4.74
7780	8096	25	2.903	10	4.91

Z1	Z2	Z3	Z5	Z6
70	100	140	180	210

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
2790	8294	5	3.113	60	4.51
2880	8623	5	3.154	60	4.35
2850	8399	5	3.199	60	4.62
3520	8221	7	2.306	30	4.9
3500	7772	7	2.28	30	4.94
3410	7521	7	2.207	30	4.27
4240	9114	10	3.24	30	4.75
4170	9130	10	3.195	30	4.36
4220	8463	10	3.358	30	4.88
5400	7996	15	1.684	10	5.1
5480	8164	15	1.746	10	4.99
5530	8519	15	1.79	10	5.07
6300	7819	20	2.301	10	5.12
6400	8070	20	2.515	10	5.1
6420	7850	20	2.231	10	5.19
6840	6680	25	2.85	10	5.05
7020	7370	25	2.685	10	5.13
6990	7420	25	2.847	10	5.09

Z1	Z2	Z3	Z5	Z6

70	100	140	180	220

Pressure (Psi)	Torque (MG)	RPM	Mass (g)	Time (s)	Diameter (mm)
2490	6400	5	1.353	30	4.17
2500	6462	5	1.357	30	4.91
2470	6290	5	1.37	30	4.5
3470	8623	7	2.46	30	4.17
3450	8023	7	2.53	30	4.16
3470	7630	7	2.48	30	4.24
4000	7417	10	1.067	10	4.96
3980	7300	10	1.039	10	4.5
3980	7300	10	1.103	10	4.9
5790	7757	15	1.719	10	4.86
5700	7270	15	1.638	10	4.45
6850	7041	15	1.626	10	4.73

Safety Assessment Form for Experiments (SAFE)

Chemical Engineering Laboratory
Department of Chemical Engineering
University of Massachusetts Amherst

Process Name	Process Location	Hazard Level **
Polymer Extrusion	GSM 61	1
Written by	**Group Code ***	**Date**
Shuaib, Balogun	D2	01/29/18

Required Non-Standard PPE:

Hard Hat	Gloves (specify type)	Face Shield	Other
NO	heat protecting gloves when handling oven	NO	PPE

Description of Procedure	Potential Hazards	Recommended Safety Procedure	Required Personal Protective Equipment
~~Extrusion~~	Hot Polymer	Handle safely	PPE, thermal gloves
Extrusion	Moving parts	~~keep feet & hands~~ keep hands & feet away	PPE

Safety Awareness

Nearest Fire Extinguisher: By Entrance to room 61
Nearest Eye Wash: by heat exchanger in 61
Nearest Safety Shower: by entrance to room 61
Nearest Emergency Exit: by Entrance to room 61
Nearest First-Aid Kit: by entrance to room 61
Nearest Telephone (Landline): by entrance to room 61
Emergency Shutdown Procedure: Press big red button

Left station in safe state (clean and orderly; chemicals and samples properly labeled or disposed)

Date	Time	TA initials
01/30/18	04:30.	Y.J.
02/01/18	03:52.	Y.J.
02/06/18	04:08	YJ
02/13/18	04:14	Y.J.

* Group letter and number ** For the purpose of this course, highest NFPA rating of chemicals used.