Effect of Processing Parameters on Polypropylene Film Properties

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Abstract *- Thin mono-layer polypropylene (PP) films were produced to study the effects of processing parameters. Main difference in the crystalline structure of the PP films is considered to be caused by the orientation of the crystal blocks. As the temperature increases, film thickness decreases. Screw motor speed (SMS) increase results in increase of film thickness. Increase of winding speed (WS) causes the films to be stretched, making them thinner. As the temperature increases, tear strength of the films increases in MD but decreases in CD. Tear strength increases in CD with increasing SMS. As WS increases, tear strength in MD decreases. As the temperature increases, tensile strength increases in MD. When SMS increases, molecular orientation increases in MD causing tensile strength of the films to increase. Tensile strength decreases with increasing SMS in CD. Increase in WS causes tensile strength of the films to increase in MD and decrease in CD.*

Keywords **-** *Burst strength, polypropylene cast film, tear strength, tensile strength, winding speed*

I. Introduction

Polypropylene (PP) finds various new uses in commercial film applications according to its product properties such as thickness, resistance to tear, tensile and burst, transparency, clarity, gloss and haze. Since PP has high tensile strength and elongation at break, low permeability and good chemical resistance as well as low price, it has been used in various packaging and other specialty applications [1].

The characteristics of cast PP films show differences not only due to their chemical structures and the additives and resin modifiers added but also due to their processing parameters in extrusion process. Therefore, determining the effect of processing parameters and process conditions in cast film extrusion is important to obtain the exact properties of the films for their end uses.

Cast film technology is the simplest technology to produce polymeric films in which the molten polymer is extruded through a slot die, fed by a single-screw extruder, onto a chilled roll in order to be cooled. Then, the solidified film is taken up from the chilled roll by a nip roll (take up roll) and transferred to a winding unit after the edges are trimmed. A limited amount of orientation is obtained in the film by this process; the orientation can be affected by the ratio between the die thickness and film thickness and by the ratio between the extrusion speed and the take up speed. Since the orientation can be easily determined in this method, cast film technology is a low cost and easy-to-handle process.

Temperature, screw motor speed and winding speed are the processing parameters that have effect on cast films. The final molecular orientation in a product depends on the thermomechanical history (melt temperature, stress, strain) of the product during processes [2]. It was reported that lower die temperature reduces the mobility of the chains to be extended at high draw ratios at the die exit [3]. Increasing screw motor speed results in the shear rate increase. At a given melt temperature, the higher the shear rate the higher the shear stress, which results in more molecular orientation in a product [2].

The aim of this study is to determine the effects of processing parameters such as temperature, screw motor speed and winding speed on the physical and structural characteristics and mechanical performance of unmodified and pure PP cast films such as thickness, crystallinity, tear strength, tensile strength and burst strength.

II. Experimental

2.1. Materials and Equipments Used

Polypropylene pellets commercially named as “30 Melt Copolymer Natural” with a density of 0.91 g/cm3 and an MFI of 34 g/10 min were bought from Premier Plastic Resins Company. No modifiers and additives were added while producing the PP cast films.

Wayne single screw extrusion machine having a 15.24 cm cast film die was used to produce polypropylene (PP) cast films in combination with a chill roll and a nip (take up) roll. The die melt was quenched onto a chill roll. The film was taken up through a pair of nip rolls onto a winder.

For tensile testing, Instron 5565 universal testing machine was used, which has 5 kN capacity and 0.001-1000 mm/min speed range. Thickness measurements were done using Testing Machines Inc., (TMI) micrometer. Crystallinity tests were performed on all film samples using a TA Instruments DSC Q-2000 differential scanning calorimetry (DSC).

2.2. Manufacturing and Testing

Twelve PP films were produced by using cast film technology. The machine parameters such as temperature, screw speed and winding speed were changed during production to observe their effects on film final properties. The machine parameters that were changed during the manufacturing process can be seen in Table 1. The barrel temperatures were the same along the barrel from feed end to the die for each sample.

Table 1 Machine parameters changed during manufacturing process of the films

Sample	Temperature (°C)	Screw Motor Speed (RPM)	Winding Speed (m/s)
Film1	190	400	0.1
Film2	205	400	0.1
Film3	215	400	0.1
Film4	220	400	0.1
Film5	225	400	0.1
Film 6	220	300	0.1
Film7	220	500	0.1
Film8	220	600	0.1
Film 9	220	400	0.12
Film 10	220	400	0.13
Film 11	220	400	0.15
Film 12	220	400	0.16

Thickness, tensile, tear and burst strength tests were performed on the samples. The effect of temperature on film thickness, tear, tensile and burst strength was investigated on films 1,2,3,4 and 5; the screw motor speed effect was investigated on films 4, 6, 7 and 8 and the winding speed effect was investigated on films 9, 10, 11 and 12. The tests were performed both in machine direction (MD) and cross direction (CD).

For tensile tests, “ASTM D 882-02 Standard Test Method for Tensile Properties of Thin Plastic Sheeting” test method was used. The nominal width of the specimens was 25.4 mm. The grip separation (gauge length) was 50 mm; the test specimens were 50 mm longer than the grip separation. The rate of grip separation (cross head speed) was 500 mm/min. Five specimens were tested from each sample for the tensile tests [4].

For tear tests, “ASTM D 1938-06 Standard Test Method for Tear-Propagation Resistance (Trouser Tear) of Plastic Film and Thin Sheeting by a Single-Tear Method” was used. The nominal width of the specimens was 25.4 mm; the length of the test specimens was 80 mm. The grip separation (gauge length) was 50 mm. The rate of grip separation was 250 mm/min. Five specimens were tested from each sample for the tear tests [5].

For burst strength tests, “ASTM D 6797-02 Standard Test Method for Bursting Strength of Fabrics Constant-Rate-of-Extension (CRE) Ball Burst Test” was used. The specimens have the dimensions of 125 x 125 mm. The CRE machine was started with a speed of 305 mm/min. and the speed was kept constant till the specimens bursted. Five specimens were tested from each sample for the burst tests [6]. For thickness tests, 10 measurements were taken from each sample. For crystallinity tests, samples were heated from -50 °C to 350 °C at a temperature increase of 10 °C/min.

III. RESULTS AND DISCUSSION

3.1. DSC Analysis and Crystallization

DSC tests were performed on all of the films. Since the melting peaks of all samples did not change much, it was concluded that the change of the crystal thickness was negligible (Fig. 1). Therefore, the main difference in the crystalline structure of the PP films is thought to be caused by the orientation of the crystal blocks [3].

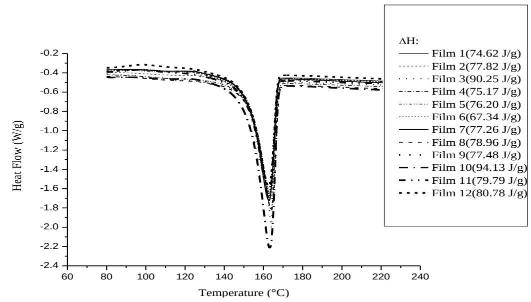

Figure 1 DSC of the PP films (heating rate: 10 °C/min)

Films 1, 2, 3, 4 and 5 were analyzed to examine the effect of temperature on crystallinity. Although the areas under the curves of DSC graphs and ΔH values (a parameter that can be used for defining crystallinity) fluctuate (Fig. 1), they show a slightly increasing trend. As the temperature is increased during PP film production process, the crystallinity of the films increases slightly as shown in Fig. 2.

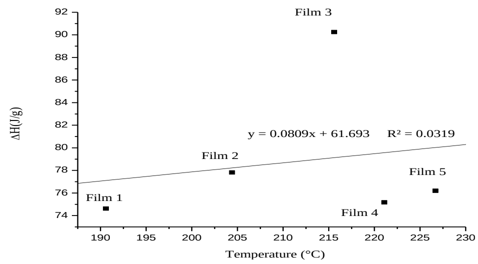

Figure 2 Effect of temperature on crystallinity

Films 4, 6, 7 and 8 were analyzed to examine the effect of screw motor speed on crystallinity (Fig. 3). As the screw motor speed increases, ΔH value increases.

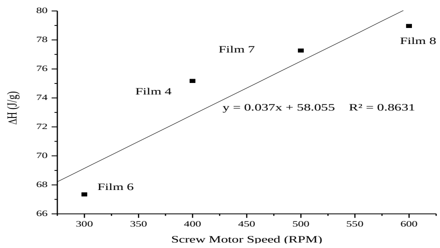

Figure 3 Effect of screw motor speed on crystallinity

Films 9, 10, 11 and 12 were analyzed to examine the effect of winding speed on crystallinity. Although the areas under the curves of DSC graphs and ΔH values fluctuate (Fig. 4), this is not enough to reach a conclusion about the winding speed and crystallinity relation.

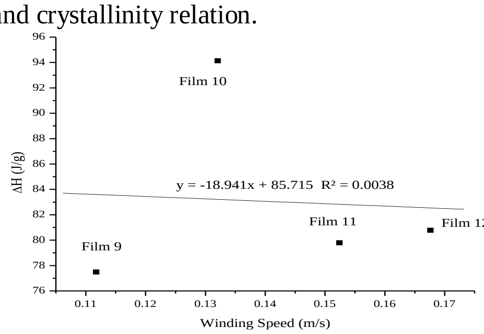

Figure 4 Effect of winding speed on crystallinity

3.2. Thickness Analysis

The results of thickness tests for all of the 12 PP film samples can be seen in Table 2.

Table 2 Thickness test results

Film #	**1**	**2**	**3**	**4**
Thickness (mm)	0.0355	0.0356	0.0321	0.0345
Film #	**5**	**6**	**7**	**8**
Thickness (mm)	0.0356	0.0224	0.0484	0.0522
Film #	**9**	**10**	**11**	**12**
Thickness (mm)	0.0332	0.0267	0.0221	0.0209

One of the extrusion machine parameters in film manufacturing process is temperature. Therefore, thicknesses of the films 1, 2, 3, 4 and 5 were measured to analyze the effect of temperature on thickness (Fig. 5). As the temperature increases, the thickness of the films decreases since the viscosity of the films decreases with increasing temperature.

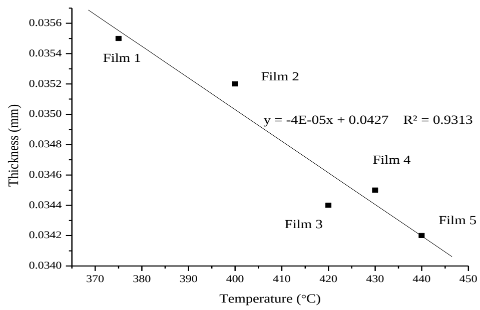

Figure 5 Effect of temperature on film thickness

Another extrusion machine parameter in film manufacturing process is the screw motor speed. Thicknesses of the films 4, 6, 7 and 8 were measured to analyze the effect of screw motor speed on thickness (Fig. 6). As the screw motor speed increases, the thickness of the films also increases since the screw transfers more polymer from the barrel to the die.

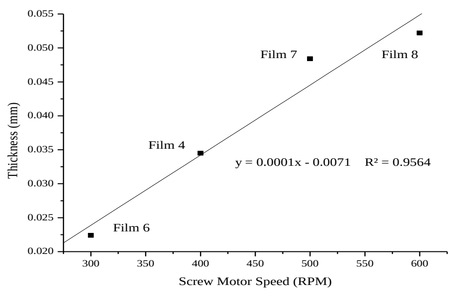

Figure 6 Effect of screw motor speed on film thickness

To analyze the effect of winding speed on thickness, thicknesses of the films 9, 10, 11 and 12 were measured (Fig. 7). As the winding speed increases, the thickness of the films drops since the increase in winding speed stretches the films and makes them thinner.

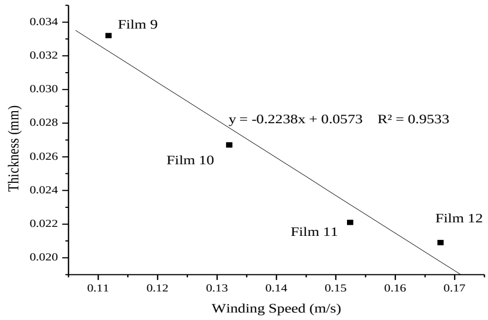

Figure 7 Effect of winding speed on film thickness

3.3. Tear Strength Analysis

Tear strength of the films 1, 2, 3, 4 and 5 were measured to determine the effect of temperature on tear strength (Fig. 8). As the temperature increases, tear strength of the films increases in MD. Since the polymer chains become more oriented in MD as the temperature decreases, tear strength becomes higher with increasing temperature. As the temperature increases, tear strength of the films decreases in CD since the polymer chains are less oriented in MD and less force is needed to tear the polymer chains in CD.

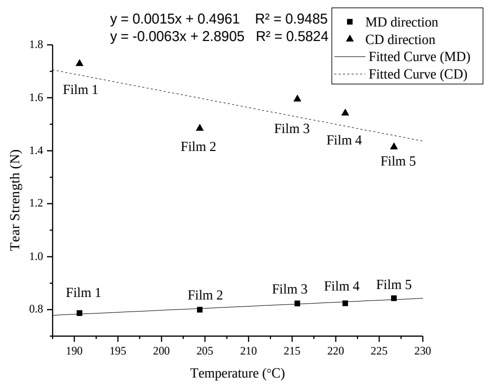

Figure 8 Effect of temperature on tear strength of the films

To analyze the effect of screw motor speed on tear strength, tear strengths of the films 4, 6, 7 and 8 were measured (Fig. 9). Although with increasing screw speed, the tear strength in MD is expected to decrease, the data do not show any specific trend. Therefore, no conclusion can be made from the data obtained. The shear rate increases with increasing screw motor speed. At a given melt temperature, higher shear rate gives higher shear stress, resulting in more molecular orientation in a product. The amount of molecular orientation is proportional to the magnitude of stress. Since the molecular orientation improves in MD, tear strength of the films increases in CD with increasing screw motor speed.

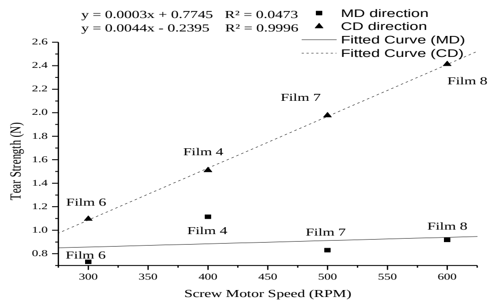

Figure 9 Effect of screw motor speed on tear strength of the films

To analyze the effect of winding speed on tear strength, tear strengths of the films 9, 10, 11 and 12 were measured (Fig. 10). As the winding speed increases, the tear strength of the films drops in MD. The orientation in MD increases due to high draw ratio. Therefore, tear strength in MD decreases with increasing winding speed. Although the tear strength of films is expected to increase in CD with increasing winding speed, the data show no specific trend.

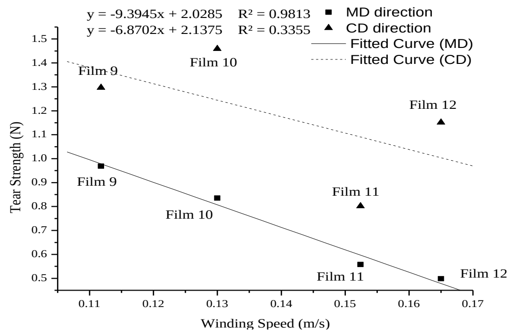

Figure 10 Effect of winding speed on tear strength of the films

3.4. Tensile Strength Analysis

Tensile strength of the films 1, 2, 3, 4 and 5 were measured to determine the effect of temperature on tensile strength (Fig. 11). At a given shear rate, lower melt temperature gives higher viscosity, resulting in higher shear rate. Lower melt temperature or higher shear rate gives rise to higher shear stress, resulting in more molecular orientation in MD. Therefore, as the molecular orientation increases due to lower temperatures, tensile strength increases. However, from Fig. 11, it can be seen that as the temperature increases, tensile strength increases both in MD and CD.

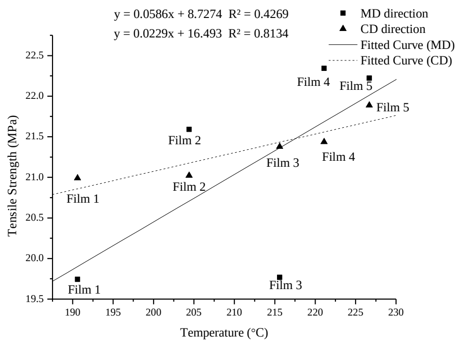

Figure 11 Effect of temperature on tensile strength of the films

To analyze the effect of screw motor speed on tensile strength, tensile strengths of the films 4, 6, 7 and 8 were measured (Fig. 12). The shear rate increases with increasing screw motor speed. At a given melt temperature, higher shear rate gives higher shear stress, resulting in more molecular orientation in a product. Since the molecular orientation increases in MD, the tensile strength of the films increases in MD. Tensile strength of the films decreases with increasing screw motor speed in CD because of the orientation in MD.

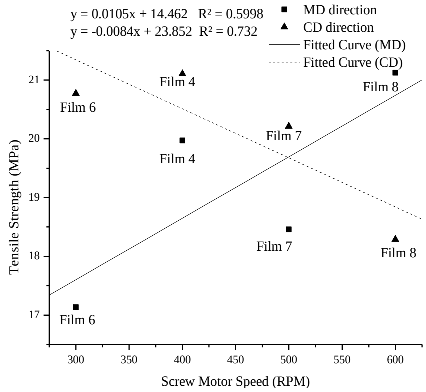

Figure 12 Effect of screw motor speed on tensile strength of the films

To analyze the effect of winding speed on tensile strength, tensile strengths of the films 9, 10, 11 and 12 were measured (Fig. 13). As the winding speed increases, the tensile strength of the films increases in MD since the orientation in MD improves due to the increasing draw ratio. The tensile strength of films decreases in CD with increasing winding speed due to the orientation increase in MD.

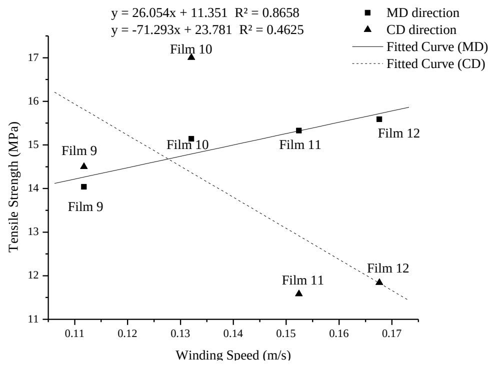

Figure 13 Effect of winding speed on tensile strength of the films

3.5. Burst Strength Analysis

During the burst strength tests, only Film 6 bursted. The tests were done by using Instron universal testing machine and there was not enough space in the machine's bursting strength equipment for highly stretchable films to extend. The graphs of the other 11 films did not show any decreasing trend at 45 mm extension. This means that the graphs obtained did not have their maximum loads since they have an increasing trend. Therefore, the burst strength values, stress at the maximum load, could not be obtained for the other 11 films.

As it is seen in Fig. 14, the graphs of all of the films show a similar trend. For the same extension value, 45 mm, Film 11 gives the lowest load value (not considering Film 6) while Film 8 gives the highest load value.

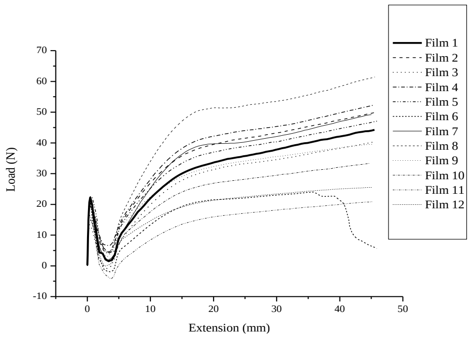

Figure 14 Burst strength of the films

The films exhibit early load peaks at the extension of nearly 0.4-0.8 mm range, but then their load values begin to decrease as the extension increases. The load values begin to increase from the extension range of 3.2-4.2 mm to the extension 45 mm.

IV. CONCLUSIONS

In this work, twelve different PP cast films were manufactured and analyzed to find the effects of machine parameters such as temperature, screw speed and winding speed on film properties such as crystallinity, thickness, tear strength, tensile strength and burst strength. These analyses were done in MD and CD directions for tear and tensile strength.

From the DSC analysis it was found that the position of the melting peak did not have a significant change. Because of this, it was assumed that the crystal thickness change was negligible. Therefore, the main difference in the crystalline structure of the PP films is considered to be caused by the orientation of the crystal blocks.

The thickness analysis was done by considering temperature, screw motor speed and winding speed. It was found that when the temperature increases, the thickness of the films decreases since the viscosity of the films decreases with increasing temperature. As the screw motor speed increases, the screw transfers more polymer from the barrel to the die which results in increase of film thickness. Increase of winding speed causes the films to be stretched, making them thinner.

Since the polymer chains become less oriented in MD as the temperature increases, tear strength becomes higher with increasing temperature. When the temperature increases, tear strength of the films decreases in CD since the polymer chains are less oriented in MD and less force is needed to tear the polymer chains in CD. Although it is expected that increasing screw speed decreases the tear strength in MD, tear strength of the films does not show any specific trend as the screw motor speed increases; as a result no conclusions can be made from the data obtained. Tear strength of the films increases in CD with increasing screw motor speed because the molecular orientation increases in MD. When the winding speed increases, the tear strength of the films decreases in MD because the orientation in MD increases due to high draw ratio. Therefore, when winding speed increases, tear strength in MD decreases. Although the tear strength of films should increase in CD with increasing winding speed, the data show no specific trend.

When the molecular orientation increases because of lower temperatures, tensile strength should increase according to the literature. However in this work, as the temperature increased, tensile strength increased in MD. When screw motor speed increases, the shear rate also increases. At a given melt temperature, higher shear rate gives higher shear stress which causes higher molecular orientation in the product. Molecular orientation increase in MD causes the tensile strength of the films to increase. Tensile strength of the films decreases with increasing screw motor speed in CD due to the orientation in MD. Increase in winding speed causes the tensile strength of the films to increase in MD since the orientation in MD increases because of the increasing draw ratio. The tensile strength of films decreases in CD with increasing winding speed because of the orientation increase in MD.

Except Film 6, the films did not burst in burst strength tests. Therefore, burst stress at the maximum load could not be obtained for the other 11 films.

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