EXPERIMENTAL INVESTIGATION OF PET AND PP FILM CASTING

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Abstract

In film casting, a polymer melt is extruded through a die before rapid cooling on a chill roll. The process stretches the material and induces some orientation in the film. In this paper, we study experimentally the effects of processing variables such as the draw ratio and the die temperature on film formation. The temperature, width and velocity profiles in the air gap are measured for films produced using polypropylene and polyethylene terephthalate.

Introduction

Film casting is an important industrial method for film production. In film casting a polymer melt is extruded through an approximately flat die and stretched in the region between the die and a chill roll (see Figure 1). This stretching induces some orientation in the film and causes a decrease in the width (neck-in) and the thickness of the film in the region between the die and the chill roll. After the film is cooled on the chill roll, it is subjected to secondary processing steps, which generally include biaxial stretching, depending on its final intended application. The success of the secondary processing steps depends on the quality of the primary film formed in the region between the die and the chill roll.

An important process parameter is the draw ratio, which is the ratio of the velocity at the chill roll to the velocity at the die exit (1). Increasing the draw ratio increases the amount of neck-in between the die and the chill roll and also leads to a decrease in the thickness of the film. The distance between the die and the chill roll (air-gap) also affects film formation since changing the air-gap length changes the flow geometry (increasing the neck-in) and the strain rate experienced by the polymer in the web. This results in variations in the width, the temperature profiles and the polymer orientation for any particular set of process conditions.

In addition to the process parameters, the characteristics of the material being processed influence the film properties. Changes in the polymer type, polymer molecular weight, and the shear and the extensional viscosity of the polymer will also affect both the film formation in the gap between the die and the chill roll and the final properties of the film.

Some problems typically encountered experimentally in film casting are edge-bead formation and draw resonance (1). Edge-bead formation results in the edges of the final film being thicker than the central portions of the film. The film edges are usually trimmed off before further processing of the film and the material is recycled. Draw resonance is an instability whereby there is a periodic variation in the film neck-in. This occurs at high draw ratios and places a limit on the draw ratio for a particular film casting operation. The draw ratio at which this instability sets in depends on the polymer material.

A primary goal in film process modeling is the development of a model that can predict the velocity field, the geometry of the film and the polymer orientation in the film in the gap between the die and the chill roll. Obtaining a valid numerical solution is complicated by the fact that the film casting process is non-isothermal, extension dominated and three-dimensional. In addition, an appropriate constitutive equation for the polymer must be chosen. In developing and evaluating these models, it is critical to acquire experimental data in order to verify the numerical predictions.

Most previous work in this field has focused on understanding the cast film process from a theoretical perspective. These studies have been geared towards developing models that predict the film formation process in the web. The models employed range from isothermal Newtonian models (1,2) to models that allow for non-isothermal conditions and/or viscoelasticity (3-5). Silagy et al. (1) were able to predict edge beads using an isothermal Newtonian membrane model. Yeow (2) uses an isothermal Newtonian model to study the stability of the film casting process. The model by Alaie and Papanastasiou (3) predicts temperature variation in the web but only in the machine direction since the model assumes that temperature is invariant over the film cross-section. More recently, effort has been focused on studying the process from an experimental point of view. Canning et al. (6)

studied film tension, velocity and width profile for a low-density polyethylene melt while Lamberti et al. (7,8) conducted studies on film crystallinity and orientation as a function of draw ratio. They found that increasing the draw ratio increases polymer orientation. Acierno et al. (9) also studied the temperature profiles for the film casting of PET. They found that increasing the air-gap length reduces the film temperature at the chill roll and that the central portions of the film cool more rapidly than the film edges.

This work is part of an on-going project aimed at understanding the effect of polymer properties and experimental conditions on the film casting process. Our goal is to completely understand the film geometry, flow field and polymer orientation. Specifically, in this paper we investigate the effects of both process parameters and material parameters on the cast film process. We focus on the impact of the draw ratio and the die temperature on the velocity, the width and the temperature profiles in the web. Results from experiments performed using both polypropylene (PP) and polyethylene terephthalate (PET) are presented.

Experimental

The materials used for the experiments are a PET sample with a T_m = 240°C and a PP sample with a T_m = 160°C. Rheological characterization of the materials was performed using a TA Instruments ARES cone and plate rheometer. Figure 2 shows the storage modulus G', the loss modulus G" and the complex viscosity η^* for PP at temperatures of 180°C and 210°C. As expected, increasing the temperature decreases the polymer complex viscosity and also affects the storage and loss moduli. Thus, it should be noted that the die temperature, and the changes in temperature as the polymer web approaches the chill roll, will have a significant effect on the film formation process between the die and the chill roll. Over the 30°C variation in temperature (which lies within that observed in the cast film web) there is a change in viscosity from approximately 200 Pa-s to 600 Pa-s. Figure 3 shows similar results for the PET at 270°C. Shear thinning in the complex viscosity curve for the PET is not as pronounced as that for PP. This may indicate that certain approximations made during model development (e.g., Newtonian approximation) may be more suitable for PET, although the extensional properties have not yet been measured. The rheological data is also important for modeling in that it facilitates the selection of constitutive equations and model parameters used for modeling the film casting process. Some previous investigators have found that the rheological data obtained for the extrudate gives better modeling results than rheological data obtained from the original polymer resin (4).

A laboratory scale cast film line was constructed for the Center for Advanced Engineering Fibers and Films (CAEFF) at Clemson University. A lab scale extruder with a 25mm screw and a 10.16 cm x 0.1 cm slit die is used. The chill roll is 30 cm wide with a diameter of 19.95cm. The gap between the die and the chill roll can be varied, although in this work an air-gap separation of 8 cm is used for the casting experiments. Typical air-gap lengths used in industry are generally much smaller than we employ here. However, our future work includes employing smaller air-gap lengths and the current dimensions allow velocity and temperature measurements to be made over a wide range of positions. The die temperature as well as the die throughput and the chill roll velocity are controlled by a computer. Thus, process variables such as the draw ratio and die temperature can be systematically varied and investigated. For the work discussed in this paper, the mass flow rates are maintained at 0.36 g/s for polypropylene and 0.48 g/s for the polyester. The draw ratio is then varied by varying the chill roll speed.

For the experimental measurements of the film properties and characteristics, instruments were mounted on a tripod equipped with translation stages to probe the entire web. Laser Doppler velocimetry (BETA LaserMike) was used to measure the velocity field in the web as a function of position in both the machine direction (MD) and the transverse direction (TD). A 1% w/w seeding of glass beads was used to provide scattering centers. Temperature profiles were determined by infrared thermography using a MIKRON infrared camera. The film neck-in as a function of position from the die and of processing conditions was measured using a digital camera.

Results and Discussion

In Figure 4, centerline temperature profiles are shown for PET at four different draw ratios. The die temperature is maintained at 280°C. The draw ratio is varied from 5.4 to 10.6. It is seen that the film temperature at the chill roll decreases with increasing draw ratio. Thus, the film cools more rapidly in the gap as the draw ratio is increased. This trend is expected since increasing the draw ratio for a given mass throughput causes increased neck-in and a reduction in film thickness due to arguments of mass conservation. This effect of draw ratio on film temperature at the chill roll was also reported in the work by Acierno et al. (9) for PET film casting.

Figure 5 shows transverse temperature profiles (as a function of distance from the die) for a film casting experiment using the PP conducted with a draw ratio of 6.4 and die temperature of 210°C. It is seen that the temperature profiles start out flat at the die but as the chill roll is approached, there is a local minimum in temperature at the center of the film. The profile indicates that central portion of the film cools at a faster rate than the film edges as the chill roll is approached. The temperature in the web is sometimes assumed to vary only in the machine direction in order to simplify models (3) but the temperature profiles shown in Figure 5 indicate that temperature in the web also varies in the transverse direction.

Figure 6 shows the width profiles for film casting of PP at a draw ratio of 6.4 and die temperatures of 240°C and 210°C. The width profiles show that increasing the die temperature causes an increase in neck-in of the film. An explanation comes from Figure 2, where it is shown that temperature has an effect on the rheology of the polymer, and an assertion by Smith and Stolle (5). In their work, they state that there is an interaction between the edge bead effect and degree of neck-in. They note that the amount of restriction imposed by the edge beads on the central portion of the film affects the degree of neck-in obtained at a given draw ratio. That increased restriction results in reduced neck-in. Further, the amount of restriction depends on the viscosity of the polymer and that increased restriction results from increased viscosity. Thus, it should be expected that increasing the die temperature will result in increased neck-in due to the reduced viscosity of the polymer.

Figure 7 shows the velocity field as a function of position for the polypropylene film with a die temperature of 220°C and DR = 11. The transverse velocity profiles as a function of distance from the die are shown. The velocity profiles show that lower velocities are obtained at the film edges than in the central portions of the film. This may be because of the thickness variation (and viscosity variations) in the web resulting from edge-bead formation. A similar trend was also observed by Satoh et al. (4). They placed tracers on the film surface near the die exit and observed the progress of the tracers from the die to the chill roll, using a digital video camera.

The velocity along the film centerline is shown in Figure 8 for polypropylene at a die temperature of 220°C and for two different draw ratios: DR = 11 and DR = 16. Values for velocity at the die exit and chill roll are calculated from the mass flow rate and chill roll speed. The velocity increases with increasing distance from the die. In addition, it is observed that the strain rate increases with increasing distance from the die and increases more rapidly as the draw ratio is increased. This trend was reported in the work by Canning at al. (6) on film casting of a low-density polyethylene melt. Near the chill roll, the velocity profile appears to show a decrease in strain rate as the polymer approaches the die.

Conclusions

Film casting experiments were conducted for polypropylene and polyethylene terephthalate in order to investigate the film response to changes in the draw ratio and the die temperature. The velocity, width and temperature profiles in the region between die and chill roll were measured as a function of position within the web. Increasing the die temperature causes an increase in neck-in, at a constant draw ratio. This is expected since temperature significantly affects the rheological behavior of polymers. Draw ratio has an effect on the velocity and temperature profiles. For the centerline velocity profile, increasing the draw ratio causes the strain rate in the web to increase more rapidly. The strain rate increases from the die to the chill roll. Transverse velocity profiles show higher velocities in the central portions of the film than at the film edges. Centerline temperature profiles show that the film cools more rapidly as the draw ratio is increased. The film temperature at the chill roll decreases with increasing draw ratio. Transverse temperature profiles indicate that the central portion of the film cools more rapidly than the film edges.

Acknowledgement

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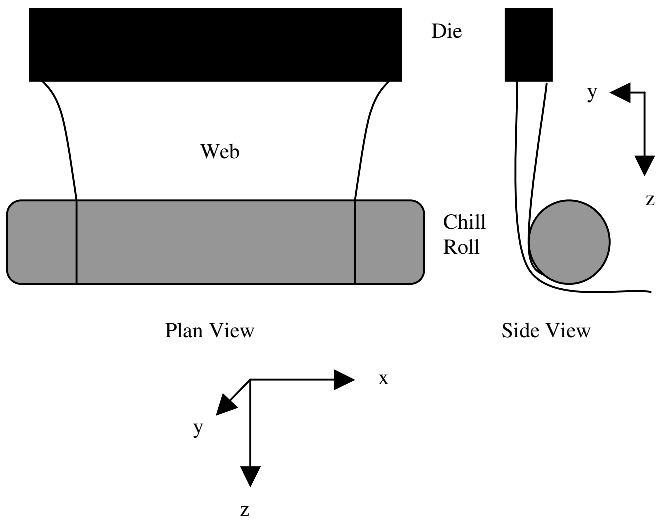

Fig. 1. Film casting Schematic

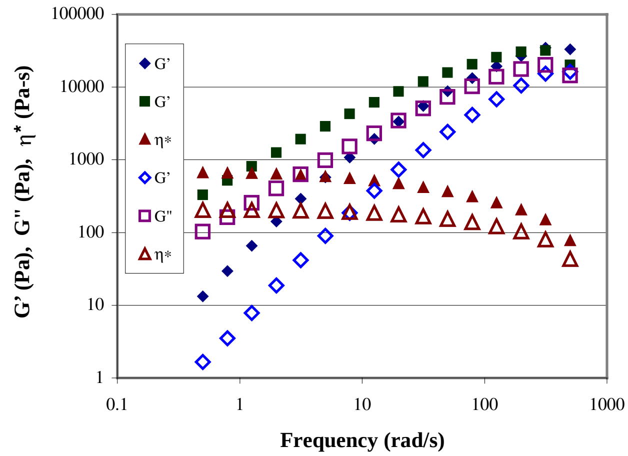

Fig. 2. Dynamic rheology properties for Polypropylene. Filled symbols are T= 180°C and blank symbols are T= 210°C.

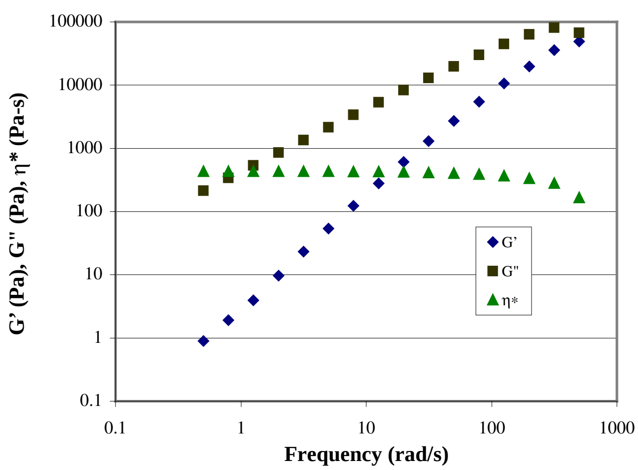

Fig. 3. Dynamic rheology properties for Polyethylene terephthalate at 270°C.

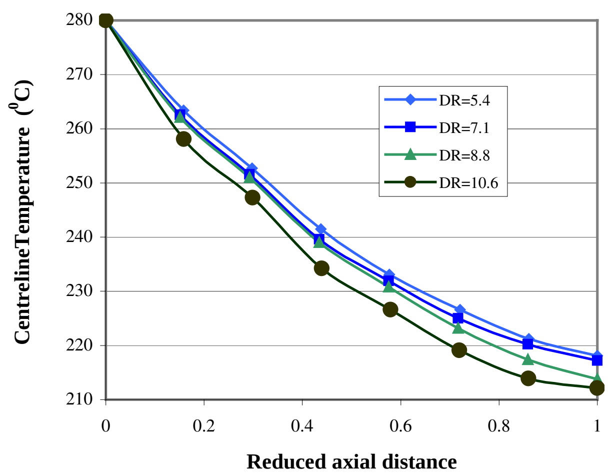

Fig. 4. Centerline temperature profile for PET.

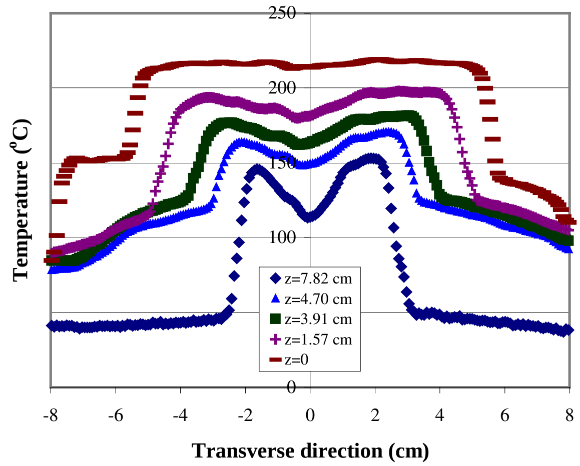

Fig. 5. Transverse temperature profiles for PP.

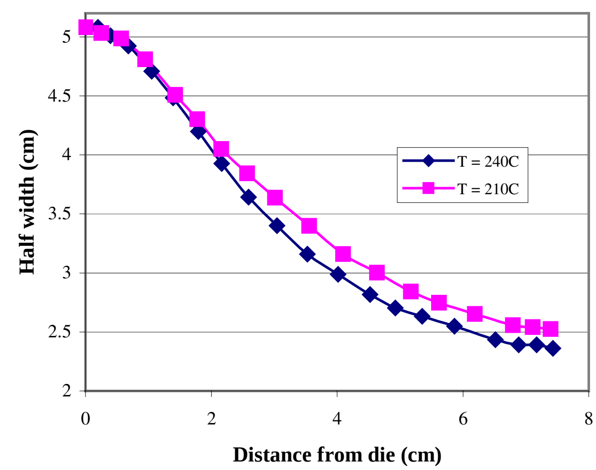

Fig. 6. Width profile for PP as function of die temperature.

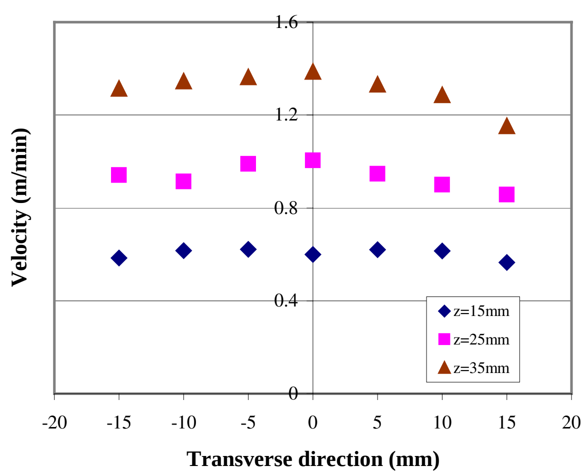

Fig. 7. Transverse direction velocity profile for PP.

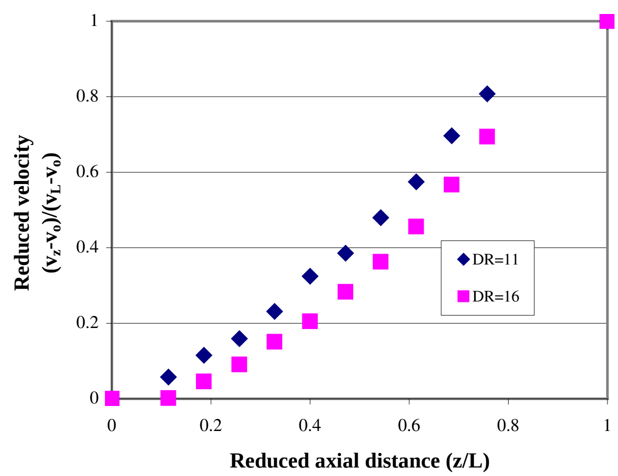

Fig. 8. Centerline velocity profile for PP as a function of draw ratio.

Keywords

Cast film; LDV; neck-in; extensional flow