An Experimental Apparatus and Effects of Testing Conditions on Elongational Flow Properties of Low-Density Polyethylene under Tensile Deformation

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Abstract : In this work, an experimental rig was designed and constructed for melt strength measurement and was assembled at the end of a single screw extruder used for production of low-density polyethylene (LDPE) melt. The experimental rig was coupled with a high speed data logging system and a personal computer for real-time measurement of melt strength of LDPE. The molten LDPE was extruded through a capillary die forming a continuous filament before being pulled down by mechanical rollers until the filament failed. A digital camera was used for measuring the actual extrudate size at failure. The experimental results suggested that the melt strength of LDPE was dependent on volumetric flow rate from the screw extruder, roller speed, and the take-up style. For ladder-step take-up, increasing roller speed resulted in increases in the drawdown forces. The drawdown forces of the LDPE melt measured under a rapid speed take-up was 40-60% greater than to those tested under a ladder-step speed take-up. The tensile viscosity of the LDPE melt slightly decreased with elongational strain rate.

Keywords: Mechanical strength, Polyethylene, Rheological properties, Tension viscosity

1. Introduction

Rheological properties of polymer meltsunder tensile deformation provide useful information on operating and control processes and property predictions for final polymer products by blown film extrusion, extrusion blow moulding, melt spinning and thermoforming. Such rheological properties are usually expressed by extension forces, melt strength, and/or elongational viscosity. It is widely accepted the critical mechanical strength of flowing polymer under tensile deformation is required to prevent the sagging and/or fracture of the extrudate during processing. Techniques to determine the melt strength include tensile tests, filament winding technique, and convergent flow [1,2]. The most widely used and commercial technique for measurement of the melt strength and elongational viscosity of polymer melts is a tensile tester so-called "Rheotens" [3,4].

In this work, mechanical strength of LDPE melt was assessed in terms of drawdown forces and elongational viscosity under various volumetric flow rates, die temperature, and filament take-up style.

2. Experimental

2.1 Raw material

Low-density polyethylene (LD1905FA), with a melt flow index of 5 g/10 min was used, and supplied by Thai Polyethylene Co., Ltd. (Bangkok, Thailand).

2.2 Design and manufacture of the experimental apparatus

In the present work, the mechanical strength of LDPE melt was evaluated under tension deformation which was achieved by simultaneously measurements of drawdown force and exact filament size (diameter) at the failure point. **Fig. 1** shows an experimental arrangement for melt strength measurement of the LDPE under filament winding process using a single screw extruder. The experimental apparatus consisted of a single screw extruder, an adaptor, force measuring unit, roller take-up device and visualization and control equipment.

2.3 Extrusion and winding of the LDPE filament and testing conditions

Since this work used a filament winding technique for evaluating the elongational flow properties of LDPE melt, drawdown force and exact filament size at failure point were required for accurate measurements. The drawdown force and filament size at failure point were recorded using a high speed data-logging and recording system. The length of spinline was fixed at 370 mm and cooling condition by ambient air. The die temperatures was 160°C. The volumetric flow rate was varied from 2.9–8.3 x10^{-7} m^3/s. In this work, two take-up styles were used as follows:

- Step-ladder take-up: In this case, the LDPE melt was extruded through a circular die to produce a continuous filament and pulled down by the rollers and the take-up device with linearly increasing velocity of the rollers until the filament had failure.

- Rapid take-up: In this case, the LDPE melt was extruded through a circular die to produce a continuous filament and rapidly pulled down by the rollers and the take-up device. The velocity of the rollers used was the maximum roller speed that failed the filament in the step-ladder take-up condition for a given volumetric flow rate in the screw extruder.

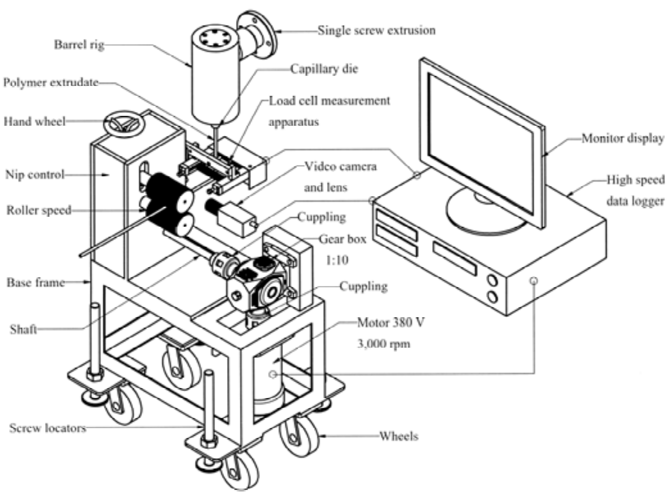

Fig. 1 Schematic of melt strength measurement unit

2.4 Measurement of elongational flow properties

All the measurements in this work were restricted to non-isothermal condition, and the reported data were averaged from at least five independent experiments. The apparent elongational viscosity ($\eta_{el,app}$) could be expressed by Equation 1 [2].

$$\eta_{el,app} = \frac{F.L}{Q \cdot \varepsilon_E} \qquad (1)$$

where F is the drawdown force at the take-up rollers, Q is the volumetric flow rate, L is the length of spinline, ε_E is elongational strain which is defined as $\ln\left(\frac{v_s}{v_0}\right)$, v_s is the stretching velocity at the rollers and v_0 is the velocity at die exit

3. Results and Discussion

3.1 Effect of volumetric flow rate

Fig. 2 shows the relationship between drawdown force and time under increasing roller speed in step-ladder form for LDPE melt at 160°C using three different volumetric flow rates. It was observed that the drawdown force increased with increasing the roller speeds of the take-up device. The increases in drawdown force could be divided into two zones depending on the level of roller speed. The drawdown forces significantly increased in low roller speeds (less than 50 seconds) while the force values tended to slightly increase or stabilize with obvious force fluctuations at higher roller speeds. At low roller speeds, the molten LDPE required a significant level of force to overcome the molecular entanglement and elastic response of the polymer melt as it exited the die. After that, the force required became smaller due to slippage of the disentangled molecular chains at higher roller speeds. The force used to deform the LDPE melt during molecular slippage condition at higher roller speeds was much lower than that used to deform the entangled LDPE melt at lower roller speeds. These changes in molecular entanglements due to increasing roller speeds are physically illustrated in **Fig. 2c.** The force fluctuations at higher roller speeds were caused by draw resonance effect [3,5]. It was interesting to note that during the transitions of each roller speed, there was overshooting effect of the drawdown forces occurring, especially at lower roller speeds. However, these overshooting forces were finally suppressed by the effect of draw resonance at higher roller speeds. For the effect of volumetric flow rate from the extruder, it was found that the drawdown force increased with increasing volumetric flow rate. This observation was in line with the work of Gupta and Bhattacharya [4]. The effect of volumetric flow rate was associated with the fact that higher volumetric flow rate or extrusion rate would produce greater elastic energy stored in the molten LDPE during the flow in the die. This view could be supported by Baldi *et al* [2].

3.2 Effect of take-up style

Fig. 3 also shows comparison of the drawdown forces at failure point by the rapid roller speeds (in circles) and by the step-ladder take-up using the same roller speed. At the failure point, the drawdown forces in the rapid take-up method was 40-60 % greater than to those in the step-ladder take up method. In the case of rapid take-up, the molecules of LDPE melt still entangled during the stretching to fail and this required a considerable amount of force to overcome the elastic resistance as stated earlier. Considering the size of the extruded filament in **Fig. 3**, it was observed that when increasing the roller speed the size of the filament progressively decreased although the drawdown force had increased. This implied that the LDPE filament had greater melt strength as the roller speed was increased. The increased melt strength of LDPE melt due to increasing stretching speed was caused by branching characteristics of LDPE and this has also been found by a number of work [3].

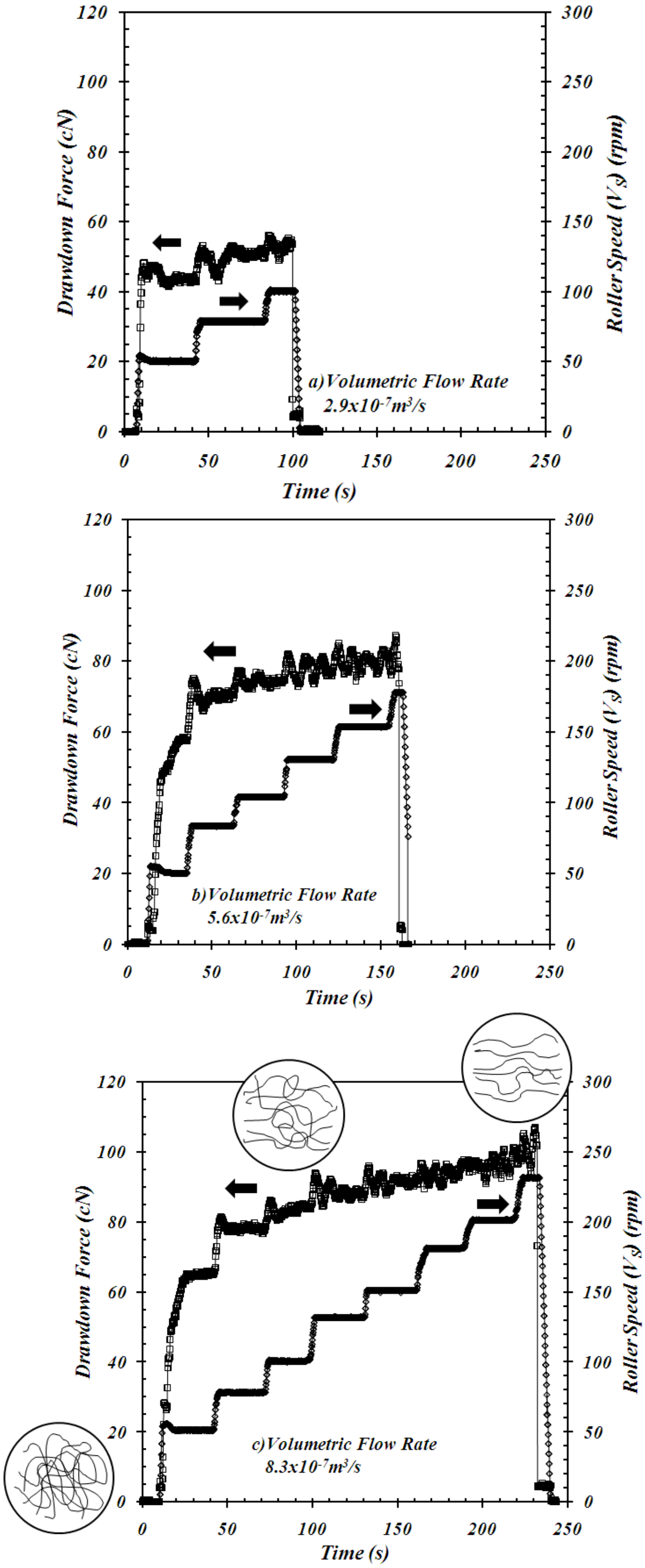

Fig. 2 Drawdown force, time and roller speed for LDPE at 160°C using different volumetric flow rates.

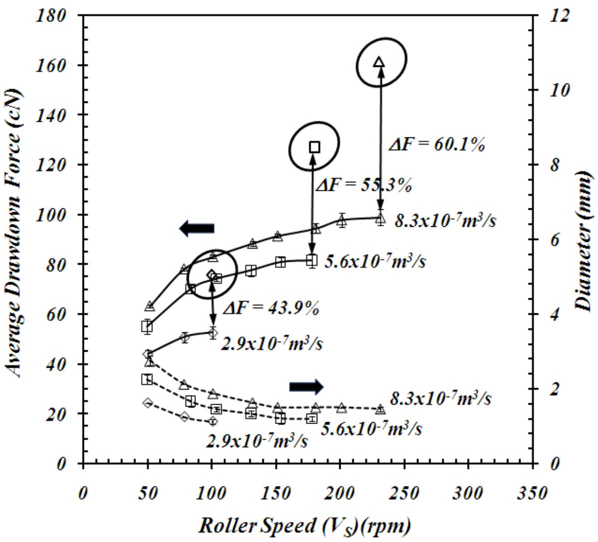

Fig. 3 Comparison of the drawdown forces at failure point by the rapid roller speeds and by the step-ladder take-up for LDPE melt at 160 °C.

3.3 Elongational viscosities

Fig. 4 shows the relationship between the apparent elongational viscosity and elongational strain rate for LDPE melt at 160 °C with three difference volumetric flow rate. It was found that the elongational viscosity decreased with increasing elongational strain rate and volumetric flow rate. The decrease in melt viscosity by the effect of volumetric flow rate was due to pseudoplastic non-Newtonian behavior whereas that by the effect of elonational strain rate was associated with the level of strain rate used in this work. According to the works by Wagner *et al* [3], Padmanabhan *et al* [6] and Collier *et al* [7] suggested that the viscosity of LDPE melt elongated at elongational strain rates of greater than 1 s^{-1} decreased with increasing deformation rate.

4. Conclusions

The experimental rig was designed and manufactured in this work could successfully be used for measurement of mechanical strength of molten LDPE. The drawdown force of LDPE melt increased with increasing roller speeds. The higher the volumetric flow rate the greater the drawdown force. The drawdown force changes were associated with the molecular disentanglement of the branched LDPE melt. Using a rapid take-up method, the drawdown force of LDPE melt increasing by 40-60% as compared to those found in the ladder-step speed take-up method. The draw resonance effect was observed at higher roller speeds. The elongational viscosity of the LDPE melt marginally decreased with elongational strain rate.

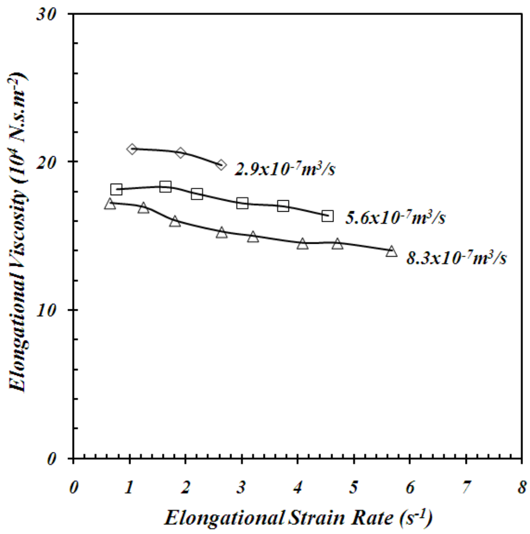

Fig. 4 The apparent elongational viscosity and elongational strain rate for LDPE melt at 160 °C.

Acknowledgments

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