An Electromagnetic Dynamic Film Blowing Technology for mLLDPE

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ABSTRACT: Metallocene linear low-density polyethylene (mLLDPE) has superior physical and mechanical properties. However, mLLDPE has very poor film blowing processibility. To overcome this shortcoming, an electromagnetic dynamic extruding film blowing system for mLLDPE was developed. A vibration force field was superposed on the entire extruding process through the screw. The die pressure, the screw load, and the power consumption decreased and the melt strength increased as the vibration frequency and amplitude increased, implying that the bubble stability enhanced, which resulted in the improvement of the processibility. In addition, experimental data show that the film strength in the transverse direction greatly increased and the film mechanical properties in machine and transverse directions became more uniform, so the film quality was improved finally. This rule was confirmed by using two additional materials, high-density polyethylene and low-density polyethylene. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 101: 83–89, 2006

Key words: films; blowing; extrusion; polyethylene; vibration force field

INTRODUCTION

Metallocene linear low-density polyethylene (mLLDPE) has good physical and mechanical properties. The film made from mLLDPE has high strength and good puncture resistance. However, mLLDPE is difficult to blow film because of its low melting point, poor melt strength, and high viscosity due to its narrow molecular-weight distribution (MWH) and low critical shear rate. For example, the screw of the film blowing machine is prone to overloading because of the high torque and die pressure owing to the high viscosity; the molten bubble easily ruptures during the film blowing process because of the low melt strength, which results in poor bubble stability.

Many efforts have been made to improve the processibility of mLLDPE. Yan et al.[1] investigated the effects of long chain branching (LCB) on the rheological properties of the metallocene polyethylene (mPE). The LCB resulted in enhancement of the shear-thinning properties, implying that the viscosity could be decreased and the processibility could be improved by increasing the shear rates. Some additives, such as Viton Freeflow RC,[2] were added to metallocene resins to improve the processibility of mLLDE. Some modifications made in the conventional film blowing apparatus for mLLDPE had been reported in the literature,[3–7] including the barrel, the screw, and the die. Exxon preferred using low-shear, barrier-type mixing screw, wider spiral clearance die, and smooth-bore extruder to lower the melt temperature, enhance the output and energy efficiency, and improve the bubble stability.[3,4] Texas disapproved barrier screw owing to imparting low shear; it said that the single-flight screw was good for better mixing and homogenization. Knights,[5] mentioned that Keller and Goffreda recommended widening the die gap to 0.080 – 0.120 in. owing to the higher viscosity of metallocene resins. Dow said that refrigerated air and internal bubble cooling (IBC) with more cooling capacity were benefical to maintain control of frost-line height (FLH), and will improve operating rates.[6]

The vibration has been employed in processing plastics for many years. An oscillation was superposed on the die by Fridman et al.[8] They found that the die pressure reduced and output increased with the increase of the oscillation amplitude. Allan and Bevis[9] and Isayev et al.[10] developed an ultrasonic waves extrusion system in 1990 and presented the effects of the oscillation amplitude and frequency on the die pressure. Results showed that the die pressure decreased as the amplitude and frequency increased. A new electromagnetic dynamic extruding technology was first developed by Qu[11] in 1990. In the new extruder, a vibration force field was applied into the

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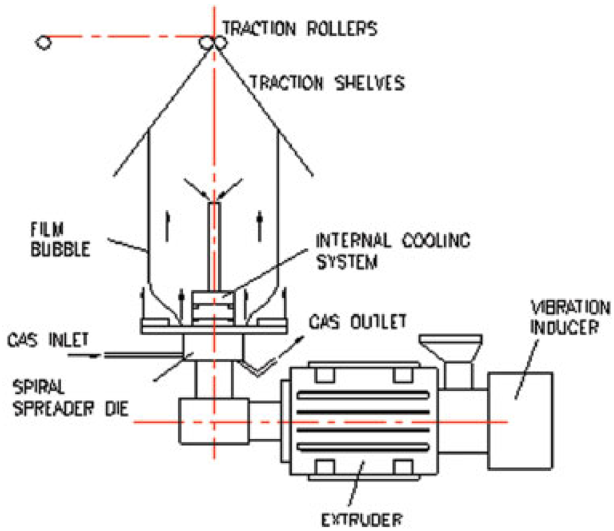

Figure 1 Schematic diagram of the electromagnetic dynamic extruding film blowing system. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

entire procedure of polymer plasticating extruding process by the screw. Later studies showed that the vibration force field reduced the energy consumption, enhanced the kneading, mixing, and plastication properties.[12,13,14] On the other hand, the product mechanical properties, such as tensile strength and impact strength, were improved by the vibration force field.[15]

Based on the virtues of the vibration force field, we introduced the electromagnetic dynamic extruding technology to the film blowing system to improve the mLLDPE processibility and film mechanical properties. This film blowing system developed for mLLDPE is the electromagnetic dynamic extruding film blowing system. Its key components include an electromagnetic dynamic plasticating extruder with a low-shear, barrier-type mixing screw, a spiral spreader die, and an internal cooling system. The screw of the extruder can not only rotate but also simultaneously vibrate axially during the extruding process. That is to say, a vibration force field was superposed upon the entire extruding process by the screw. The effects of the vibration frequency and amplitude on the die pressure, the power consumption, and the melt strength were investigated. Results showed decreases in the die pressure and the power consumption, and enhancement in the melt strength, indicating that the film blowing processibility of mLLDPE was improved. The ultimate objective of film blowing is to produce film with good physical and mechanical properties. Experimental data of the mechanical properties for mLLDPE showed the tensile strength in the transverse direction (TD) greatly enhanced, which resulted in improvement of the film uniformity. Similar phenomena were observed in the experiments for high-density polyethylene (HDPE) and low-density polyethylene (LDPE). All experimental data showed improvements in the processibility and film quality when the vibration force field was superposed on the extruding process.

EXPERIMENTAL

Materials

mLLDPE (1018CA, melt index 1.0 g/10 min, density 0.917 g/cm^3) supplied by EXXon Mobile Chemical, LDPE (4B 951–050, melt index 1.0 g/10 min) and HDPE (F600) were used in this study.

Setup

Figure 1 shows a schematic diagram of the electromagnetic dynamic extruding film blowing system for mLLDPE. It consists of an extruder with a screw with a diameter of 22 mm and a length/diameter (L/D) ratio of 28 : 1; a spiral spreader die with a clearance of 1.5 mm; an internal cooling system; a vibration inducer mounted on the back side of the barrel whose metal plank can axially vibrate periodically.

Procedure

Principle of the electromagnetic dynamic plasticating extruder

The electromagnetic dynamic plasticating extruder, different from the traditional extruder, is the main component of the film blowing system. Its barrel and screw are placed in the rotor cavity of motor and the later is fixed to the rotor coaxially, as shown in Figure 2. The screw can rotate periodically along with the rotor rotation induced by the electromagnetic loop. On the other hand, back side of the screw is fixed to the metal plank of the vibration inducer, implying that it can vibrate in the axial direction along with the plank

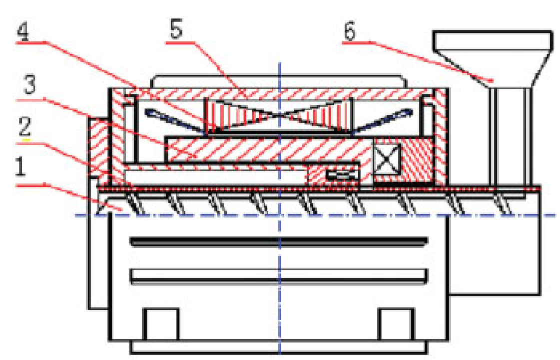

Figure 2 Electromagnetic dynamic plasticating extruder. 1, screw; 2, barrel; 3, rotor; 4, stator; 5, frame; 6, hopper. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

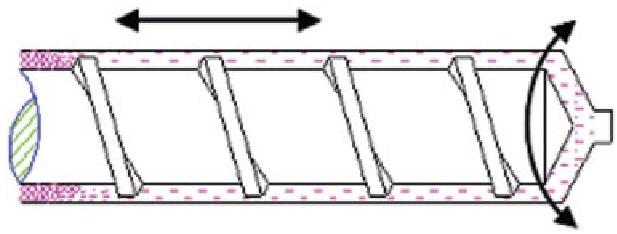

Figure 3 Schematic diagram of the rotation and axial vibration of the screw. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

vibration induced by the vibration inducer. The rotor rotation and plank vibration were controlled by different currents. The vibration amplitude and frequency can be changed by the vibration inducer independently. When the screw rotates and simultaneously vibrates axially in film blowing, as shown in Figure 3, polymer feeding, melting, and mixing are in the vibration force field, indicating that the vibration is superposed on the entire extruding process by the screw. The vibration is beneficial for plasticating and mixing.[14]

The temperature profile is one of the key parameters for the bubble stability. The temperature near the hopper must be low enough to prevent the polymer from clogging in the hopper owing to melting too early. The die temperature is the most important. The surface melt fracture (SMF) is prone to appear because of the low critical shear rate while the die temperature is too low, and the bubble easily ruptures owing to the low melt strength if the die temperature is too high. Based on the experiments, it is found that the barrel temperature profile with saddle-shape is beneficial to blow film, corresponding to the report in literature,[1] which said a "hump" temperature profile can help bring about a more uniform melt than a "ramp" profile. The extrusion temperature profiles for mLLDPE, HDPE, and LDPE from the hopper to the die were set as 180/230/220/210/200/190°C, 190/230/220/210/200/190°C, and 160/180/190/180/175/170°C, respectively. The screw rotating speed was 130 rpm for all the materials used in this study. The TURs for mLLDPE, HDPE, and LDPE were 42.5, 18, and 21, respectively. The BURs for mLLDPE, HDPE, and LDPE were 2, 2.86, and 2.7, respectively. A vibration force field was superposed by the screw during the film blowing process. The vibration frequency and amplitude were controlled by different electric currents, and were regulated independently. The vibration frequency was varied from 0 to 12 Hz with a regular interval of 2 Hz when the amplitude was 0.2 mm, and the amplitude was varied from 0 to 0.2 mm with a regular interval of 0.05 mm when the frequency was 6 Hz to investigate their effects on the processibility and mechanical properties. The die pressure and power consumption at each vibration parameter were recorded when extruding became steady. The films were collected and stored for 48 h. Finally, dumbbell-shaped specimens were punched out from thin films to determine the tensile strengths.

Measurement of melt strength

The melt strength of mLLDPE at each vibration parameter was measured on the electromagnetic dynamic plasticating extruder. The melt strength is a measurement of the weight of the polymer melt which can hang onto the die exit of the extruder for 3 min before being broken off. For operating simplification, four electrical heating bands were used on the barrel. The temperature profiles were 180, 230, 220, and 190°C for the feed zone, the compression zone, metering zone, and the die, respectively. After equilibrium for 6 min in the barrel, the mLLDPE melt was pushed out completely from the barrel. A small amount of the melt was hung onto the die exit. The time between the expulsion of the melt and the breaking-off of the melt from the die exit was recorded. The melt that broke off from the die exit was weighed. Four measurements were made at each vibration parameter, and the data were interpolated to the weight of the extrudate that could hang onto the die exit for 3 min.[16,17]

Measurement of mechanical properties

Merlin Series 5566 Testing System produced by INSTRON Company was used to measure the mechanical properties of the film samples in accordance with GB1040–92.

RESULTS AND DISCUSSION

Die pressure

The effects of the vibration frequency and amplitude on the die pressure are shown in Figure 4. The die pressure greatly decreased as the vibration amplitude increased. For example, the die pressure at the amplitude of 0.2 mm decreased by 1.15 MPa compared with zero amplitude. It initially decreased and then approached a plateau different from zero with the increase of the vibration frequency.

The marked decrease of the die pressure implied that the melt viscosity lowered, which resulted in a reduction in the resistance of the melt flowing through the die and the decrease of the screw torque, which prevented the screw from over loading. So, the film blowing processibility of mLLDPE was improved by superposing the vibration force field.

Power consumption

The power consumption of the system decreased with the increased vibration frequency and amplitude, as

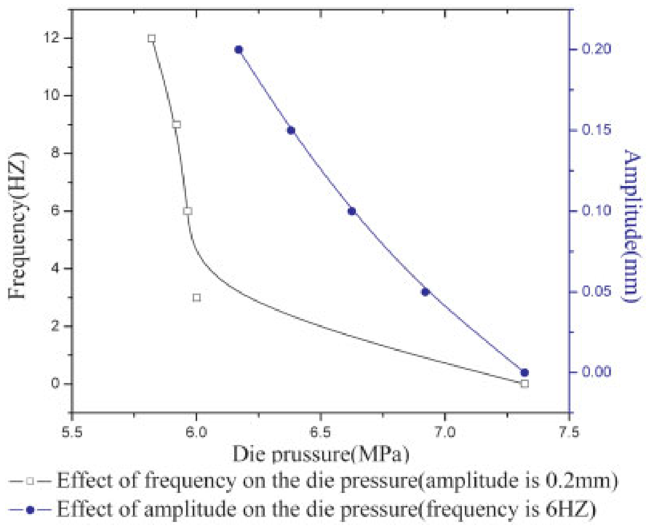

Figure 4 Effects of frequency and amplitude on the die pressure (using mLLDPE). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

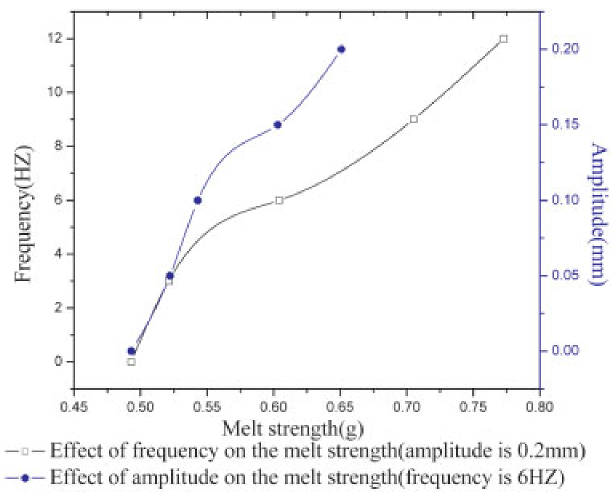

Figure 6 Effects of frequency and amplitude on the melt strength (using mLLDPE). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

shown in Figure 5. The decreased power consumption indicated the amperage diminished, implying that the screw torque decreased.

It was found from previous experimental data that the vibration force field had strong effects on the rheological properties of mLLDPE melt. It lowered the melt viscosity, which led to the decrease of the die pressure and screw torque. Thus, the film blowing processibility of mLLDPE was improved.

Melt strength

Figure 6 show the effects of the vibration frequency and amplitude on the mLLDPE melt strength. The melt strength largely increased with the increase of vibration frequency and amplitude. And the frequency appeared to have stronger effect on the melt strength than the amplitude. The increased melt strength effectively prevented the molten bubble from easily rupturing, implying that the bubble stability was improved.

Mechanical properties

Figures 7 and 8 show the effects of the vibration frequency and amplitude on the tensile strengths of mLLDPE film in machine and transverse directions, respectively. When frequency was zero, that is, the vibration was not superposed, the tensile strength in

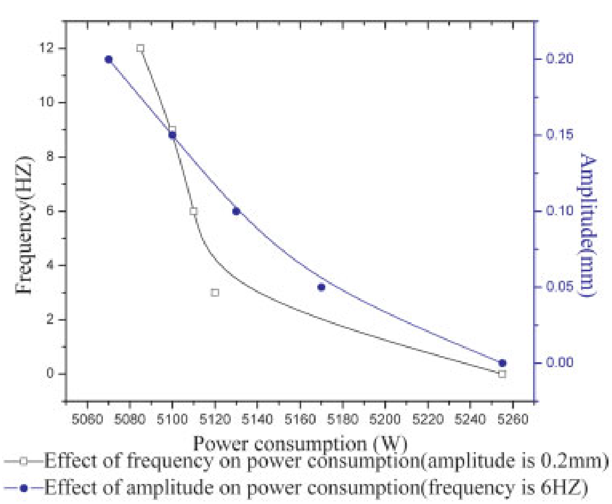

Figure 5 Effects of frequency and amplitude on the power consumption of system (using mLLDPE). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

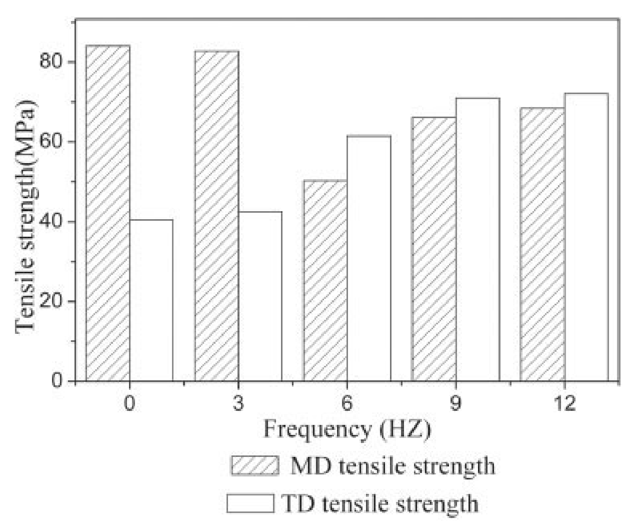

Figure 7 Effects of frequency on the tensile strengths of mLLDPE films in the machine and transverse directions (amplitude is 0.2 mm).

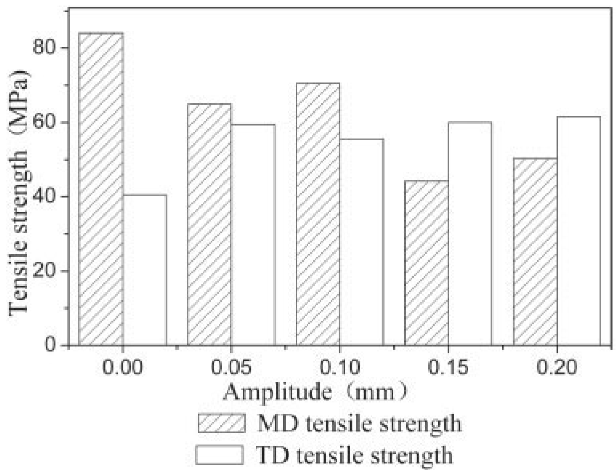

Figure 8 Effect of amplitude on the tensile strengths of mLLDPE films in the machine and transverse directions (frequency is 6 Hz).

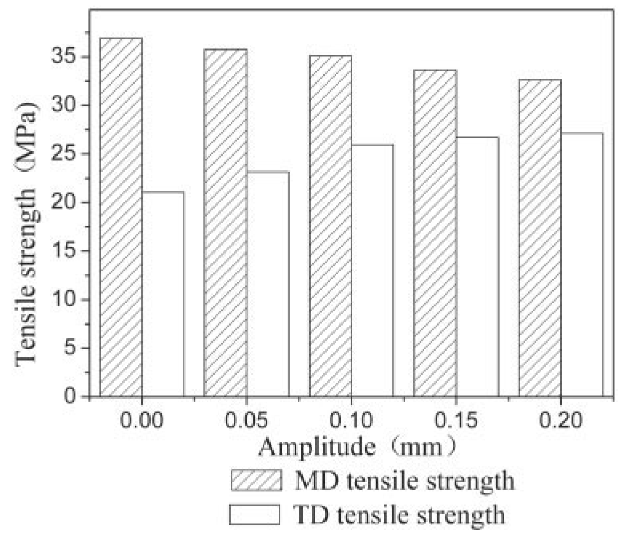

Figure 10 Effects of amplitude on the tensile strengths of HDPE films in the machine and transverse directions (frequency is 6 Hz).

the machine direction (MD) was much higher than that in TD. The TD tensile strength increased and the MD tensile strength decreased as the vibration frequency increased, as shown in Figure 7. The two strengths tended to be uniform. In a similar pattern, the TD tensile strength increased and the MD tensile strength decreased with the increase of the amplitude, and the two strengths tended to be uniform, as shown in Figure 8. In addition, the effect of the frequency was stronger than that of the amplitude.

To prove the generalization of this rule of the polymer mechanical properties, HDPE and LDPE were studied. Figures 9–12 show the tensile strengths of HDPE and LDPE as functions of the vibration frequency and amplitude. The TD tensile strengths of HDPE and LDPE showed enhancement as the vibration frequency and amplitude increased, similar to mLLDPE. All the tensile strength data show that the vibration force field had different effects on the film mechanical properties depending on the material. The effects on mLLDPE films were stronger than that on HDPE films and LDPE films owing to the special molecular structure of mLLDPE.

For general film, the tensile strength in MD is higher than that in TD because the molecular orientation in MD is much larger than that in TD in film blowing. So, the general film easily ruptures in TD. However, when the vibration force field was superposed on the ex-

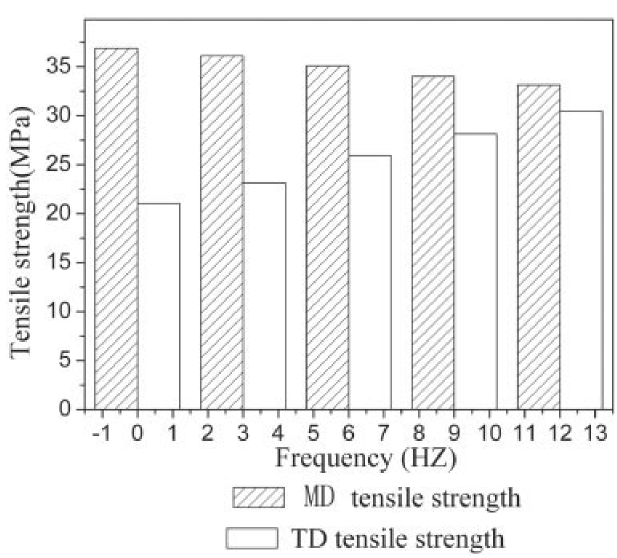

Figure 9 Effects of frequency on the tensile strengths of HDPE films in the machine and transverse directions (amplitude is 0.2 mm).

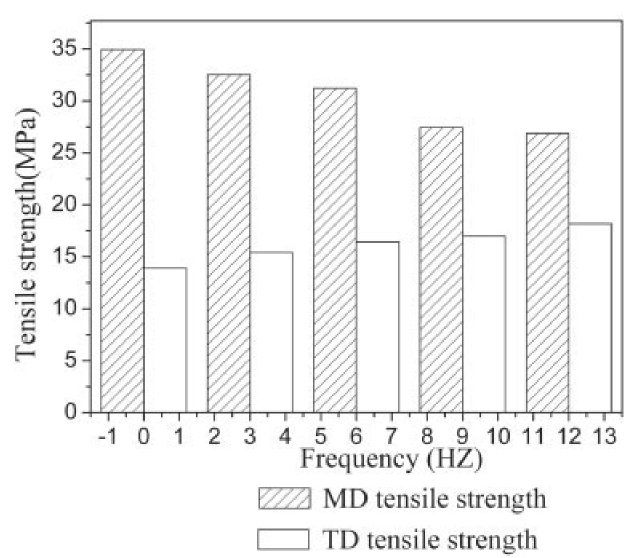

Figure 11 Effects of frequency on the tensile strengths of LDPE films in the machine and transverse directions (amplitude is 0.2 mm).

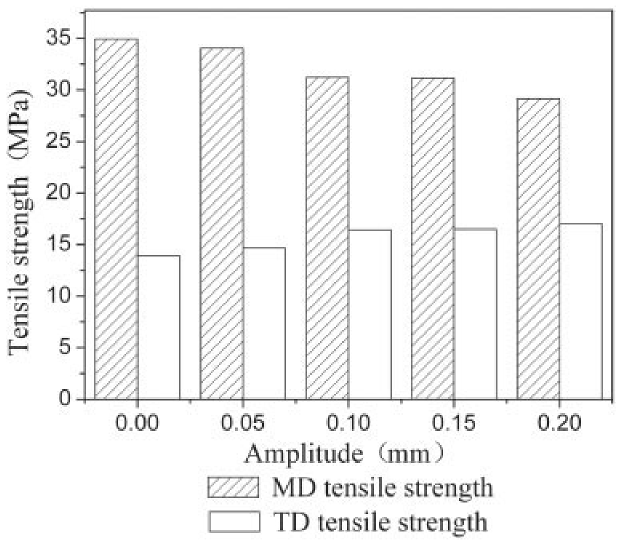

Figure 12 Effects of amplitude on the tensile strengths of LDPE films in the machine and transverse directions (frequency is 6 Hz).

truder by the screw during the film blowing process, the polymer molecules in the barrel strained along both the flowing direction and the axial direction because of the screw rotation and axial vibration, implying that the molecular orientation in the axial direction increased and anisotropy enhanced. Consequently, the TD tensile strength increased and MD tensile strength decreased as the vibration frequency and amplitude increased, as shown in Figures 7–12. Thus, superposition of the vibration force field could overcome the disadvantage of the nonuniformity of the film mechanical properties.

Analysis

According to the theory of free volume,[18] an entire macromolecular chain moves by the movement of the chain segments, like the movement of an earthworm. Macromolecular chains easily entangle with each other inside the polymer melt because of their long molecular chains. When the vibration force field was superposed by the screw on the extruding process, the molten resins would vibrate periodically along with the screw axial vibration, which increased the shearing friction between the molecular chains and generated plenty of heat. In addition, the periodic vibration pressed and loosened the polymer melt, which resulted in molecular chains easily disentangling and moving. Much shear and heat generated by the axial vibration led to the decrease of the viscosity and the enhancement of the fluidity of the molten resin. This explains why the die pressure and power consumption decreased with the increase of the vibration frequency and amplitude. The theoretical analysis was reported elsewhere.[19]

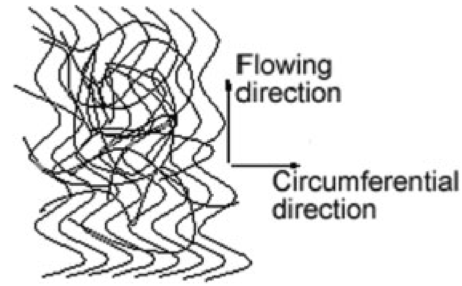

Figure 13 Alignment of molecular chains in the barrel without axial vibration.

For general extruder, the molecular orientation in the flowing direction is much larger than that in other directions inside the barrel owing to the stress imposed by the screw rotation. The schematic diagram of the molecular chain alignment in the barrel is displayed in Figure 13. Most of the chains aligned along the flowing direction and few of them aligned along the circumferential direction. After leaving the die, the polymer melt biaxially stretched because of the drag force of the nip roll and air pressure inside the bubble. The MD orientation was much larger than the TD orientation because TUR was bigger than BUR., which resulted in higher film strength in MD than that in TD.

When the axial vibration was superposed, the entire process of solid transmitting, melting, and melt transmitting was on the action of the vibration force field. In fact, the polymer melt bore a complex shear forces in the flowing direction and axial direction imposed by the screw rotation and axial vibration, which caused the molecular chains to align along the two directions and cross each other, as shown in Figure 14. So, the molecular anisotropy enhanced, which led to the increase of the melt strength. In addition, the enhanced anisotropy gave the increase in the tensile strength in TD and significant improvement of the uniformity of film mechanical properties.

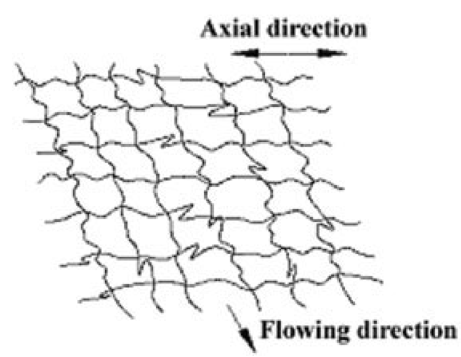

Figure 14 Alignment of molecular chains in the barrel when the axial vibration was superposed on the extruding process.

CONCLUSIONS

An electromagnetic dynamic film blowing technology for mLLDPE was introduced by investigating the die pressure, power consumption, melt strength, and mechanical properties as functions of the vibration force field. The die pressure and power consumption decreased and melt strength increased with increasing vibration frequency and amplitude, which led to the enhancement of the bubble stability and improvement of processibility. In addition, the tensile strengths in TD of all materials used in this study enhanced and the uniformity of the mechanical properties in MD and TD was improved with increased vibration frequency and amplitude, implying that the film quality was improved. Therefore, the electromagnetic dynamic film blowing technology gave an effective method to resolve the problem of difficulty to process mLLDPE and nonuniformity of the film mechanical properties.

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