Frictional Properties of Polyolefins Treated with Fluoroelastomer Processing Aids

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SYNOPSIS

A friction measurement system was designed that made possible the measurement of the friction coefficient between a polymer melt and a metal die wall. The shear stresses developed in the capillary rheometer and the friction coefficient measured in the friction measurement system were compared in an attempt to understand the mechanism of fluoroelastomer processing aids (FPA) in the extrusions of polypropylene (PP) and linear low-density polyethylene (LLDPE). The apparent viscosity drops of LLDPE treated with FPA were larger than those of PP treated with FPA. The friction coefficient drops of LLDPE treated with FPA were also larger than those of PP treated with FPA. High viscosity FPA showed a moderate friction coefficient drop in the actual extrusion of PP even though it showed only a poor effect in the capillary rheometer. The frictional forces were calculated from the friction coefficient measurement made during extrusions of FPA-treated and untreated samples. © 1995 John Wiley & Sons, Inc.

INTRODUCTION

The fluoroelastomer processing aids (FPA) are being used to improve processability and to eliminate melt fracture in linear low-density polyethylene (LLDPE). Several studies[1–9] have described both general and specific applications of these processing aids and have also speculated on the mechanism by which they work. These FPA are believed to act by establishing a slip layer of FPA on the metal surface in the die. It was also reported that the FPA required some induction time to wet the die wall and the effect of the FPA-coated layer was retained (on the die wall) for a substantial time period.[3,5,10]

The effect of the polymer–wall interface was discussed by Ramamurthy.[11] Kalika and Denn[12] also mentioned the adhesion of polymer on the die wall related to the onset of slip. Generally, the amount of slip was measured from a plot of shear rate versus die radius $(1/R)$, as suggested by Mooney.[13] This Mooney plot was used to quantify the effect of FPA, which affected slip between polymer and die wall.

The frictional forces were measured by Guignard[14] in the study of poly(vinyl chloride) (PVC) lubricant. A new technique was also developed in this work to measure the friction coefficient of molten polymer against a metal surface. Rheological data from the capillary rheometer, along with the frictional properties of polymer treated with FPA, were used to study the effects of fluoroelastomer processing aids.

EXPERIMENTAL

Fluoroelastomer Processing Aids

Four FPAs of different molecular weight copolymers of vinylidene fluoride and hexafluoropropylene were used in this study. This material can be represented structurally by the formula[15]

$$-[(CF_2-CH_2)_x-(CF-CF_2)_y]_n-$$
$$\overset{\displaystyle CH_3}{\underset{\displaystyle |}{}}$$
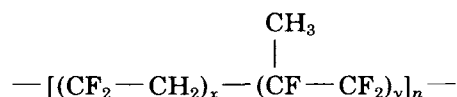
These copolymers have fluorine content of between 65 and 66%.[16] They differed in molecular weight, as

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Table I Fluoroelastomer Processing Aids

Sample	$\bar{M}_n$	Mooney Viscosity[a]	Notation
A	10,000	0	FPA (0)
B	50,000	20	FPA (20)
C	70,000	35	FPA (35)
D	85,000	48	FPA (48)

[a] Test temperature: 121°C.

evidenced by their Mooney viscosities, and are referred to as FPA(XX) where XX denotes a specific Mooney viscosity. The measurements of Mooney viscosity were performed according to ASTM method D-1646-81 at 121°C. Fluoroelastomer processing aids were provided by the 3M Company. General information is given in Table I.

Polymers

Two different viscosity levels of polypropylene (PP) and two different viscosity levels of LLDPE were used. They are shown in Table II and referred to as PP(XX) or LLDPE(XX) where XX denotes a melt index. Polypropylenes were the commercial products supplied by Himont, and LLDPE were supplied by Exxon.

Instron Capillary Rheometer

Rheological properties of the polymers were measured using an Instron capillary rheometer (Model 1125). The Instron capillary die used had diameter 0.729 mm and L/D ratio 39.0. The high L/D ratio die was used to minimize end effects. End effect and Rabinowitch corrections were not applied in this work.

Fluoroelastomer processing aids were dry blended with polymer chip to the required concentrations. A few words are in order to justify this procedure.

It is generally accepted that FPA functions as a processing aid by coating the die wall. Hence the uniformity in the bulk polymer is not especially critical. The proper functioning of FPA requires a certain induction time to wet the die wall and the induction time can sometimes exceed an hour. To avoid this long induction time, an excessive amount of FPA was used in this work. Normal FPA concentration in industrial usage is considerably lower (100–1000 ppm) than the 5000 ppm used in our test. In this situation, simple dry mixing should be enough to carry out our objectives. And in our Instron rheometer work, the consistent results obtained support this statement. The polymer chips were loaded and allowed to melt for 10–20 min in the rheometer barrel prior to data acquisition. For a given capillary die, polymer, processing aid, extrusion temperature, and the same sequence of crosshead speeds were used in each run. Crosshead speed was changed only after a steady-state force trace was observed. Before each run, the rheometer barrel and the die were cleaned and flushed with methyl ethyl ketone (MEK), which is a very effective solvent for the FPA.[5]

Determination of Wall Slip Velocities

The magnitude of wall slip in capillary flow was determined by the Mooney analysis.[13] The analysis of slip in the capillary leads to the following equations:[13,17]

Apparent shear rate:

$$\dot{\gamma}_a = \frac{4Q}{\pi R^3} = \frac{4\bar{u}}{R} = 4u_s \frac{1}{R} + \dot{\gamma}_{\text{true}}$$

$$= 4u_s \frac{1}{R} + \frac{4}{\tau_w^3} \int_{\tau}^{\tau_w} \tau^2 \dot{\gamma} \, d\tau \tag{1}$$

where $\dot{\gamma}_a$ is the apparent shear rate, Q is the volume flow rate, R is the radius of the capillary, $\bar{u}$ is the average fluid velocity of the fluid, u_s is the slip ve-

Table II Polypropylenes and LLDPE

Polymer	Designation	MI[a]	Maker	Notation
PP	PRO-FAX 6823	0.5	Himont	PP(0.5)
PP	PRO-FAX 6623	1.7	Himont	PP(1.7)
LLDPE		0.5	Exxon	LLDPE(0.5)
LLDPE		1.0	Exxon	LLDPE(1.0)

[a] Test temperatures: PP, 230°C; LLDPE, 190°C.

Table III   Dimensions of Capillary Dies[a]

Diameter (mm)	Length (mm)	L/D
1.615	54.12	33.7
0.729	28.45	39.0
0.522	19.91	38.1
0.333	11.79	35.4

[a] Capillary dimensions were checked by the silicone rubber mold technique.

locity at the wall, τ_w is the shear stress at the wall, τ is the shear stress, $\dot{\gamma}$ is the shear rate, and $\dot{\gamma}_{true}$ is the true wall shear rate.

Differentiating the above equation with respect to $1/R$ at constant shear stress at the wall, τ_w, one obtains:

$$\left.\frac{\partial(4\bar{u}/R)}{\partial(1/R)}\right|_{\tau_w} = 4u_s \qquad (2)$$

Thus, the plot of the apparent shear rate, $\dot{\gamma}_a = (4\bar{u}/R)$ vs. $1/R$ at constant τ_w should give a straight
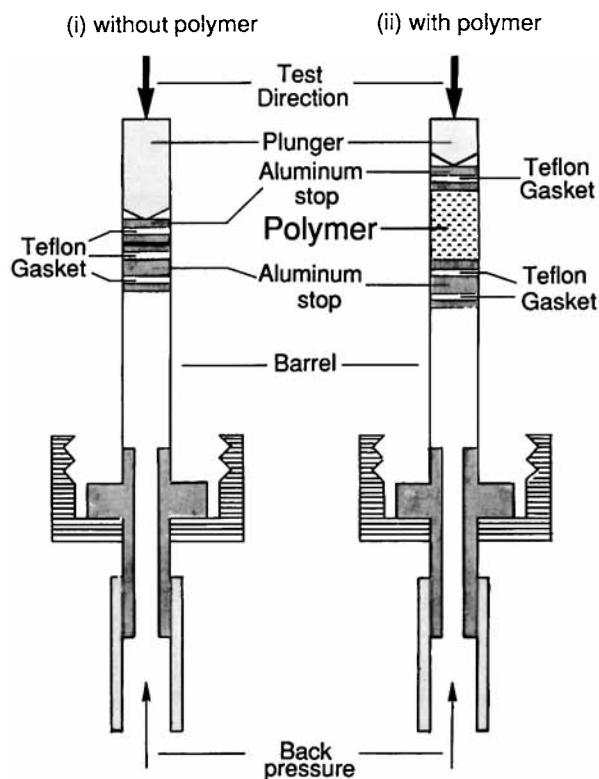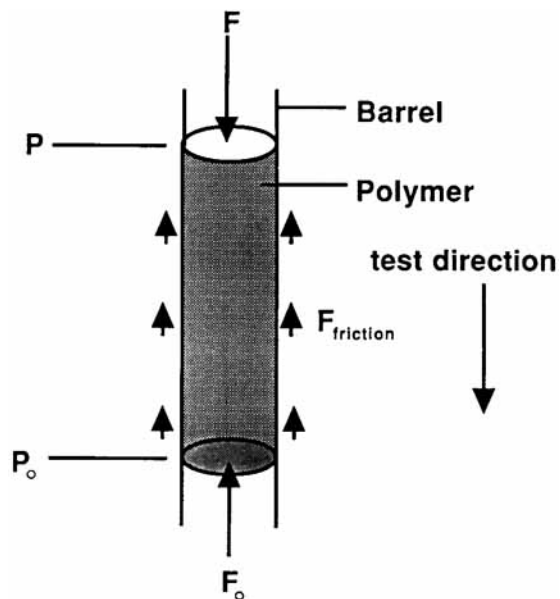

Figure 2   Schematic diagram of forces involved during measurement of the friction coefficient.

line with a slope $4u_s$. To determine the slip velocity u_s, capillaries with the same length-to-diameter ratios but with different diameters are used.

The value of $4u_s$ can then be used to obtain the true shear stress–shear rate behavior free from the slip effect. The contribution of slip to total volu-
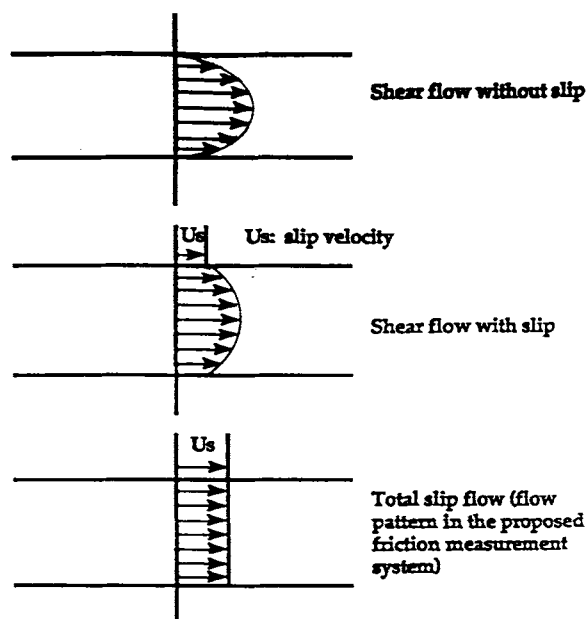

Figure 1   Experimental setup for measurement of friction coefficient.

Figure 3   Polymer flow patterns in the flow channel.

Table IV Relationship between the Amount of PP(0.5) and the Barrel Length in Contact with the Polymer

Amount of PP (g)	1.0	2.0	3.5	5.0	7.0
Barrel length,[a] L (cm)	1.54	3.08	5.40	7.71	10.8

[a] Barrel diameter: 0.9525 cm ($\frac{3}{8}$ in).

metric flow rate can be found as follows. The flow rate due to slip, Q_s, given by

$$Q_s = \pi R^2 u_s \tag{3}$$

Thus, the ratio of flow due to slip, Q_s, over the total flow rate, Q, is given as follows:[12]

$$(Q_s/Q) = (u_s/\bar{u}) = (4u_s/R\gamma_a) \tag{4}$$

The Instron capillary dies used in the determination of slip velocity are shown in Table III.

Measurement of Friction Coefficient

Friction data at melt temperatures have been very limited due to experimental difficulties. However, Guignard[14] measured the frictional forces of molten polymer in the study of PVC lubricant. But his method was not suitable to the FPA test because of the excessively long time required to clean the residual FPA from the screw and the head in the extruder.

To simplify cleaning of the residual FPA after each test, the Instron capillary rheometer was used, with some modification, to measure the friction coefficient of molten polymer against a metal surface. The experimental setup is illustrated in Figure 1.

Polymer was contained between two movable aluminum plugs and back pressure was applied with nitrogen gas from the bottom of the barrel. The plunger was pushed down at a particular speed and a steady state was maintained. At steady state, the pushing force was measured with and without polymer.

The schematic diagram of the forces involved during the measurement is shown in Figure 2 and the flow patterns in the flow channel were compared in Figure 3. The flow pattern in the proposed friction measurement system was regarded as a total slip flow.

The calculations of friction coefficient are as follows: If D is the diameter of the barrel and L is the length of the barrel contacted by the polymer, the area of the barrel wall contacted with polymer:

$$A_w = \pi DL \tag{5}$$

and the area of barrel cross section:

$$A_x = \frac{\pi D^2}{4} \tag{6}$$

If μ is the friction coefficient, N is the normal force to the barrel wall, P is the pressure at the bottom of the upper aluminum plug, and P_0 is the pressure at the top of the lower aluminum plug, at steady state, the force of polymer friction against the metal wall is

$$F_f = \mu N = \mu\left(\frac{P + P_0}{2}\right)A_w \tag{7}$$

and the force difference, with and without polymer (F and F_0 are measurable):

$$F - F_0 = (P - P_0)A_x \tag{8}$$

Table V Frictional Force without Polymer (F_o) and with Polymer (F)[a]

		F_o (lbf)	F (lbf)				
Barrel length, L (cm)		0.00	1.54	3.08	5.40	7.71	10.8
Plunger speed (in/min)	1.0	14.5	14.8	14.8	17.0	17.6	19.5
	2.0	14.6	15.0	16.5	20.5	21.0	24.0
	5.0	14.8	16.7	18.5	24.5	27.5	34.0
	10.0	15.0	18.3	21.3	29.5	33.5	45.0

[a] Back pressure: 9.94 lbf (90 psi), PP(0.5), 210°C.

Then we have

$$\mu = \frac{P - P_0}{2(P + P_0)} \times \frac{D}{L} \qquad (11)$$

Because $F = PA_x$, and $F_0 = P_0 A_x$, the friction coefficient, finally, may be written as follows:

$$\mu = \frac{F - F_0}{2(F + F_0)} \times \frac{D}{L} \qquad (12)$$

where μ is the friction coefficient, F is the measured force with sample polymer, F_0 is the measured force without sample polymer (namely, back pressure and a small frictional force due to the aluminum plugs), D is the diameter of the barrel, and L is the length of the barrel contacted by the polymer.

This system makes possible the measurement of the friction coefficient of a molten polymer against a metal surface and also allows estimation of the external lubricity of processing aids.

RESULTS AND DISCUSSION

Friction Coefficient of Polymer

To estimate the calculated values based on the friction coefficient equation [Eq. (12)], several L's (barrel length in contact with polymer) and several plunger speeds were tested. The forces were measured at several speeds such as 1, 2, 5, and 10 in/min. Also, the amount of polymer, 0, 1, 2, 3.5, 5, and 7 g, was tested to study the relationship between friction coefficient and the length of barrel in contact with the polymer. Polymer Himont PP(0.5) was used at 210°C with 90 psi of back pressure applied.

The barrel length in contact with the polymer was determined by the amount of polymer put into the barrel. The relationship between the amount of polymer and the barrel length in contact with the polymer is shown in Table IV.

Figure 4 Frictional forces vs. plunger speed at various barrel lengths in contact with polymer melt (PP MI 0.5, 210°C, back pressure 90 psi).

If the force difference that exists between measurements with and without polymer is totally due to polymer friction against the metal wall, the force by polymer friction will be the same as the force difference, with and without polymer:

$$F_f = F - F_0 \qquad (9)$$

Namely,

$$\mu\left(\frac{P + P_0}{2}\right)A_w = (P - P_0)A_x \qquad (10)$$

Table VI   Friction Coefficients of PP(0.5) against Stainless Steel Wall at 210°C

Barrel length, L (cm)		1.54	3.08	5.40	7.71	10.8
Plunger speed (in/min)	2.0	0.0042	0.0094	0.0148	0.0111	0.0107
	5.0	0.0186	0.0172	0.0208	0.0185	0.0174
	10.0	0.0306	0.0267	0.0287	0.0236	0.0221
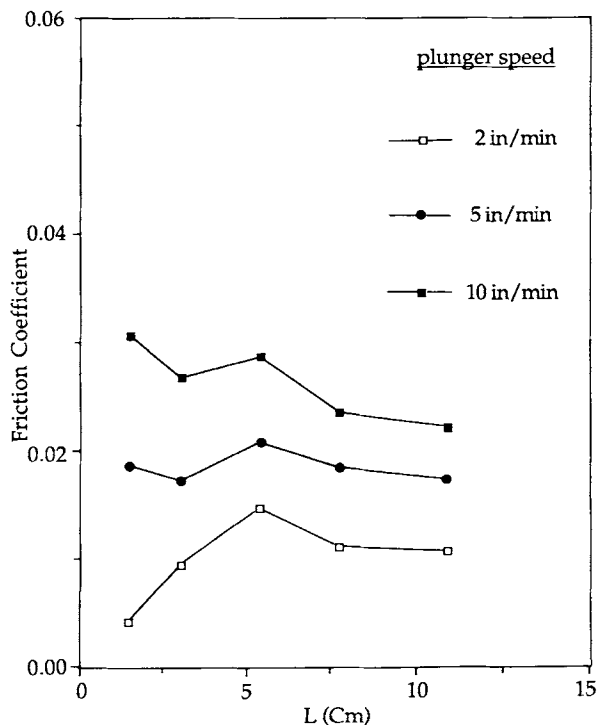
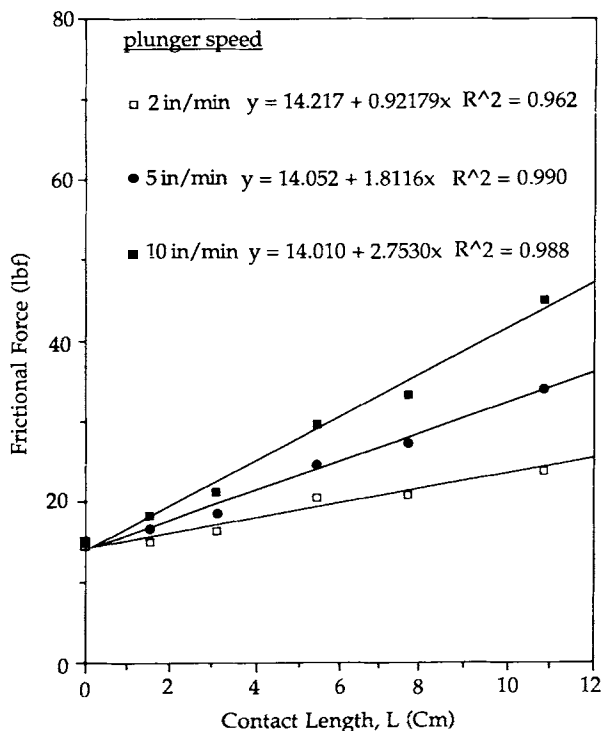**Figure 5**   Friction coefficient vs. barrel length contacted with polymer melt (PP MI 0.5, 210°C).

Table VII F_o, $\Delta F/\Delta L$, and μ at $L = 0$ (PP MI 0.5, 210°C)

Plunger Speed (in/min)	F_o (lbf)	$\Delta F/\Delta L$ (lbf/cm)	μ
2.0	14.6	0.92	0.015
5.0	14.8	1.81	0.029
10.0	15.0	2.75	0.044

The frictional forces measured in our experimental test are shown in Table V. The frictional forces in Table V were plotted in Figure 4. As shown in Figure 4, the frictional force increased as the plunger speed increased, and it also increased as the barrel length in contact with the polymer increased.

It was observed that the frictional force without polymer (F_0) increased little as the plunger speed increased when the barrel length was zero, namely, without polymer. This means that the difference of frictional forces, $F - F_0$, varies as a result of changes in F. Therefore, the frictional forces with polymer (F) are clearly distinguishable from the frictional forces without polymer (F_0) when the plunger speed is high enough and the barrel length in contact with the polymer (L) is long enough.

Figure 6   Frictional forces vs. barrel length contacted with polymer melt (PP MI 0.5, 210°C).
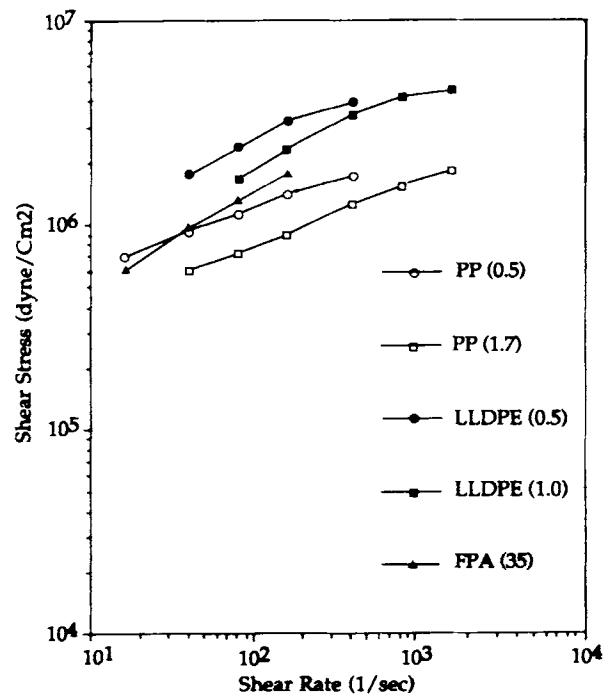

Figure 7   Shear stress vs. shear rate for PP, LLDPE, and FPA(35) (210°C, die 0.729 mm).

The frictional coefficients are shown in Table VI and are also plotted in Figure 5. As shown in Figure 5, the friction coefficients are high at the high plunger speeds, and the friction coefficients are unstable at short L. However, the friction coefficients were stable above $L = 5$ cm (equivalent to about 3 g of PP).

Theoretically, if L goes to zero, the value of $F - F_0$ also goes to zero. But the friction coefficient (μ) is sensitive to small experimental error (a small error in $F - F_0$) when the denominator L is small in our friction coefficient equation [Eq. (12)] because $(F - F_0)/L$ is very sensitive to small L.

The equation of friction coefficient can be modified as follows:

$$\mu = \frac{D}{2(F + F_0)} \times \frac{\Delta F}{\Delta L} \tag{13}$$

When $L \to 0$, $F \to F_0$. So

$$\lim_{L \to 0} \mu = \left(\frac{D}{4F_0} \times \frac{\Delta F}{\Delta L} \right) \tag{14}$$

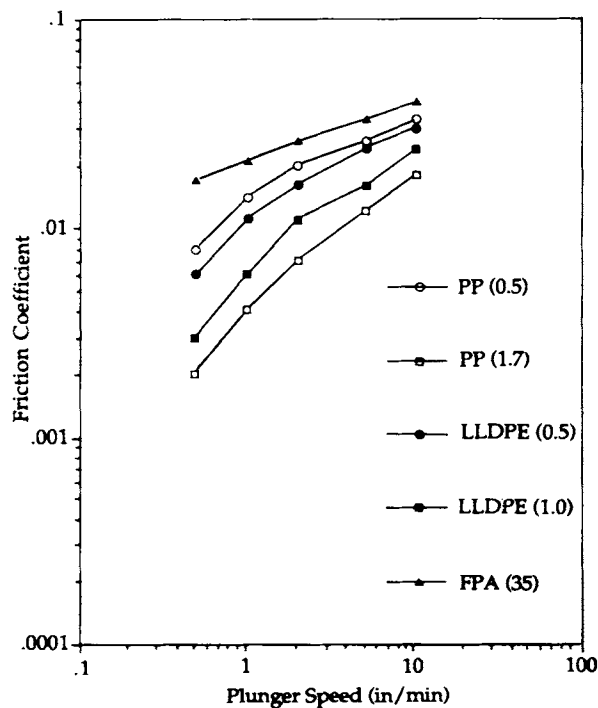where $\Delta F/\Delta L$ can be determined from the measur-
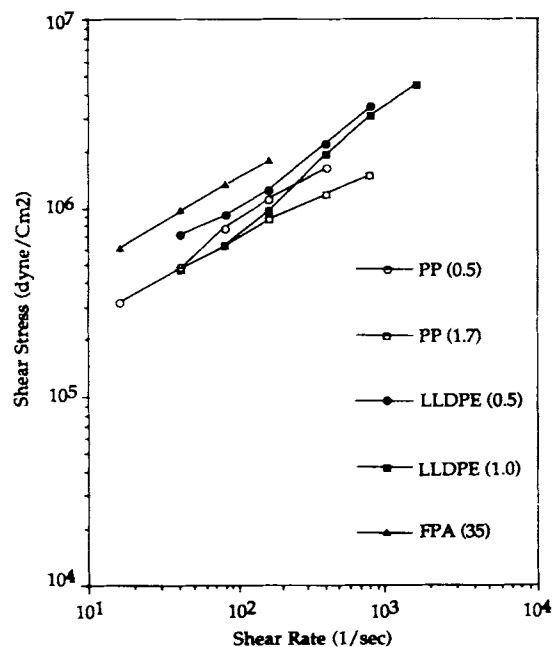

Figure 9 Shear stress vs. shear rate for PP and LLDPE treated with FPA(35) (210°C, FPA(35)-0.5% treated, die 0.729 mm).

able data. For example, $\Delta F/\Delta L$ was 2.75 lbf/cm at plunger speed 10 in/min from the plot of F vs. L as shown in Figure 6.

Figure 8 Friction coefficient vs. plunger speed for PP, LLDPE, and FPA(35) (210°C, L 5.4 cm, back pressure 90 psi).
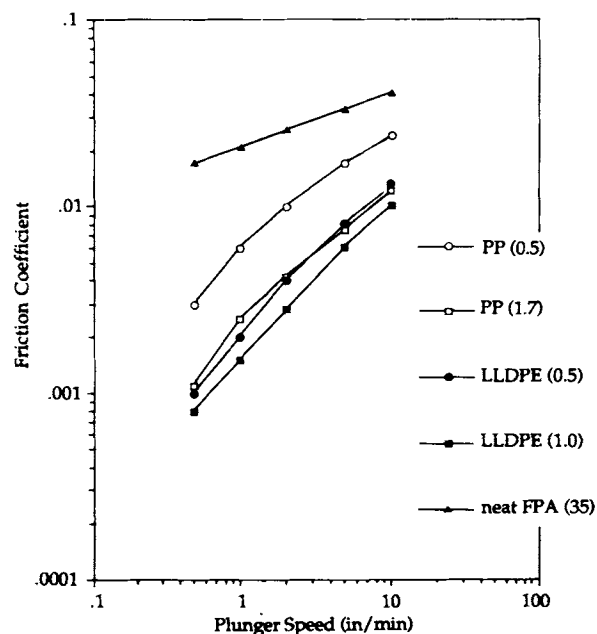

Figure 10 Friction coefficient vs. plunger speed for PP and LLDPE treated with FPA(35) (210°C, L 5.4 cm, back pressure 90 psi). *Polymer/FPA(35) = 3.5 g/0.1 g, FPA charged first and polymer later.

Then the friction coefficient at $L = 0$ can be calculated as follows:

$$\lim_{L \to 0} \mu = \frac{0.9525 \text{ cm}}{(4)(15.0 \text{ lbf})} \times 2.75 \text{ lbf/cm} = 0.044 \quad (15)$$

Therefore, this value of μ at $L = 0$ is independent of the barrel length contacted with polymer, L. F_0, and $\Delta F/\Delta L$, and μ at $L = 0$ were summarized in Table VII.

Frictional Properties of FPA-Treated PP and LLDPE

The amount of slip at a particular shear stress could be a function of the frictional characteristic between the polymer and the die wall. Therefore the shear stresses in the capillary rheometer and the friction coefficients in the friction measuring device were compared to try to understand the effect of FPA in PP and LLDPE extrusions.

The shear stresses and the friction coefficients of PP(0.5), PP(1.7), LLDPE(0.5), LLDPE(1.0), and FPA(35) were compared in Figures 7 and 8, respectively. The shear stresses in decreasing order were LLDPE(0.5), LLDPE(1.0), FPA(35), PP(0.5), and PP(1.7), as shown in Figure 7, but the friction coefficients in decreasing order were FPA(35), PP(0.5), LLDPE(0.5), LLDPE(1.0), and PP(1.7), as shown in Figure 8. The FPA(35) exhibited a high friction coefficient, and it is believed that little or no slip occurs in the extrusion of FPA(35). It is also noticeable that in spite of the high shear stresses of LLDPE(0.5) and LLDPE(1.0), as compared with that of PP(0.5), the friction coefficient of PP(0.5)
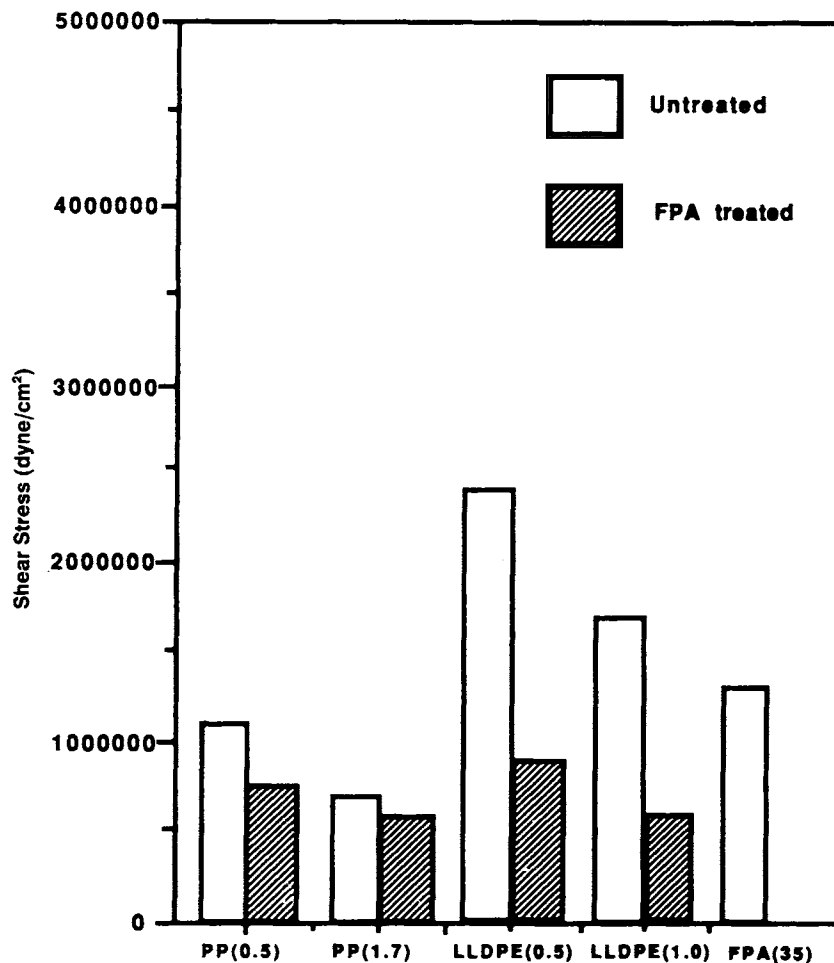

Figure 11 Comparison of shear stresses (shear rate at 79 s^{-1}), FPA(35)–0.5% treated and untreated.
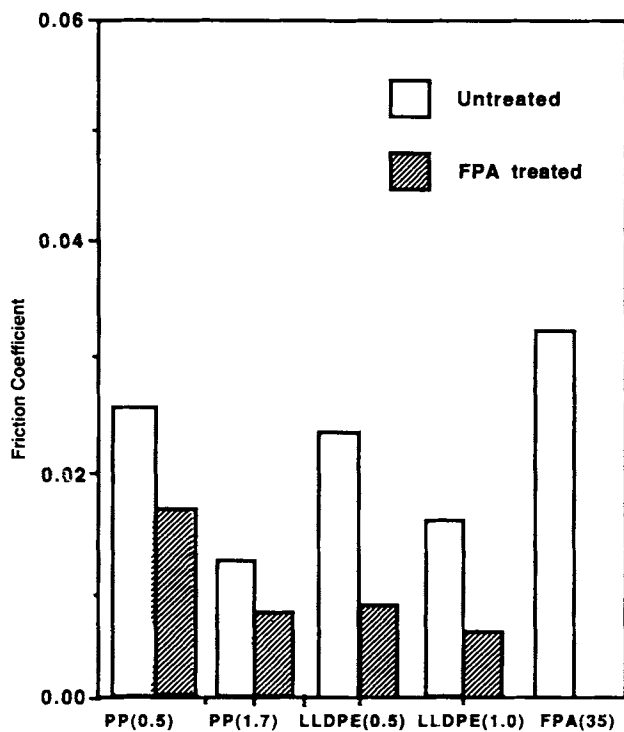
Figure 12   Comparison of friction coefficients (plunger speed 5 in/min), FPA(35) treated and untreated.

those of PP treated with FPA(35). The friction coefficients of LLDPE treated with FPA(35) also dropped more than those of PP treated with FPA(35). In the case of FPA(35) treatment, the FPA(35) provides greater reduction of friction coefficient and greater slip in the extrusion of LLDPE than in the extrusion of PP. Consequently, it causes a larger drop in shear stress in LLDPE than in PP.

It also shows that the shear stresses of untreated LLDPE were much higher than those of untreated PP, but the shear stresses of FPA-treated LLDPE were almost at the same level as those of PP. This can probably be explained on the basis that when slip occurred at the die wall in the capillary, the slip canceled a large portion of the calculated shear rate, and the actual shear rate to develop the velocity gradient of the flow was probably much lower than the calculated shear rate.

The shear stresses and the friction coefficients of PP(0.5) treated with FPA(20), FPA(35), and FPA(48) were compared in Figures 13 and 14, respectively. The shear stress reduction of PP(0.5) treated with FPA(48) was much lower than those of PP(0.5) treated with FPA(20) and FPA(35), as shown in Figure 13. But the friction coefficient of PP(0.5) treated with high viscosity FPA(48) was al-
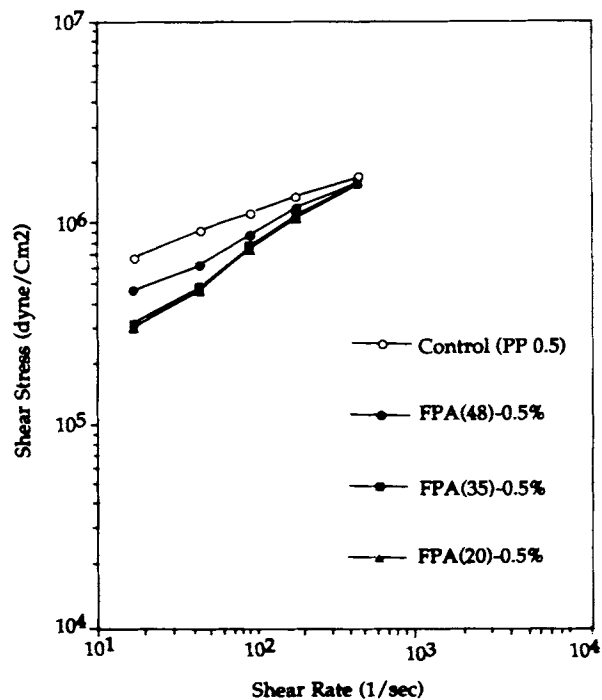
was higher than those of LLDPE(0.5) and LLDPE(1.0).

The shear stresses of PP(0.5), PP(1.7), LLDPE-(0.5), and LLDPE(1.0) treated with FPA(35)–0.5% were compared in Figure 9, and the friction coefficients of PP(0.5), PP(1.7), LLDPE(0.5), and LLDPE(1.0) treated with FPA(35) were also compared in Figure 10. In the friction coefficient measurement, 0.1 g of FPA(35) was loaded into the barrel first and 3.5 g of polymer was later put into the barrel to ensure the presence of FPA on the die wall.

In the case of FPA treatment, the shear stresses and the friction coefficients of LLDPE(0.5), LLDPE(1.0), and PP(1.7) were at approximately the same level, but the friction coefficient of PP(0.5) was higher than those of LLDPE(0.5), LLDPE(1.0), and PP(1.7). It is believed that PP(0.5) exhibited higher friction in the FPA-coated die compared with LLDPE. The low friction coefficient of PP(1.7) may be due to its low viscosity compared with that of PP(0.5).

The shear stresses and the friction coefficients of PP and LLDPE, untreated and FPA-treated, were compared in Figures 11 and 12. The shear stresses of LLDPE treated with FPA(35) dropped more than

Figure 13   Shear stress vs. shear rate for PP treated with FPA (PP MI 0.5, 210°C, die 0.729 mm).

Friction Coefficient

Plunger Speed (in/min)

Control (PP 0.5)-3.5gr

PP/FPA(48)=3.5/0.1
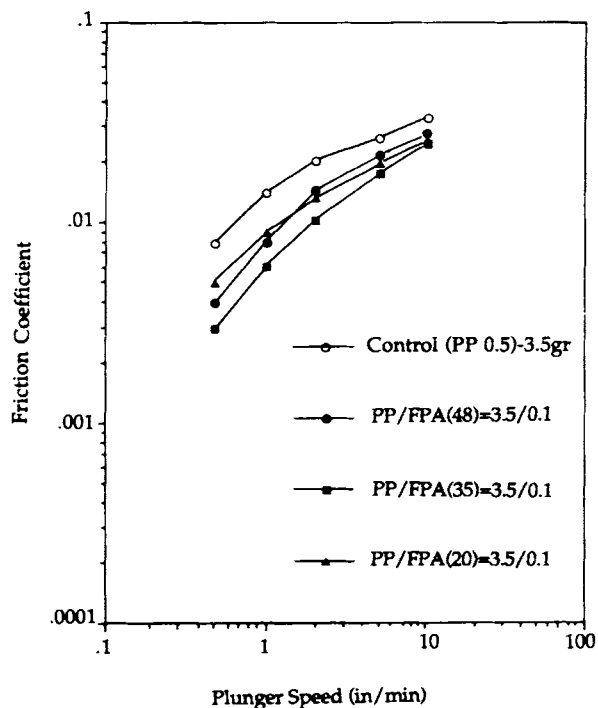
PP/FPA(35)=3.5/0.1

PP/FPA(20)=3.5/0.1

Figure 14 Friction coefficient vs. plunger speed for PP treated with FPA (PP MI 0.5, 210°C, L 5.4 cm, back pressure 90 psi). *Polymer/FPA = 3.5 g/0.1 g, FPA charged first and polymer later.
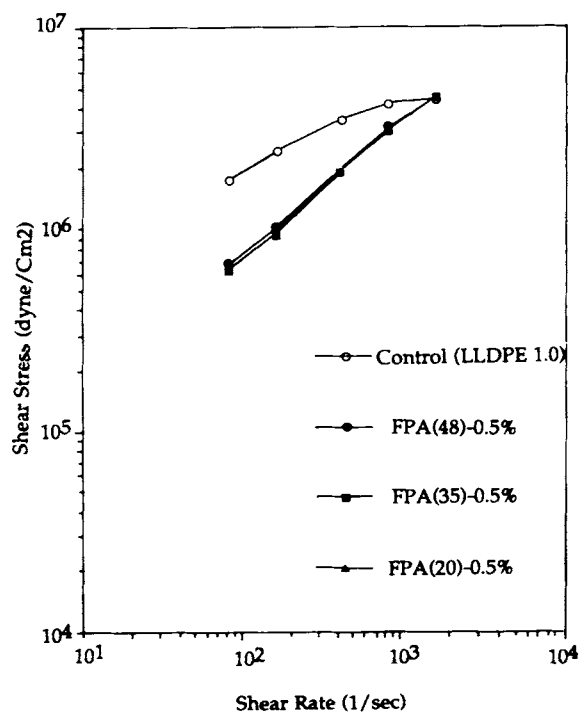
Shear Stress (dyne/Cm2)

Shear Rate (1/sec)

Control (LLDPE 1.0)

FPA(48)-0.5%

FPA(35)-0.5%

FPA(20)-0.5%

Figure 15 Shear stress vs. shear rate for LLDPE treated with FPA (LLDPE MI 1.0, 210°C, die 0.729 mm).

Friction Coefficient

Plunger Speed (in/min)

Control (LLDPE 1.0)-3.5gr

LLDPE/FPA(48)=3.5/0.1

LLDPE/FPA(35)=3.5/0.1
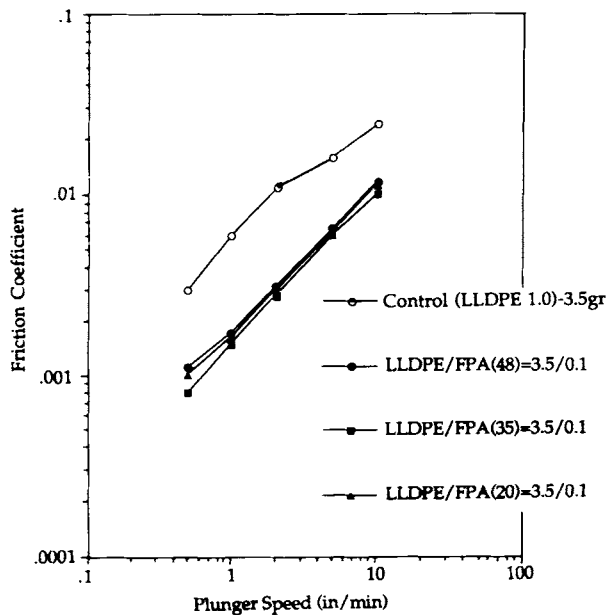
LLDPE/FPA(20)=3.5/0.1

Figure 16 Friction coefficient vs. plunger speed for LLDPE treated with FPA (LLDPE MI 1.0, 210°C, L 5.4 cm, back pressure 90 psi). *Polymer/FPA = 3.5 g/0.1 g, FPA charged first and polymer later.

most the same as that of PP(0.5) treated with low-viscosity FPA(20), as shown in Figure 14. Medium viscosity FPA(35) showed the lowest friction coefficient.

The shear stresses and the friction coefficients of LLDPE(1.0) treated with FPA(20), FPA(35), and FPA(48) were compared in Figures 15 and 16, respectively. The shear stress reductions of LLDPE(1.0) treated with FPA(20), FPA(35), and FPA(48) were essentially the same, and the friction coefficients of LLDPE(1.0) treated with FPA(20), FPA(35), and FPA(48) were almost the same.

The reductions of shear stress and friction coefficient were plotted against the Mooney viscosity of FPA in Figure 17. The reductions in shear stress and the friction coefficient of LLDPE(1.0) were much higher than those of PP(0.5) regardless of Mooney viscosity of FPA.

Frictional Force in Extrusion

To understand the frictional force at the wall in the extrusion, it is useful to quantify the frictional force. The calculated frictional forces are shown in Table VIII.

The F_{shear}'s of PP(0.5) and LLDPE(1.0) both treated with FPA(35)-0.5% were very close, although the F_{shear} of PP(0.5) untreated was much

The respective F_{slip} values were much higher than F_{sv} values; namely, the frictional forces calculated using the reduced average velocity were much higher than the frictional forces obtained using the friction coefficient. It is believed that the main reason for this difference was caused by the difference of absolute pressure. The extrusion pressure in the capillary rheometer was almost 10 times higher than that in the friction measurement system. The real friction coefficient in the capillary rheometer was expected to be much higher than that in the friction coefficient measurement system. However, the amount of frictional force was far lower than the total extrusion pressure. Therefore, the frictional force itself was not the significant factor in the total extrusion pressure, but the frictional force could be a criterion for onset of slip at a particular shear rate.

SUMMARY

With FPA added as an external lubricant, the extrusion pressure drop occurred due to slip between the polymer and the die wall. The newly developed friction measurement system permitted measurement of the friction coefficient of a molten polymer against a metal surface and, together with capillary rheometer data, it presents a very useful general technique to assist in the understanding of the mechanism of FPA in extrusion.

The friction coefficients of LLDPE treated with FPA dropped more than those of PP treated with FPA. In the case of FPA treatment, the FPA pro-
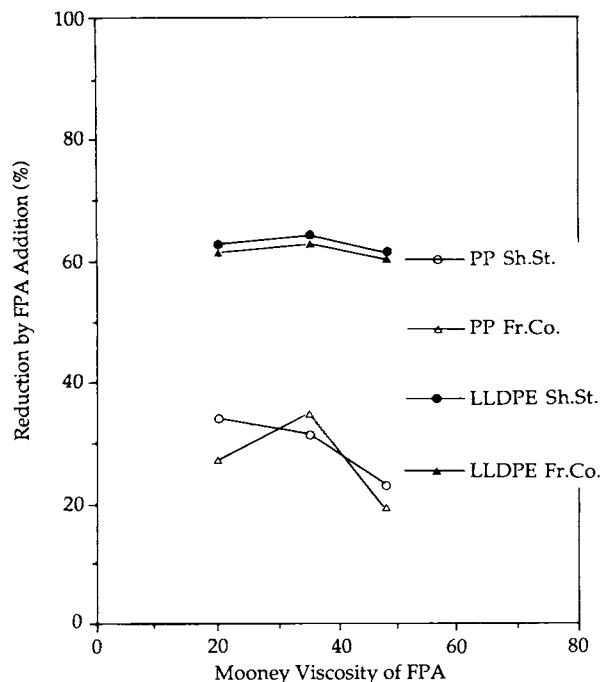

Figure 17   Reduction of shear stress (Sh.St., shear rate 79 s^{-1}) and friction coefficient (Fr.Co., plunger speed 5 in/min) for PP (0.5) and LLDPE (1.0) (Data selected from Figs. 13–16).

lower than that of LLDPE(1.0) untreated. Therefore it seems highly likely that the high extrusion force (F_{total}) of LLDPE(1.0) untreated was probably due to the low slip velocity, essentially no-slip at the wall.

Table VIII   Calculation of Frictional Force^a

	Untreated PP(0.5)	FPA(35)–0.5% Treated PP(0.5)	Untreated LLDPE(1.0)	FPA(35)–0.5% Treated LLDPE(1.0)
F_{total}	279 lbf	192	432	155
AV	0.723 cm/s	0.723	0.723	0.723
SV	0.18 cm/s	0.44	0.02	0.47
AV − SV	0.543 cm/s	0.283	0.703	0.253
$\dot{\gamma}_{w(AV-SV)}$	60.0 s^{-1}	31.1	77.1	27.8
F_{shear}	265 lbf	189	428	152
F_{slip}	14 lbf	3	4	3
μ_{sv}	0.026	0.023	0.005	0.010
F_{sv}	3.3 lbf	2.0	1.0	0.7

^{a} Shear rate: 79 s^{-1}; temp.: 210°C; die: $D = 0.0729$ cm, $L/D = 39.0$. F_{total}, extrusion force measured from the capillary rheometer; AV, average velocity calculated from the equation, $\bar{u} = (R/4)\dot{\gamma}_{w,o}$; SV, slip velocity determined from the shear rate versus $1/R$ plot; AV − SV, reduced average velocity (subtracted slip velocity); $\dot{\gamma}_{w(AV-SV)}$, reduced shear rate (true shear rate), which is responsible for F_{shear}; F_{shear}, extrusion force at $\dot{\gamma}_{w(AV-SV)}$; F_{slip}, $F_{total} - F_{shear}$, which is equivalent to frictional force; μ_{sv}, friction coefficient measured from the friction measurement setup; F_{sv}, frictional force calculated from the equation $F = (\Delta P/2)(\pi DL)\mu_{sv}$.

vided a greater reduction of friction coefficient and greater slip in the extrusion of LLDPE than in the extrusion of PP. Consequently, it caused a greater drop of shear stress in LLDPE than that in PP.

The extrusion behavior of FPA-treated PP was sensitive to the viscosity of the FPA. This was not the case for LLDPE, where it was found that a wide range of FPA viscosity showed the same shear stress drop and same friction coefficient drop in the extrusion of LLDPE.

It is speculated that when a large slip occurs at the wall, the actual shear rate associated with the velocity gradient is much lower than the calculated shear rate, since the latter includes the slip portion. When an external lubricant such as FPA was added, the extrusion pressure was determined by the reduced shear rate (true shear rate), $\dot{\gamma}_{w(AV-SV)}$, which was much lower than the apparent shear rate.

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