Further Observations of the Interface Shape of Conjugate Fibers

INTRODUCTION

In recent years, several research groups have investigated the interface shape of the extrudate when two polymers are coextruded side by side either through a circular tube or a rectangular channel. Some researchers[1-7] performed experimental studies, and others[8-13] performed theoretical studies in order to better understand the effects of the processing variables (e.g., shear rate and melt temperature) and the rheological properties of the individual components on the interface shape of the extrudate.

Today, it is generally agreed among researchers that the viscous component tends to be convex at the interface and that the less viscous component tends to preferentially wet the wall of the die. In other words, the elasticity of the fluids concerned appears to play a secondary role in determining the interface configuration of two phases.

In the present study, the authors carried out a further experimental study in which, over the range of wall shear stresses tested, the viscosity ratio of the two polymers chosen (high-density polyethylene and polystyrene) reverses due to the variation of melt temperature, whereas the elasticity ratio remains constant, independent of melt temperature. In this way, it was possible to test the role of viscosity ratio, relative to elasticity ratio, in determining the interface configuration of the two phases. Also investigated was the effect of stretching, if any, on the inferface shape of the extrudate.

EXPERIMENTAL

The apparatus used for experiment was essentially the same as that used in an earlier study[2] except for the cooling device. In the present study, we used a water tank to rapidly quench the fiber. Figure 1 gives a schematic of the apparatus which consists of two extruders, a feedblock, a spinneret, a quench tank, and a variable take-up device. The heart of the apparatus is the proper design of the feedblock which controls the two melt streams to ensure that the interface is flat on arrival at the die inlet. Figure 2 gives a schematic of the design of the feedblock, which has a knife-edged flow divider. The two melt streams, fed separately into the feedblock, meet each other at the die inlet, and the combined stream flows through the capillary and leaves the die exit.

In the present study, the variables studies were (1) the ratio of the volumetric flow rate of the two melt streams, (2) the melt temperature, (3) the L/D ratio of the circular die, and (4) the stretch ratio of the extrudate. At each extrusion condition, extrudate samples were collected and were later cross-sectioned to determine the shape of the interface.

Polymers coextruded were low-density polyethylene (LDPE) with polystyrene (PS), high-density polyethylene (HDPE) with polystyrene (PS), and polypropylene (PP) with polystyrene (PS).
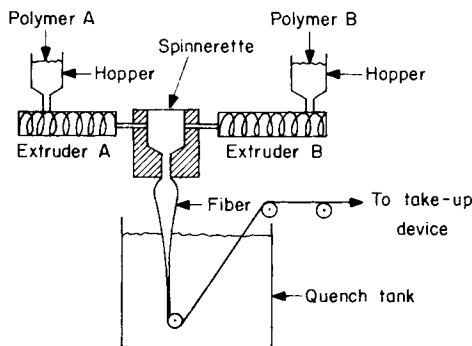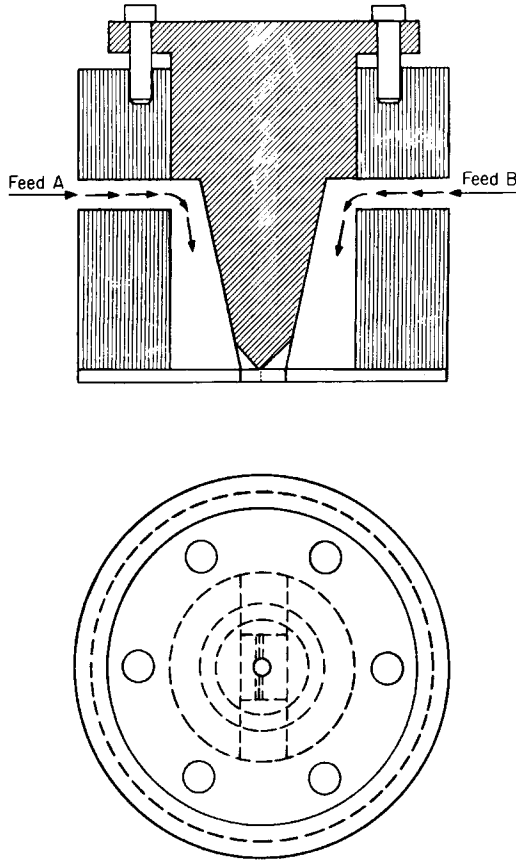

Fig. 1. Schematic of the experimental apparatus.
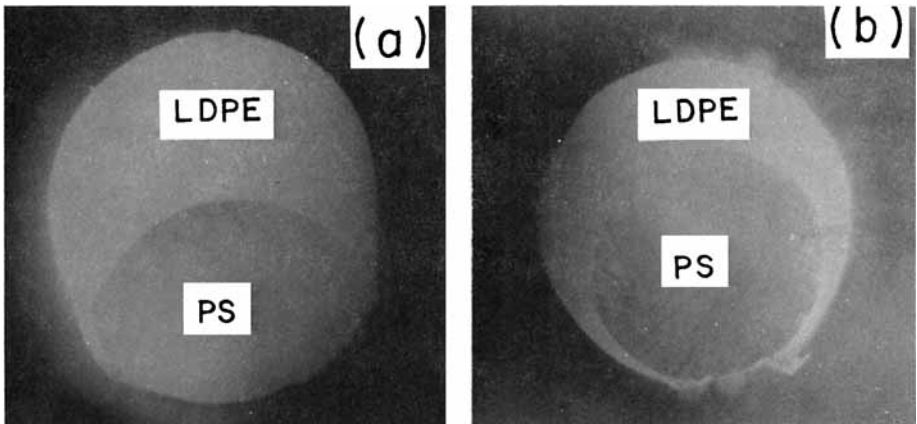
Fig. 2. Schematic of the design of the feedblock.

Fig. 3. Interface shape for the LDPE/PS system with different L/D ratios: (a) $L/D = 4$; (b) L/D = 11. Extrudate sample was collected with no stretching; $T = 200°C$.

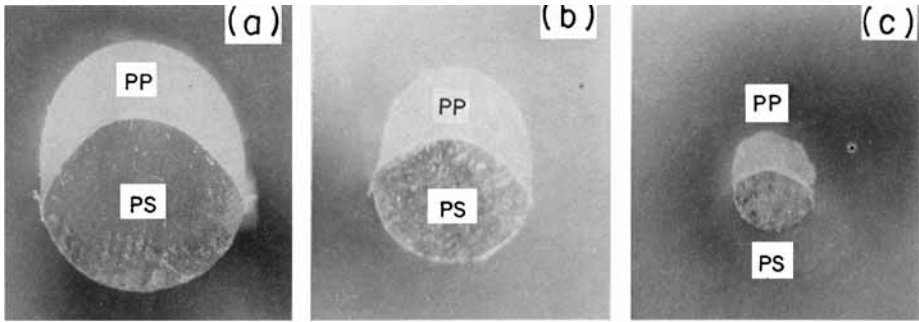Fig. 4. Interface shape for the PP/PS system ($T = 200°C$) at different stretch ratios: (a) V_L/V_0 = 0 (no stretching); (b) $V_L/V_0 = 4.1$; (c) $V_L/V_0 = 6.7$. The L/D ratio is 4.0.

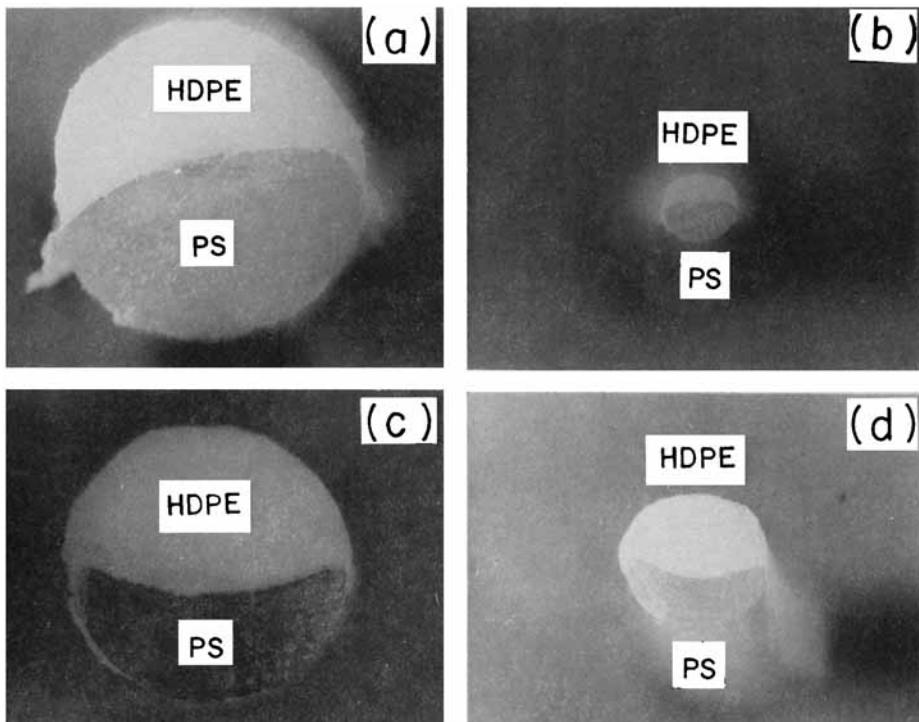Fig. 5. Interface shape for the HDPE/PS system as affected by melt temperature: (a) $T = 200°C$, $V_L/V_0 = 0$; (b) $T = 200°C$, $V_L/V_0 = 5.2$; (c) $T = 240°C$, $V_L/V_0 = 0$; (d) $T = 240°C$, $V_L/V_0 = 3.1$. The L/D ratio is 4.0.

RESULTS AND DISCUSSION

Figure 3 shows representative interface cross sections of the low-density polyethylene (LDPE) and polystyrene (PS) system, extruded through circular tubes having L/D ratios of 4 and 11. The extrudate samples were collected at a position very close to the die exit so that the interface shape would be little affected by stretching (due to the gravitational force). It is seen in Figure 3 that, at an L/D ratio of 4, the PS protrudes into the LDPE, and, at an L/D ratio of 11, the PS is completely surrounded by the LDPE, giving rise to a sheath-core configuration.
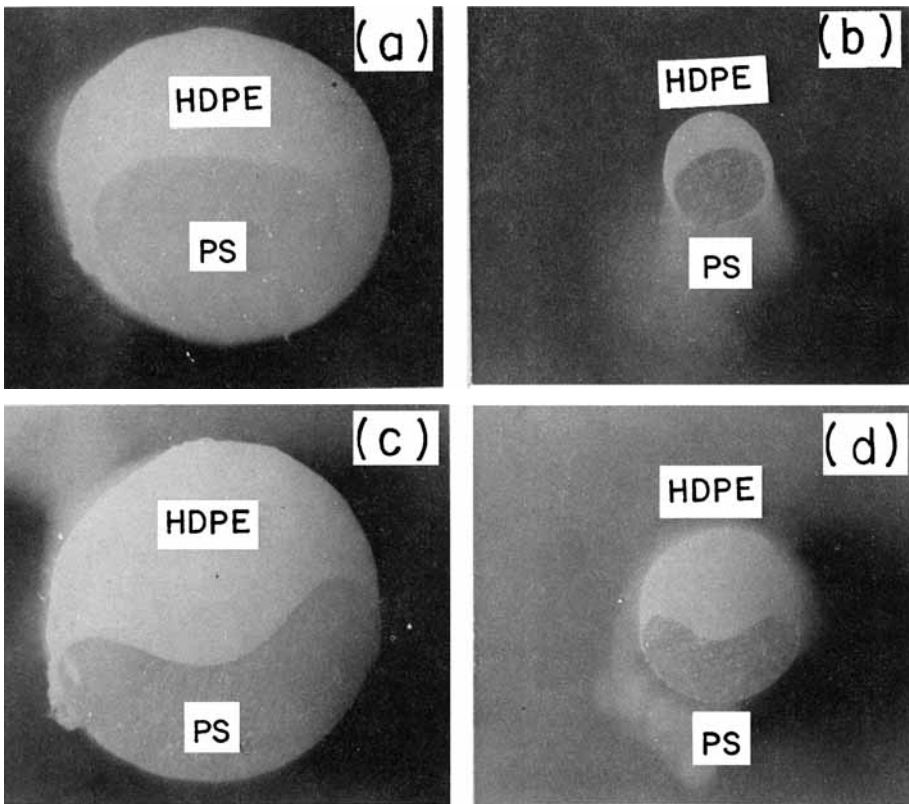
Fig. 6. Interface shape for the HDPE/PS system as affected by melt temperature: (a) $T = 200°C$, $V_L/V_0 = 0$; (b) $T = 200°C$, $V_L/V_0 = 5.5$; (c) $T = 240°C$, $V_L/V_0 = 0$; (d) $T = 240°C$, $V_L/V_0 = 5.5$. The L/D ratio is 11.

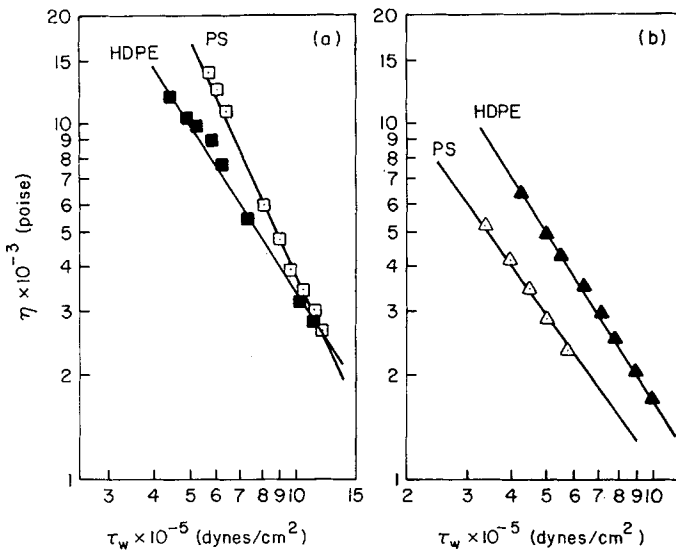Fig. 7. Viscosity vs. shear stress for the HDPE/PS system at two different melt temperatures: (a) $T = 200°C$; (b) $T = 240°C$.
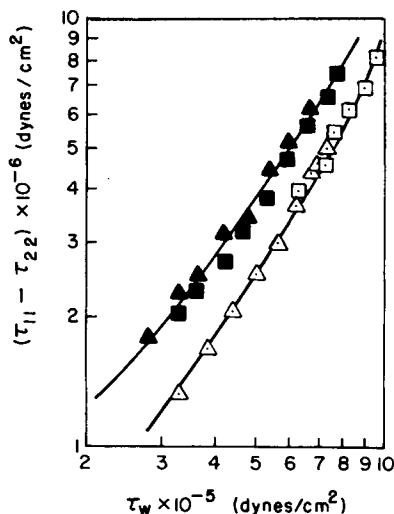
Fig. 8. First normal stress difference vs. shear stress for the HDPE/PS system at two different melt temperatures. Closed symbols for HDPE: (■) 200°C; (▲) 240°C; open symbols for PS: (□) 200°C; (△) 240°C.

Figure 4 shows representative interface cross sections of the polypropylene (PP) and polystyrene (PS) system, extruded through a circular tube having an L/D ratio of 4. The three photographs in Figure 4 represent interface cross sections at different stretch ratios. It is seen that stretching does not affect the interface configuration. Similar observations were made for the LDPE/PS system.

Figure 5 shows representative interface cross sections of the high-density polyethylene (HDPE) and polystyrene (PS) system, extruded through a circular tube having an L/D ratio of 4. It is seen that, at a fixed melt temperature, the interface shape is little influenced by stretching. However, as the melt temperature is increased from 200 to 240°C, interface curvature reversal is seen. That is, at 200°C, the PS protrudes into the HDPE, and at 240°C the HDPE protrudes into the PS. Essentially the same tendency is seen in Figure 6 when the L/D ratio of the die is increased from 4 to 11.

Earlier experimental observations[1,2,4-6] show that the component which protrudes into the other component must have the greater viscosity. According to rheological measurements,[14] this is, in fact, the case for both the PS/LDPE and PS/PP systems at 200°C over the range of wall shearing stresses tested. However, it is also true that the PS has a lower elasticity, in terms of either the first normal stress difference $\tau_{11} - \tau_{22}$ and/or recoverable elastic strain $S_R = (\tau_{11} - \tau_{22})/\tau_{12}$ than either LDPE or PP. Therefore, it is not clear what contribution the fluid elasticity makes to the interface configuration of two phases.

Figure 7 gives plots of melt viscosity versus shear stress, and Figure 8 plots of first normal stress difference versus shear stress, for polystyrene (PS) and high-density polyethylene (HDPE) melts at 200° and 240°C. It is seen in Figure 7 that, over the range of extrusion conditions tested (i.e., wall shear stress below 0.9×10^6 dynes/cm^2), at 200°C the PS is *more* viscous than the HDPE, whereas at 240°C the PS is *less* viscous than the HDPE. On the other hand, the ratio of melt elasticities of the two components (PS and HDPE) remains essentially constant, independent of temperature, as may be seen in Figure 8. It can be concluded, therefore, that the interface curvature reversal given in Figures 5 and 6 is attributable to the viscosity ratio reversal of the two components (i.e., PS and HDPE) as the melt temperature is increased from 200° to 240°C.

Southern and Ballman[1,5] and Lee and White[4] have reported their observations of interface curvature reversal, when, at a fixed melt temperature, the viscosity ratio reversal was obtained by increasing the shear rate, that is, for polymer systems that give rise to crossovers of the viscosity–shear rate curve as the shear rate is increased.

To summarize, the results presented above support the findings of other investigators,[1,4,5] namely, that irrespective of relative values of the fluid elasticity on the opposite sides of the interface, the low-viscosity component is always to be concave toward the high viscosity component. That is, the low viscosity component tends to encapsulate the high-viscosity component. Furthermore, the

stretching of the extrudate does not appear to influence the interface shape of two phases, at least over the range of stretch ratios tested in the present study. However, we do not wish to rule out the possibility that very high stretch ratios commonly occurring in commercial spinning (say, above 100) can conceivably affect the interface shape of two phases. In our study reported here, we were not able to obtain high stretch ratios for the reason that, due to the incompatibility of the polymer systems employed, thread breakage occurred at and above a stretch ratio V_L/V_0 of about 10.

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