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Frictional heating of extruded polymer melts

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Rheo-particle image velocimetry and thermal imaging results show that frictional and viscous heating act synergistically to produce significant temperature increases when a melt is extruded under slip conditions.

Extrusion is the most efficient and commonly used method for melting plastic resins, as well as for incorporating additives, colors, and fillers into the molten polymers. Extrusion is also used to impart a shape to the polymer melt and produce continuous profiles (e.g., filaments and tubes), and is frequently coupled with other shaping processes, such as blow molding and film blowing. During the extrusion of polymer melts, distortions of the extrudates and melt-flow instabilities can arise. Indeed, these phenomena are characteristic of highly entangled linear polymers (e.g., polyethylenes, rubbers, and polysiloxanes). The presence of these phenomena can therefore often limit the productivity of extrusion-based processes, and ways to reduce their effects are required.

It has previously been noted that extrusion instabilities are related to the slippage of the polymer melt at the die walls.[1] In particular, the extrusion of polymer melts under strong slip conditions causes several macroscopic phenomena because of dynamic friction at the die wall.[2] These phenomena include the elimination of some flow instabilities, the delay of the appearance of extrudate distortions, monotonic flow curves, significant decreases in extrusion pressure, as well as electrification (known as tribocharging) of the melt. The strong slip conditions can be achieved with the use of low-surface-energy coatings in extrusion dies,[3,4] as well as with some dies that are made of high-surface-energy materials (e.g., brass or other copper alloys).[5,6] Indeed, there are various commercial polymer processing aids (PAs) that can be used to induce slip in extrusion dies. In addition to the strong slip conditions, dynamic friction at the polymer–die interface causes an increase in the temperature of the melt (which depends on the slip velocity). This type of (slip-induced) melt heating is known as 'frictional heating' to distinguish it from the more well-known viscous heating.[7] This frictional heating is relevant for polymer processing operations, but it has not yet been properly investigated.

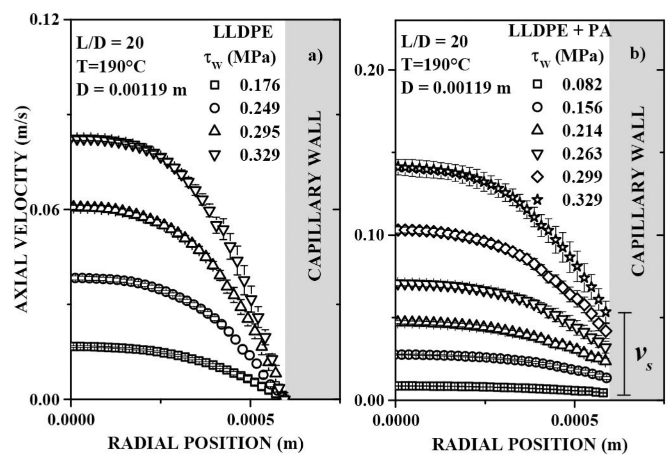

Figure 1. *Experimentally determined velocity profiles for (a) the pure linear low-density polyethylene (LLDPE) melt and (b) the blended mixture of the LLDPE and the fluoropolymer processing aid (LLDPE + PA). These profiles were obtained for different wall shear stresses (τ_w) that were below the critical level (τ_c), at which the onset of unstable stick-slip flow occurs. v_s: Slip velocity. L: Length. D: Diameter. T: Temperature.*

In our work,[8] we have therefore studied the relationship between slip flow and frictional heating for a pure linear low-density polyethylene (LLDPE), and for a blended mixture of LLDPE and a fluoropolymer PA (LLDPE + PA). For our investigation, we conducted continuous extrusion of these materials through a capillary die and we were able to separate the effects of viscous and frictional heating.[8] We also used rheo-particle image velocimetry (Rheo-PIV)[2] and non-contact temperature measurements to describe the flow kinematics of the two LLDPE samples (i.e., with and without slip) and to relate these results to the rising temperature of the polymer melt.

We obtained velocity profiles, through the use of Rheo-PIV, for both the pure LLDPE and the LLDPE + PA melts (see Figure 1). For these measurements, the melts were subjected to different levels of wall shear stress (τ_w) that were below the critical value (τ_c), i.e., at which the onset

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10.2417/spepro.006553 Page 2/3

of unstable stick-slip flow occurs. These results indicate that the pure LLDPE melt did not exhibit any slip, whereas the LLDPE + PA melt exhibited a large amount of slip.

We also determined the slip velocity (v_s) for the LLDPE and LLDPE + PA melts from the velocity profiles and plotted these results as a function of τ_w (see Figure 2). We find that v_s increases with τ_w according to two different power-law-type slip regimes, i.e., where τ_w is less than τ_c and where τ_w is greater than τ_c. In addition, we note that the slip velocity values for both the pure LLDPE and the LLDPE + PA mixture are comparable when τ_w is greater than τ_c. This indicates that the addition of the PA is almost irrelevant for extrusion at high shear rates. Moreover, it reflects the dominance of interfacial interactions over bulk interactions in the melt when they are processed at high shear rates. We also observe a significant contribution of slip to the total flow rate (as high as 60%). This type of outcome has previously been interpreted as being caused by plug-like flow of the melt.[9]

During our experiments, we also measured the rising temperature (ΔT) of the extrudates at the die exit, under both slip and no-slip flow conditions. These results are shown in Figure 3 as a function of the apparent shear rate and in Figure 4 as a function of the wall shear stress. We observe a continuous increase in ΔT with increasing apparent shear rate, with similar results for both processing conditions (i.e., for both melt samples). Our ΔT results exhibit substantially different behavior, however, when plotted as a function of τ_w (see Figure 4). In this case, there is a clear difference between the ΔT results that are obtained from the slip and no-slip conditions. The ΔT values obtained for the LLDPE + PA melt (under strong slip conditions) are higher than those

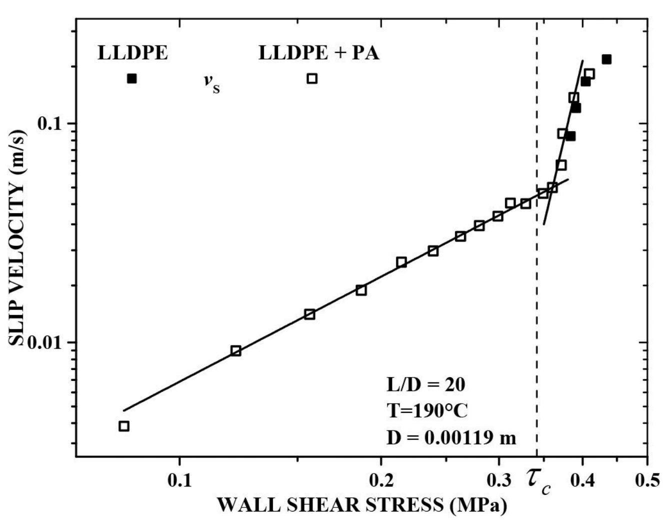

Figure 2. *Slip velocity (v_s) of the LLDPE and LLDPE + PA melts, as as function of τ_w. The two slip regimes are apparent from their different slopes.*

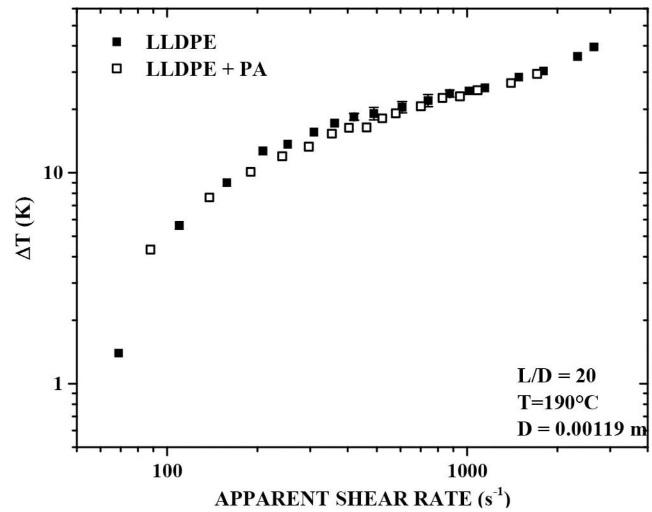

Figure 3. *Temperature increase (ΔT) of the extrudates, measured at the die exit, under both slip (i.e., for the LLDPE + PA blend) and no-slip (for the pure LLDPE) flow conditions. The results are shown as a function of the apparent shear rate.*

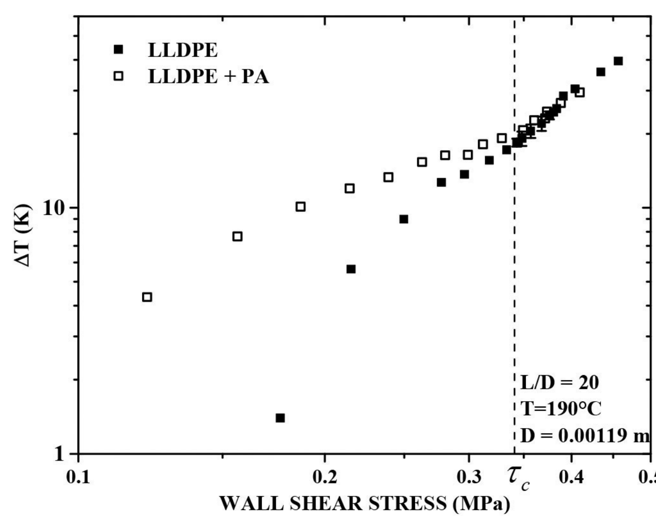

Figure 4. *ΔT of the extrudates, measured at the die exit, under both slip (i.e., for the LLDPE + PA blend) and no-slip (for the pure LLDPE) flow conditions. The results are plotted as a function of τ_w.*

for the pure LLDPE sample when τ_w is less than τ_c, but they are about equal when τ_w is greater than τ_c.

Our results indicate that in the presence of slip, frictional and viscous heating acted synergistically to produce higher temperatures in

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the melt. Indeed, under strong slip conditions, we observed significant temperature rises during extrusion of up to about 39K. According to numerical simulations of viscous heating[10] for polymer melts, the largest temperature increase should occur close to the capillary wall and this should be observed as a flattening of the velocity profiles. From our Rheo-PIV measurements, however, we do not detect such changes in the velocity profiles. To fully describe the increasing temperature of polymer melts during extrusion, in the presence of slip, we therefore believe that a new solution for momentum and energy conservation equations is required (i.e., in which both frictional and viscous heating are considered).

In summary, we have conducted a rheo-particle image velocimetry study of pure LLDPE and an LLDPE + PA mixture to investigate the relationship between slip flow and frictional heating during melt extrusion. Our results illustrate some aspects of continuous extrusion of LLDPE (under strong slip conditions) and rising melt temperature that have not previously been observed. For instance, we have found a clear difference between the viscous and frictional heating that occurs before the onset of the stick-slip flow regime. We have also shown that in the presence of slip, frictional and viscous heating act synergistically to produce greater temperature increases in the melt. Our results can be used to establish appropriate slip boundary conditions, and can be usefully compared with numerical simulation data. We also note that it is possible for frictional heating to occur for pure polymers (i.e., in the absence of PAs), but mainly for high-molecular-weight linear polymers. In our ongoing work, we are thus studying the effect of frictional heating on resins with different molecular characteristics.

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