THE EFFECT OF COATHANGER DIE MANIFOLD SYMMETRY ON LAYER UNIFORMITY IN MULTILAYER COEXTRUSION

Joseph Dooley, Hyunwoo Kim, Patrick C. Lee, and Robert Wrisley
The Dow Chemical Company, Midland, MI

Abstract

Multilayer coextrusion is a process in which two or more polymers are extruded and joined together in a feedblock or die to form a single structure with multiple layers. This paper will discuss the effect of die manifold channel symmetry of the flow of coextruded structures through coathanger style dies.

Introduction

Many polymers are extruded through various styles of dies to produce monolayer and multilayer products. Coextrusion is a common method used for producing multilayer structures. Coextrusion is a process in which two or more polymers are extruded and joined together in a feedblock or die to form a single structure with multiple layers. This technique allows the processor to combine the desirable properties of multiple polymers into one structure with enhanced performance characteristics. The coextrusion process has been widely used to produce multilayer sheet, blown film, cast film, tubing, wire coating, and profiles [1-6].

This paper will discuss the effect of die manifold channel symmetry on the flow of coextruded structures through coathanger style dies. Experimental and numerical data will be shown on the flow of coextruded polymer melts through several different die manifold channels containing different levels of symmetry. These data will then be used to show how the flow and layer distribution of coextruded structures is affected by the symmetry or asymmetry of the die channel.

Background

Many different types of monolayer and coextruded polymeric structures are currently produced using different styles of dies. However, analyzing the flow of polymer melts through dies can be difficult due to the complex three dimensional flow patterns that exist [7-10]. This analysis becomes even more complex when multiple layers of different materials are introduced into the structure through coextrusion methods [11-21].

Shaping operations for polymers cover a wide range of technologies producing products such as flat sheet, cast film, blown film, pipe, bottles, fibers, profiles, and many others. Since each of these products requires a different die to shape the polymer into its final form, the number of die types that have been developed is enormous. Because of the large number and different styles of die designs, many die distribution manifold styles have been developed. These designs have varying levels of channel symmetry depending on the final product shape and the difficulty in the fabrication of the die. The purpose of this work was to experimentally and numerically determine the flow and layer distribution of coextruded structures flowing through coathanger style dies containing distribution manifold channels with different levels of geometric symmetry.

Experimental

A commercially available resin, STYRON 484 High Impact Polystyrene (HIPS) resin manufactured by Americas Styrenics was used in the experiments. This resin has a Melt Flow Index of 2.8 (dg/min, 5 kg weight, 200 ºC) and a specific gravity of 1.04. The rheology of this resin at our processing temperature of 215 ºC is shown in Figure 1.

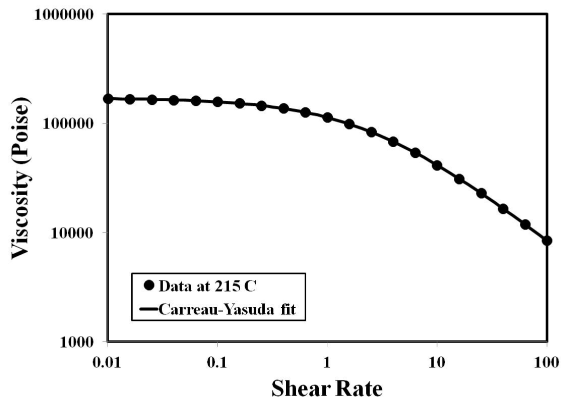


Figure 1. Rheology of HIPS Resin at 215 ºC.

The coextrusion line used in this study consisted of two 31.75 mm (1.25 inch) diameter, 24:1 L/D single screw extruders and a 25.4 mm (1.0 inch) diameter, 24:1 L/D single screw extruder. The extruders fed individual gear pumps to ensure uniform flow of the polymer melts to the feedblock and dies. The gear pumps were attached to a feedblock by transfer lines that contained variable depth thermocouples to ensure consistent and uniform temperatures from the extruders. A feedblock was used to produce layered coextruded structures with either 3 or 200 layers. These layer arrangements allowed us to look at both simple (3 layer) and more complex (200 layers) systems as they flowed through the die. The layered structures consisted of 10% skin layers and an 80% core by volume. Coextruded structures were made using the same material in each extruder with different colored pigments added to each to allow determination of the interface location in the structure.

A schematic diagram of the extrusion line set-up is shown in Figure 2. This simplified diagram shows only two of the three extruders that can be used in this system. This system can be configured in different combinations to produce the 3 layer and 200 layer coextruded structures described earlier.

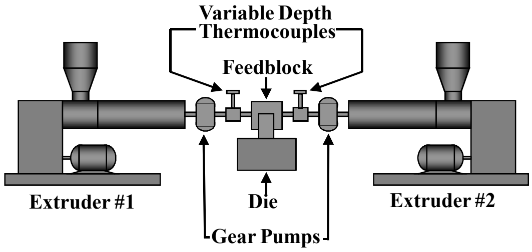


Figure 2. A schematic diagram of the extrusion line.

The flow through a coathanger style die is shown schematically in Figure 3.

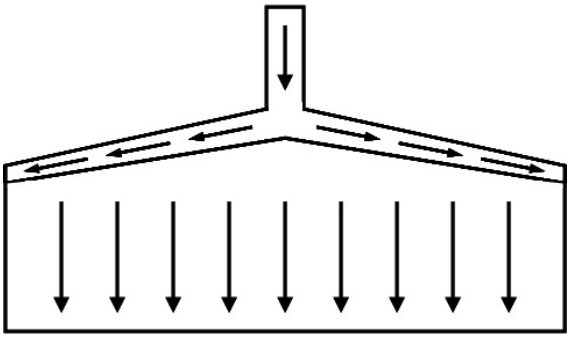


Figure 3. A schematic diagram showing the flow through a coathanger die geometry.

Figure 3 shows how the flow enters the distribution manifold at the top and then is distributed across the die width and then flows downward through the land region.

Attached to the exit of the feedblock were coathanger style dies containing different cross-sectional geometries in their distribution manifolds. These geometries are shown schematically in Figure 4.

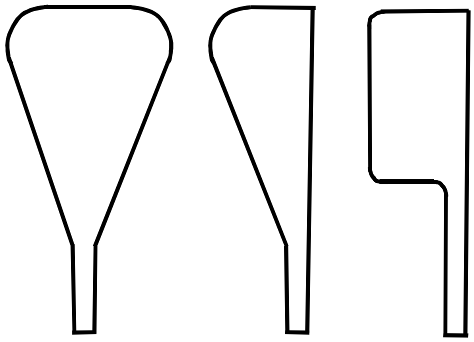


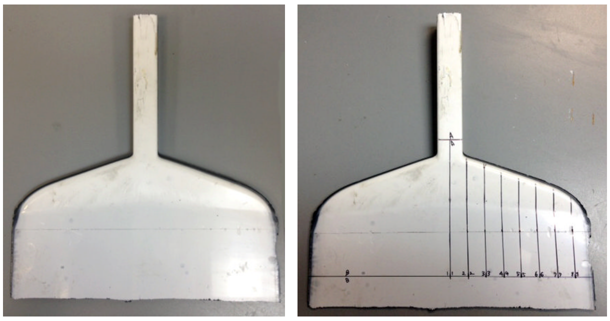
Figure 4. Coathanger die manifold cross-sectional geometries.

Figure 4a shows a teardrop shaped manifold geometry commonly used in many coathanger style dies. This geometry is symmetric about its vertical centerline. Figure 4b shows a half teardrop shaped manifold geometry. This type of geometry is not symmetric about its vertical centerline. This type of manifold is used when a streamlined design is desired but when only one face of the die is machined with a distribution manifold. This is more common when machining a blow molding head or a blown film die. Figure 4c shows a manifold geometry that is rectangular in shape and has no taper at the bottom of the channel. This manifold is highly asymmetric about its vertical centerline and not well streamlined. These three manifold geometries allowed us to study the symmetry effects on the flow and distribution of coextruded structures.

For a typical experiment, the coextrusion line was run for 30 minutes to ensure that steady-state conditions had been reached. The experiments were run at a temperature of 215°C and an extrusion rate of 9.0 kg/h. When steady state was reached, the extruders were stopped simultaneously and the coextruded material was cooled while still in the die channel, solidifying the material. After it had cooled to room temperature, the polymer "heel" was removed from the die and cut into sections to expose the cross-sectional faces along the die. This procedure allowed the major deformations of the interfaces to be examined.

Results

The experimental setup shown in Figure 2 was first run with an 8 inch wide coathanger die containing the cross-sectional geometry shown in Figure 4a. The frozen heel produced in this experiment is shown in Figure 5. Figure 5a shows the die heel top surface as it was removed from the die while 5b shows the die bottom surface labeled where it will be cut into sections to expose the cross-sectional faces along and across the die.



(a) (b)

Figure 5. "Frozen" heel from the die with a symmetrical manifold geometry similar to the diagram in Figure 4a. The top (a) and bottom (b) surfaces are shown.

The initial experiments using the die with the symmetric manifold were run with a three layer structure with the skins pigmented white and the core pigmented black so that the interface locations could be determined.

Figure 6 shows a cross-sectional cut of the three layer structure before it enters the die distribution manifold. This Figure shows that the entering structure is symmetric and the layers are fairly uniform in thickness. The uniformity of these layers has been slightly affected by the highly viscoelastic properties of this polystyrene resin, as has been discussed previously (11-21). However, for the purposes of this study, these slight non-uniformities were thought to have little impact on the results of these experiments.

Figure 6. The three layer structure prior to entering the die distribution manifold.

Figure 7 shows the cross-sectional cuts for a 3 layer structure in the symmetrical die manifold. The image on the far left is near the centerline of the die and the image on the far right is near the edge of the die. These images show the progression of the layer interface locations as the structure flows down the distribution manifold from left to right.

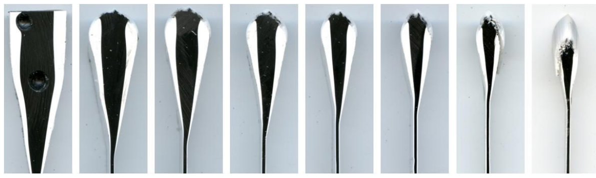


Figure 7. Cross-sectional cuts for a 3 layer structure in a symmetrical manifold. Flow progresses down the channel from left to right with the image on the left taken from near the center of the die and the image on the right taken from near the edge of the die.

Note in Figure 7 that the thicknesses of the skin layers remain relatively constant as the structure flows down the distribution manifold.

Figure 8 shows the relative thicknesses of the skin and core layers from the left to the right edge of the die in the land region. In this Figure, the core is shown in black and the skins in white. This Figure shows that the skin layer thicknesses are fairly uniform across the width of this structure. When this same experiment was done with a 200 layer sample, the results were very similar.

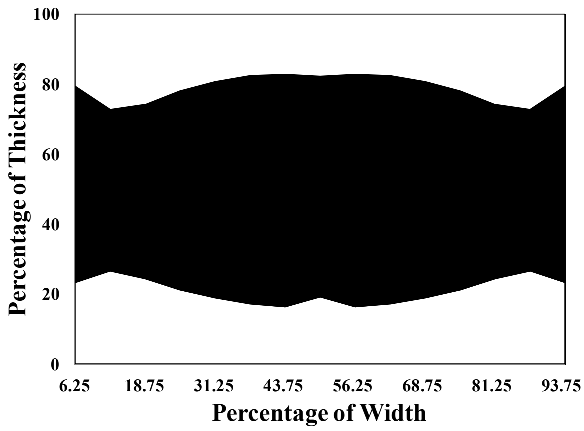
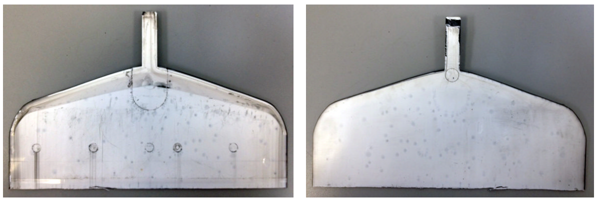


Figure 8. Skin and core layer thicknesses across the width of the die land for a 3 layer structure in a symmetrical manifold.

The next experiment consisted of running the three layer sample through the half teardrop asymmetric die manifold shown in Figure 4b. The 10 inch wide frozen heel produced in this experiment is shown in Figure 9. Figure 9a shows the die heel top surface as it was removed from the die while 9b shows the bottom surface. This Figure shows that the distribution manifold is cut only in the top surface as was shown in Figure 4b.



(a) (b)

Figure 9. "Frozen" heel from the die with an asymmetrical half teardrop manifold geometry similar to the diagram in Figure 4b. The top (a) and bottom (b) surfaces are shown.

Figure 10 shows the cross-sectional cuts for a 3 layer structure in the half teardrop asymmetrical die manifold. These images show the progression of the layer interface locations as the structure flows down the distribution manifold from left to right.

Figure 10. Cross-sectional cuts for a 3 layer structure in a half teardrop asymmetrical manifold. Flow progresses down the channel from left to right with the image on the left taken from near the center of the die and the image on the right taken from near the edge of the die.

Figure 11 shows the relative thicknesses of the skin and core layers from the left to the right edge of the die in the land region. This Figure shows that the bottom skin layer thickness is fairly uniform across the width of this structure, although the center is slightly thicker than the edges. However, the top skin layer, which is the side of the die in which the distribution manifold was cut, shows significantly more asymmetry with the layer being thinner near the center and thicker at the edges of the die.

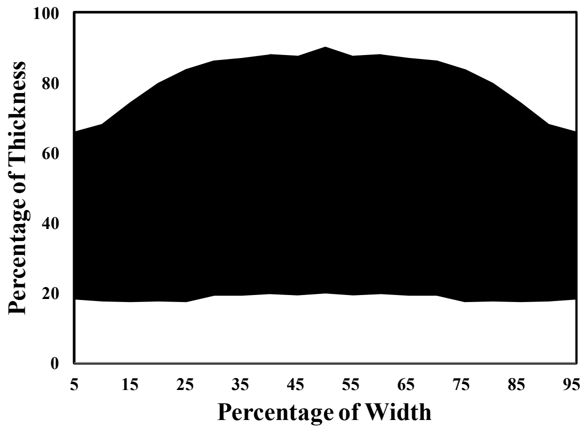


Figure 11. Skin and core layer thicknesses across the width of the die land for a 3 layer structure in a half teardrop asymmetrical manifold.

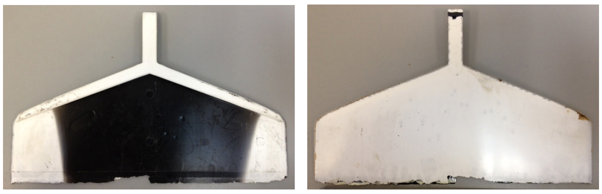
When this same experiment was done with a 200 layer sample, the results were very similar. However, running a 200 layer sample does yield more information on the flow of the layers compared to a 3 layer sample. Figure 12 shows an example of a 200 layer sample from near the center of the half teardrop distribution manifold. The black layers in the image are actually bands of 25 alternating black and white layers but they are too small to see in this picture. However, the thicker white layers between the 25 layer bands are visible and show the paths that the layers take as they flow (from right to left in this image) from the distribution manifold and down through the land region.

Figure 12. A cross-sectional view of the two hundred layer structure near the center of the die with the half teardrop distribution manifold.

Figures 10 through 12 all show that the slight amount of asymmetry in the half teardrop distribution manifold affected the distribution of the layer thicknesses in this structure. Comparing Figure 8 for the symmetrical manifold and Figure 11 for the half teardrop manifold also shows this affect. It appears that the asymmetry causes more of the top skin to flow down the distribution manifold rather than flowing down towards the land. This causes the top skin layer to be thinner near the center of the die and thicker near the edge, as is shown in Figure 11.

The next experiment consisted of running the three layer sample through the rectangular asymmetrical die manifold shown in Figure 4c. The 10 inch wide frozen heel produced in this experiment is shown in Figure 13. Figure 13a shows the die heel top surface as it was removed from the die while 13b shows the bottom surface.

Note that the bottom surface is completely white while the top surface is white in the distribution manifold and the edges of the land but black in the middle of the land area. This is significantly different than the white surfaces shown in Figure 5 for both surfaces of the heel produced using the symmetric die manifold.



(a) (b)

Figure 13. "Frozen" heel from the die with an asymmetrical rectangular manifold geometry similar to the diagram in Figure 4c. The top (a) and bottom (b) surfaces are shown.

Figure 14 shows the cross-sectional cuts for a 3 layer structure in the rectangular asymmetrical die manifold. These images show the progression of the layer interface locations as the structure flows down the distribution manifold from left to right.

Figure 14. Cross-sectional cuts for a 3 layer structure in a rectangular asymmetric manifold. Flow progresses down the channel from left to right with the image on the left taken from near the center of the die and the image on the right taken from near the edge of the die.

Figure 15 shows the relative thicknesses of the skin and core layers from the left to the right edge of the die in the land region. In this Figure, the core is shown in black and the skins in white. This Figure shows that the skin layer thicknesses are very non-uniform across the width of this structure. Note that the skin layer on the bottom is thicker in the center and thinner on the edges. The top skin layer by comparison is even more asymmetrical than the bottom skin layer. The top skin layer is non-existent in the center of the sample but it becomes very thick at the edges of the die. When this same experiment was done with a 200 layer sample, the results were very similar.

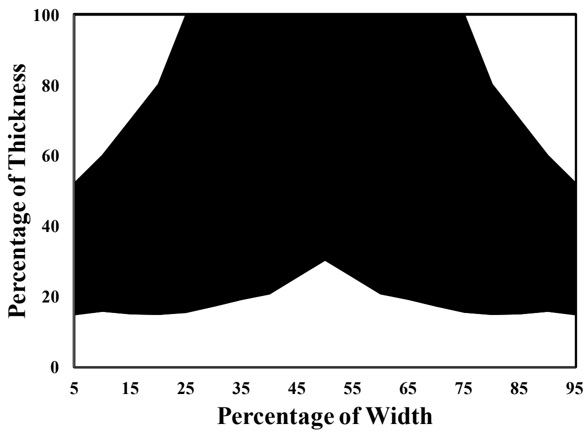


Figure 15. Skin and core layer thicknesses across the width of the die land for a 3 layer structure in a rectangular asymmetrical manifold.

Figures 13 through 15 all show that the large amount of asymmetry in the rectangular distribution manifold affected the distribution of the layer thicknesses in this structure. Comparing Figure 8 for the symmetric manifold, Figure 11 for the half teardrop manifold, and Figure 15 for the rectangular manifold shows that as the level of asymmetry of the distribution manifold increases, the non-uniformity of the layer distribution also increases. It appears that as the asymmetry of the distribution manifold increases, more of the skin layers flow down the distribution manifold rather than flowing towards the land. This causes the skin layers to be thinner near the center of the die and thicker near the edge.

Numerical

In order to better understand the flow patterns in the various die geometries and how they affected the layer distributions, numerical models were developed using Computation Fluid Dynamics (CFD) techniques. ANSYS Polyflow© [22], a three dimensional (3D) finite element program, was used to model the flow through coathanger die geometries with distribution manifolds similar to those shown in Figure 4.

Simulation of the flow of fluid in a die involves the numerical solution of the equations governing viscous fluid flow on the specified computational domain, subject to the stated boundary conditions. Steady, laminar flow of an isothermal, incompressible, non-Newtonian fluid, such as that in a coathanger die, can be described by the following forms of the equations of continuity and motion:

$$\nabla \cdot \underline{u} = 0 \qquad (1)$$

$$\rho \underline{u} \cdot \nabla \underline{u} = -\nabla p - \nabla \cdot \underline{\underline{\tau}} \qquad (2)$$

where ρ, $\underline{u}$, p, and $\underline{\underline{\tau}}$ are the density, velocity vector, pressure, and deviatoric stress tensor, respectively. Equation (2) shows the equation of motion in stress-divergence form. This is the form typically used for flows involving non-Newtonian fluids, as it properly accounts for the spatial variation of viscosity.

In order to solve these equations for polymer flow, an appropriate rheological constitutive equation must be determined. In this study, a Carreau-Yasuda model was used. The Carreau-Yasuda model is one of several different generalized non-Newtonian viscosity models which can be used to describe the shear rate dependence of a polymer's viscosity. Because of its flexibility, the model has proven useful in describing the rheological behavior of a variety of polymers.

Figure 16 shows a discretized flow domain, or mesh, for a coathanger die with a rectangular, asymmetrical distribution manifold. This Figure shows that flow through only half of the die was simulated due to the symmetry of the model about the center plane. This mesh was used with appropriate boundary conditions and constitutive equations to determine the 3D flow fields within the die.

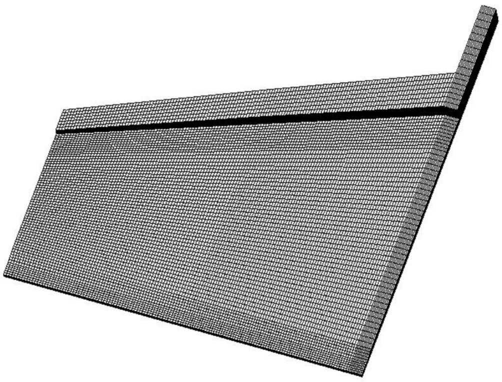
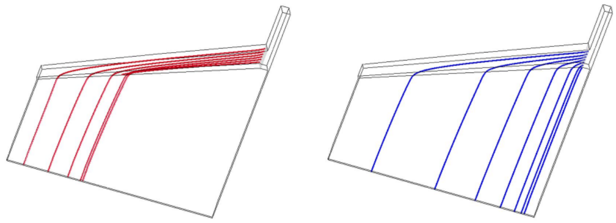


Figure 16. Finite element mesh for a rectangular asymmetrical manifold.

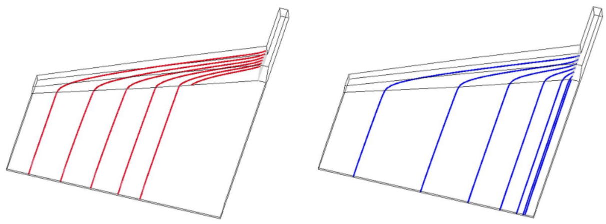
Figure 17 shows a particle path plot for the die with the rectangular, asymmetrical distribution manifold shown in Figure 16. In this plot, a series of equally spaced, massless particles are placed at the upper (17a) and lower (17b) interface locations between the skin and core layers near the entry to the distribution manifold and allowed to flow through the geometry and indicate the subsequent locations of those interfaces. This Figure shows that the upper skin layer (17a) does not flow down to the land immediately but moves a significant distance down the distribution manifold before it enters the land region. The lower interface (17b) follows a more normal flow path which distributes the interface across the width of the die. The results of these plots agree with the experimental results shown in Figures 13 through 15.



(a) (b)

Figure 17. Particle path plots tracing the upper (a) and lower (b) interface locations in a 3 layer structure in a rectangular asymmetrical manifold.

The next geometry simulated was similar to Figure 16 but a 45 degree taper was added to the exit of the distribution manifold. This creates geometry similar to the half teardrop geometry shown in Figure 4b. Figure 18 shows a particle path plot for the die with the half teardrop, asymmetrical distribution manifold. In this plot, a series of equally spaced, massless particles are placed at the upper (18a) and lower (18b) interface locations between the skin and core layers near the entry to the distribution manifold and allowed to flow through the geometry and indicate the subsequent locations of those interfaces. This Figure shows that the upper skin layer (18a) does not flow down to the land immediately but moves a significant distance down the distribution manifold before it enters the land region. The lower interface (18b) follows a more normal flow path which distributes the interface across the width of the die. The results of these plots agree with the experimental results shown in Figures 9 through 11.

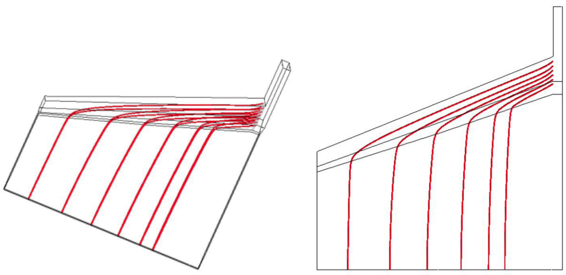


(a) (b)

Figure 18. Particle path plots tracing the upper (a) and lower (b) interface locations in a 3 layer structure in a half teardrop asymmetrical manifold.

Comparing Figures 17 and 18 shows that the lower skin layer interfaces are fairly similar but the upper skin interfaces are different. The half teardrop manifold geometry is slightly more symmetrical than the rectangular manifold geometry and so the upper skin interface begins to flow down into the land region sooner giving a somewhat more uniform layer distribution across the die.

The next geometry to be simulated was similar to Figure 18 but mirrored about the axis of the surface opposite the distribution manifold. This creates geometry similar to the symmetrical teardrop geometry shown in Figure 4a. Figure 19 shows particle path plots for the die with this distribution manifold geometry. In this plot, a series of equally spaced, massless particles are again placed at the upper and lower interface locations between the skin and core layers near the entry to the distribution manifold and allowed to flow through the geometry and indicate the subsequent locations of those interfaces. This Figure shows that the upper and lower skin layers flow uniformly across the die, which is expected because of the symmetry of this geometry. In fact, Figure 19b shows that if the results are viewed from the front of the manifold, the particle paths for the upper and lower skin interfaces are identical and appear as single lines. The results of these plots agree with the experimental results shown in Figures 5 through 8.



(a) (b)

Figure 19. Particle path plots showing the upper and lower interface locations in a 3 layer structure in a symmetrical teardrop manifold, where (a) and (b) show different viewing angles of the final results.

Conclusions

A unique series of experiments and numerical simulations were conducted to determine the effect of die manifold channel symmetry on the flow of coextruded structures through coathanger style dies. Experimental and numerical data were developed on the layer uniformity of coextruded structures which were processed through several different die manifold channels containing different levels of symmetry. As the asymmetry of the die manifold increases, more of the skin layers on the manifold side flow down the distribution manifold rather than flowing towards the land. This causes the skin layers to be thinner near the center of the die and thicker near the edge. The data show that as the asymmetry of the distribution manifold increases, the layer uniformity of the coextruded structure decreases.

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