Internal flow optimization in a complex profile extrusion die using flow restrictors and flow separators

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Received: 30 June 2021 / Accepted: 27 October 2021 / Published online: 13 January 2022
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Abstract
The control of flow balance at the die exit is the key for successful extrusion of polymers. The complex cross-sectional variation in real-world hollow extrusion profiles intrinsically promotes flow imbalance in the die cavity. Special considerations are required for designing extrusion dies for such profiles. The die design for a complex door frame profile was computationally optimized in this study with the aid of a commercially available software package. The velocity distribution at the die exit, post-die extrudate deformation, temperature distribution, and pressure distribution of a traditional die was investigated in detail and found to be inadequate. A modified die incorporated three distinct features, flow restrictors, flow separators, and approach angle of the torpedoes, to achieve a balanced and uniform velocity at the die exit. The flow restrictors and flow separators were added in the pre-parallel zone. Flow restrictors were added on top and bottom of the torpedoes to increase the restriction on polymer flow. A unique inclined flow restrictor was introduced to achieve uniform internal melt flow. Flow separators were added at junctions of outer wall and inner vertical walls to separate the polymer flow into different sections and minimize cross flow between these sections. The addition of these features proved to be highly effective for balancing the velocity distribution at the die exit. The combination of 3-D modeling and simulation is a cost-effective and time efficient approach for optimizing complex die designs before manufacturing.

Keywords Profile extrusion · Die design · Flow optimization · Post-die extrudate deformation

1 Introduction
Extrusion is the most utilized process for high volume manufacturing of constant cross-section plastic products, such as pipes, tubes, and sheets [1]. Complex hollow profiles are also produced via a “profile extrusion” technique for diverse applications in the construction industry. Door and window frames are presumably the best example of complex hollow profiles. Such profiles have intricate cross-sections with large variations in wall thicknesses, intrinsically promoting an unbalanced polymer melt flow inside the extrusion die. The complexity of profile extrusion processes requires critical attention and expertise to the die design process for balanced internal flow. The extrusion dies for complex profiles are often designed empirically and the processing conditions are adjusted during the operation to obtain an acceptable product, which is neither efficient nor optimal. With the advent of computer-aided engineering (CAE) approaches and availability of powerful computers and software packages, it is now possible to evaluate different designs in a virtual environment and develop extrusion dies with balanced flow. This has made the entire die design process more efficient and economical [2]. However, the process still requires an experienced user with a thorough understanding of the polymer melt rheology and the flow behavior of the melt in the cavity die.

One important consideration for designing an extrusion die is to have a uniform velocity distribution across the entire cross-section of the profile at the die exit. Post-die extrudates are typically in semi-solid form and can deform readily if the extrusion die is not balanced properly. The internal polymer flow is relatively easier to balance for simple profiles such as slits, conduits, and rods. For complex profiles, the die geometry and the final shape of the extrudate are difficult to determine because of the die swell phenomena that occurs during polymer extrusion [3]. The different thicknesses of the walls impose varying degrees of flow restrictions and
naturally result in an unbalanced melt flow in the die cavity. The flow of polymer in the thicker section is less restricted as compared to that in the thinner section. This results in a higher flow velocity in thicker sections, a lower flow velocity in thinner sections, and the melt from a higher velocity tends to flow toward the melt with a lower velocity. This flow redistribution can cause profile deformation after the die exit. Hence, it is imperative to understand the velocity distribution inside the complex profile extrusion dies as well as predict post-die extrudate deformation for efficient and cost-effective production in an industrial setting.

A conventional extrusion die has four sections (zones): adapter, transition zone, pre-parallel (pre-land) zone, and parallel (land) zone [4]. Polymer coming out of the extruder goes into the adapter that connects the extrusion die to the extruder and transitions from primarily rotational to longitudinal motion. The material then flows through each subsequent zone until it reaches the die exit. In the transition zone, polymer flow changes from circular shape to complex shape by either expanding or compressing, depending on shape and size of the profile. In the pre-parallel zone, the melt flow is redirected in a controlled fashion to the parallel zone, where the polymer is extruded to its final shape and held to ensure adequate dimensional stability.

Typically, there are two methods for balancing the flow through an extrusion die [5]. The first approach involves adjusting land lengths of the pre-parallel and parallel zones and/or incorporating flow restrictors for controlling the polymer melt velocity in the die effectively. For a complex profile die, this implies a change in the length and approaching angle of torpedoes to attain an identical polymer flow at the die exit. The approaching angle of torpedoes can be changed by adjusting the shape of the torpedoes in the area where the torpedoes are expanding.

The second approach involves the incorporation of flow separators inside the extrusion die to separate the melt flow into different sections in a controlled fashion. Flow separators are incorporated in the pre-parallel zone to form different flow channels for the polymer melt. These flow channels can control the polymer flow volume and guide the polymer melt to the parallel zone. The primary objective to minimize melt cross flow is often referred to as an “avoid cross-flow” strategy [6]. This method is often used in complex profile extrusion dies since cross flow occurs more frequently in between the sections in such dies. Flow separators are added on top of the gap between each torpedo to separate polymer flow into vertical and horizontal sections.

In this research, a computer-aided design approach was utilized to design an extrusion die for a complex hollow profile with uniform flow velocity at the die exit. The design strategy involved incorporation of both flow restrictors and separators at strategic locations in the die. A novel flow restrictor design was proposed and its efficacy on the melt flow uniformity at the die exit was evaluated by numerical simulations. The non-isothermal polymer melt flow inside the extrusion die assembly was numerically simulated with the aid of a software package. The influence of strategically placed flow separators and restrictors on the internal melt flow and the associated effects on the melt temperature, pressure, and shear stresses were studied in detail. Post-die extrudate deformation was also analyzed and was related to polymer velocity distribution.

2 Extrusion die design strategy

A complex hollow extrusion profile utilized in an actual production facility for the fabrication of wood polymer composite (WPC) door frames was selected. The cross-sectional view of the profile is presented in Fig. 1. The overall width of the profile is 200 mm and the overall height is 37 mm with a uniform outer wall thickness of 2.6 mm. The vertical inner walls have a thickness of 2.0 mm. The bottom left and right sections are thicker with serrated features, the thickness of these sections is 3 mm. A plastic part gets inserted into the gap between the serrated overhang and the main body during installation of such a door frame, and the serrated features provide additional friction and a tighter fit during this process. The small square opening on the right top corner holds a soft rubber bumper in application. These profile features provide significant challenges in designing...
an extrusion die that would provide a uniform velocity distribution at the die exit.

A die similar in design to the actual die utilized in the production line was initially considered for this study. The detailed die design is presented in Fig. 2. The total die length was 264 mm between die inlet and exit, with a pre-parallel zone length of 75 mm and a parallel zone length of 85 mm. In the transition zone, the polymer flow was changed from circular shape to the complex shape of the extrudate. In the pre-parallel zone, the melt flow was redirected in a controlled fashion to the parallel zone, where the polymer was extruded to its final shape. A series of torpedoes in the pre-parallel and parallel zone (Fig. 2b) was added to ensure that the final shape was formed accurately. The die was designed without any consideration of the melt flow behavior in the die assembly. No flow separators or restrictors were incorporated in this initial design.

Although the die was utilized in the industry for wood plastic composite (WPC) door frames, polyvinyl chloride (PVC) was considered in the numerical simulations to investigate the melt flow behavior in this study. The WPC relevant for door frames typically consists of wood flour or powder mixed with PVC and wide range of additives with specific functionalities such as heat stabilizers [7], impact modifiers [8], lubricants, and processing aids [9]. Actual WPC formulations can be diverse and are often proprietary. As such their rheological properties are seldom studied and publicly reported on in detail. Hence, a generic rigid PVC was considered for the numerical simulations. It was surmised that actual WPC formulations utilized in industry would have similar trends in rheological properties as the PVC.

The melt flow behavior in the initial die (Fig. 2) was modeled with the aid of Altair Inspire Extrusion Polymer software. The spatial distribution of the velocity of the melt at the die exit was critically assessed. An innovative approach was adopted to minimize cross flow and velocity imbalance at the die exit. Both flow restrictors and flow separators were incorporated in the pre-parallel zone. Traditionally, either flow restrictors or flow separators are incorporated in the die. Additionally, the geometry of the flow restrictors was changed from the traditional rectangular cross-section to triangular shapes to fine tune the flow behavior. The approach angle of the torpedoes was changed as well to attain optimal flow behavior at the die exit.

3 Modeling of polymer melt flow

3.1 Material and rheology properties

A generic rigid PVC was considered for numerical simulations. The rheological behavior of the PVC is expected to be similar to the wood polymer composites. The properties of different PVCs are not vastly different, and PVC constitutes about 50% of the formulations by weight, while majority of the other half are filler materials such as wood.
flour or calcium carbonate. The primary focus is on the efficacy of flow separators and restrictors on balancing the flow in the die. The parameters derived from the simulation might not be identical to the experimentally derived counterparts but the trends about the efficacy of the die designs would be unambiguously true.

A cross-WLF model was utilized to model the rheological properties of the PVC. In this model, the viscosity ($\eta$) is determined as follows [10]:

$$\eta = \frac{\eta_0}{1 + (\frac{\tilde{\gamma}}{\gamma_c})^{1-n}}$$  \hspace{1cm} (1)

where $\eta$ is the melt viscosity (Pa·s), $\eta_0$ is the zero-shear viscosity or the “Newtonian limit” in which the viscosity approaches a constant at very low shear rates, $\tilde{\gamma}$ is the shear rate (1/s), $\gamma_c$ is the critical stress level at the transition to shear thinning or reference shear stress, and $n$ is the power law index in the high shear rate regime.

The zero-shear viscosity $\eta_0$ is calculated by the following equation [11]:

$$\eta_0 = D_1 \exp \left[ -\frac{A_1(T - T^*)}{A_2 + (T - T^*)} \right]$$  \hspace{1cm} (2)

where $T^* = T_{g} + D_3p$ and $A_2, A_1p, A_2$ are experimentally derived empirical coefficients. $p$ is the pressure on the polymer melt.

The cross-WLF model is a 6 parameter model that describes both shear thinning and Newtonian behaviors [12]. It is the most common model that considers the effects of shear rate, temperature, and pressure on the viscosity and offers a best fit for most viscosity data [13]. The WLF model (equation 2) for temperature dependence is generally applicable for amorphous polymers at moderate temperatures [12]. It is appropriate for this work as PVC could be considered as an amorphous polymer. An alternative model for temperature dependence, the Arrhenius model, primarily applies to semi-crystalline polymers and amorphous polymers at high temperatures ($T > T_g + 100K$) [12].

| Viscosity model | parameters |
|-----------------|------------|
| $D_1$ (Pa·s)    | 8.4184 e+18 |
| $A_1$           | 33.7371    |
| $A_2$ (K)       | 51.6       |
| $T^*$ (K)       | 353        |
| $\tau^*$ (Pa)   | 5100.37    |
| $n$             | 0.274187   |

The appropriate rheological constants for the PVC as obtained from Altair Inspire Extrusion Polymer software database is provided in Table 1. The relevant physical properties for the PVC are shown in Table 2.

### 3.2 Simulation conditions

The simulation conditions were chosen to be representative of real manufacturing conditions for PVC window profiles and have been adopted from the literature. The inlet velocity at the beginning of the transition zone was set to be 12.5 mm/s. The adapter area for the die was 2358 mm², resulting in a volumetric flow rate of 0.10611 m³/h. The resultant mass flow rate was calculated to be 88.37 kg/h, assuming the density of PVC to be 832 kg/m³. The inlet melt temperature and wall temperature were set at 428 K (155 °C) and 443 K (170 °C) respectively. The post-die extrudate was simulated for 100 mm in a stress-free condition. This condition is applied to all boundaries of the extrude. In order to simulate a real convection condition, the cooling temperature of the extrudate was set to be 303K (30° C), and a convection heat transfer coefficient of 1 W/m²K was utilized. These parameters were kept identical for all the numerical simulations. In the simulations, a no-slip condition was assumed at the die wall. The polymer melt was considered to be an incompressible fluid [14].

### 3.3 Mesh generation

The 3D model of the polymer melt in the die was spatially discretized using the Altair HyperMesh™ finite element pre-processor. A combination of hexahedral and tetrahedral elements was utilized to conform to the complex geometry accurately and obtain results with adequate detail. Hexahedral elements were applied on the parallel zone and post-die extrudate since there was no geometry change at these sections [15]. Tetrahedral elements were applied on the transition zone and the pre-parallel zone to adequately represent the complex geometry changes at these sections. The total number of nodes and elements were 906,891 and 2,258,636, respectively. The meshed model is shown in Fig. 3(a). The part was divided into different sections for the simulation software. The different sections of the polymer melt are presented in different shades of gray in the figure. The lightest
gray is the melt in the transition zone, the lighter gray is the melt in the pre-parallel zone, the darker gray is the melt in the parallel zone, and the darkest gray is the post-die extrudate. An expanded two-dimensional view of the connection of pre-parallel and parallel zone is presented in Fig. 3(b). The tetrahedral elements in the pre-parallel zone are at the top while the hexahedral elements are shown in the parallel zone in the bottom section in the figure.

**4 Results and discussion**

**4.1 Initial extrusion die results**

The flow velocity distribution at the die exit of the conventional die is shown in Fig. 4. Because of the different thicknesses in the different sections of the profile, the polymer melt experienced varying degrees of restriction. This resulted in an imbalanced flow distribution at the die exit. The velocity varied by more than 2 times from section to section at the die exit. The average velocity in the outer section with a thickness of 2.6 mm was 25.9 mm/s. The average velocity in the inner sections with 2.0 mm thickness was 13.0 mm/s. In the serrated sections at the bottom left and right, the average velocity was 33.0 mm/s, as shown in Fig. 4. The thickness of these sections was 3 mm. The highest velocity (45 mm/s) was observed at the bottom left and right sections at the intersection of the thick horizontal serrated sections and the thin vertical inner sections (Fig. 4b). The melt velocity was generally higher at the center of most of the junctions between the horizontal sections and inner vertical sections. The flow was less restrictive at these regions because they were further away from the die walls, hence the increased velocity.

The simulated post-die extrudate deformation in x-, y-, and z-axes at a distance of 100 mm out of the die is shown in Fig. 5. The x-axis is horizontal, and the y-axis is vertical on the plane of the paper. The z-axis is vertical to the plane of the paper parallel to the extrusion direction. The deformation was primarily confined to the outer peripheries. The horizontal deformation (x-axis) was minimal. The maximum deformation (1.3 mm) was at the right side. The deformation in the y-axis direction was somewhat symmetric. A maximum deformation of ~ 9 mm was observed at the serrated sections at both bottom left and right. The maximum deformation along z-axis was also at the serrated sections at bottom left and right, the magnitude was ~13.5 mm. The effect of the distortions on the three orthogonal directions will act collectively on the extrudate. The simulated extrudate cross-section at 100 mm out of the die is presented in Fig. 6 in solid color overlaid on the outline of the intended cross-section. The outer left and right sections deformed upwards while the middle part deformed in the opposite direction. The overall distortion was maximum at the bottom section (15.8 mm), coinciding with the region with maximum velocity at the die exit. The results indicate that the conventional die would produce a deformed extrudate which would most likely be unacceptable in practice.

Pressure distribution in the melt in the die cavity was simulated, the results are shown in Fig. 7a. The pressure at the die exit was set to be at atmospheric pressure (0.1 MPa, zero-gauge pressure). The highest pressure (20.17 MPa) was observed at the beginning of transition zone. The pressure decreased continuously from the transition zone to the die exit. At these pressures, PVC is not expected to degrade in any fashion. The temperature distribution in the melt in the die cavity is shown in Fig. 7b. PVC, being a thermally sensitive material, is prone to degradation at high temperatures > 250° C [16]. The die inlet temperature was set at 428 K (155° C) and the extrusion die wall temperature at 443 K (170° C). The temperature stayed within this range for the most part. The temperature in certain regions in the polymer melt exceeded the die wall temperature to a maximum of ~180° C. It was believed to be caused by shear heating of the melt at the die wall.
4.2 Modifications of extrusion die and effects on flow balancing

An optimal extrusion die should have a uniform flow distribution at the die exit, ensuring minimal post-die extrudate deformation. Traditionally, the length of the parallel zone is increased to reduce the flow imbalance. In this research, the length of the parallel zone was kept constant. A series of innovative modifications were incorporated in the initial die to achieve a more uniform flow distribution at the die exit.

1. Flow restrictors were added on the top and bottom of each torpedo in the pre-parallel zone for added restriction to polymer melt flow in these sections as shown in Fig. 8 for one of the representative torpedoes. The flow restrictors, highlighted with a crosshatch pattern in the figure, were set to be 1.6 mm in height, 31.5 mm in width, and 75 mm in length. In addition, a pair of inclined restrictors was added in the pre-parallel zone to further reduce the velocity in the serrated sections. The velocity was highest in these sections in the initial die. A cross-sectional view of the modified extrusion die with the inclined restrictors is shown in Fig. 9. The inclined restrictor had a triangular cross-section, the maximum height was set to be 2 mm at the junction of the vertical section and the serrated section and gradually reduce to a sharp end at the edge of the serrated section. The width of the inclined restrictor was 27.5 mm and the length was 75 mm. A minor flow restrictor on the vertical wall of the torpedo of the right section was also incorporated.
in the modified die. This minor flow restrictor was set to be 0.9 mm in height, 21 mm in width, and 75 mm in length.

2. A set of flow separators was added between each torpedo at the top and the bottom of the die to minimize the cross flow between the outer section and inner vertical section as shown in Fig. 10. The isometric view of the left side of the pre-parallel zone from the back of the die is shown in the figure; the separator is highlighted with a crosshatch pattern and marked as well. Each separator was 3.15 mm in height, 2 mm in width and 85 mm in height.

3. In addition, the gap between the torpedoes was increased from 2 mm to 4 mm in the parallel zone to reduce the flow restriction. In the modified die, the polymer flow was thus compressed later than the original conventional die. These modifications are highlighted in Fig. 11. Additional space between torpedoes was provided in the pre-parallel zone as well, to enhance the flow velocity.

The final dimensions and positions of the aforementioned features in the modified die were achieved in an iterative fashion. The flow velocity at the die exit was simulated for a specific combination of flow restrictors and flow separators, and their number, position, and dimensions were adjusted systematically to realize an optimal design.

The velocity distribution at the die exit of the final modified die is presented in Fig. 12. The average velocity of the extrudate increased modestly from 23 mm/s in the original die to 26 mm/s in the modified die. However, the velocity distribution improved drastically in the modified die. The average flow velocity was 28.0 mm/s in the outer 2.6 mm sections in the modified die as compared to 25.9 mm/s in the same section in the original die. The average velocity in the inner 2.0 mm sections increased to 23.0 mm/s in the modified die from 13 mm/s in the original die. The flow velocity at the serrated sections reduced to 25.0 mm/s in the modified die from 33 mm/s in the original die. Furthermore, the
modified die successfully eliminated the high velocity “hot spots” at the junctions between the vertical and horizontal sections observed in the original die (Fig. 12b).

With a more balanced velocity distribution, the magnitude of post-die extrudate deformation was also reduced. The deformation of the extrudate at 100 mm from the die exit along the three orthogonal directions for the modified
The deformation along $x$-axis (Fig. 13a) was minimal in the original die (1.3 mm maximum). It was further reduced to 0.97 mm with the modified die. The deformation along $y$-axis was nominal for most part (Fig. 13b) with the modified die. A significant improvement was observed on the right side of the extrudate. The deformation of the serrated section on the right side was ~3 mm (as compared to ~9 mm with the original die). The serrated section on the left side had a maximum deformation of 7.8 mm. Minor adjustment of the restrictors in this section could further minimize the deformation. The deformation along the $z$-axis experienced the most improvement (Fig 13c). The maximum deformation along the $z$-axis was reduced to 6.4 mm with the modified die from 13.5 mm with the original die. The simulated extrudate cross-section at 100 mm out of the die, shown in Fig. 14, reflected the efficacy of the modified die as well. The deformation was minimal for most part, only minor deformation was observed in the top left section and serrated section in the bottom right. In an extrusion production line, the extrudate will pass through a calibrator unit usually located very close to the die exit. The primary function of the calibrator is to shape the semi-solid extrudate to its final dimensions as it cools to room temperature [17]. In this research, the deformation of the extrudate was measured at 100 mm from die exit to amplify the distortions. At the calibrator location, the deformation will be lower than the values presented earlier. It is expected that the calibrator will be able to rectify the deformation observed at the bottom-left and top-right corners of the extrudate with the modified die.

The temperature and pressure distribution in the polymer melt in the modified die were also determined. It was observed that the addition of the flow restrictors and the flow separators did not change the pressure distribution drastically. The pressure decreased continuously from the transition zone to the die exit in a similar fashion as with the initial die. The maximum pressure was observed at the beginning of the transition zone (~26 MPa). The maximum temperature in the melt in the modified die was ~180°C, identical to the melt in the original die. However, the maximum temperature was observed more frequently in the melt in the modified die. PVC is not expected to degrade in any fashion under these conditions.
5 Conclusion

An innovative die design approach was introduced for balancing the melt flow in a complex hollow extrusion profile die for a door frame. The Altair Inspire Extrude Polymer software package was utilized to assess the flow velocity at die exit, the associated extrudate deformation and the temperature and pressure distributions in the polymer melt in the die cavity. The flow characteristics of a standard prototype die were initially determined to be highly non-uniform. A series of die features were incorporated to develop a modified die. The features included flow restrictors and flow separators in the pre-parallel zone. A unique inclined flow restrictor was found to be critical for balancing the melt flow at the peripheral overhanging sections.

The inclined flow restrictor had a triangular cross-section in contrast to traditional restrictors that have a rectangular cross-section. The gaps between the torpedoes were also adjusted. The velocity differential at the die exit was reduced from 40 mm/s in the initial extrusion die to ~5 mm/s with the modified die. The maximum deformation of the extrudate at 100 mm from the die exit was reduced from 11 mm with the initial die to 4 mm with the modified die. The incorporation of the flow separators and flow restrictors did not affect the temperature and pressure distributions detrimentally in the die cavity. It is anticipated that this work would provide realistic guidance for the design of complex hollow profile extrusion dies to the practitioners in the field.
Acknowledgments The guidance and support provided by Coleen Mantini and Jennifer Laubach who oversee the program is greatly appreciated.

Funding The research was funded by the State of Pennsylvania through the PA Manufacturing Fellows Initiative (PMFI) and the Manufacturing PA Innovation Program.

Data availability All the data and material are available upon request to the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The publisher has the permission of the authors to publish the given article.

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