The Design Optimisation of the Co-extrusion of a Wood-like Grain Surface Composite Polymer Profile

Wang Qi-bing
Engineering Training Centre, Huaihai Institute of Technology & Jiangsu Marine Resources Development Research Institute, Lianyungang, 222005, China

SUMMARY

A wood-like grain surface composite polymer profile (or wood-like profile) was fabricated by the extrusion moulding of melting multi-component polymers through a co-extrusion die, with two extruders feeding the co-extrusion die simultaneously. To improve the extrusion velocity uniformity of melting composite polymers, and decrease the distortion of wood-like grain profiles, this study treats the velocity equality among sub-regions in the wood-like profile cross-sections at the exit of the co-extrusion die as its optimisation objective. Meanwhile, the compression section gap, which exerts a significant influence on flow uniformity is selected as the design variable. Finite element numerical simulation and an ERP system are adopted to optimise the design in combination with a CAD/CAE network system co-extrusion die expert database of concurrent engineering. The optimisation design of case studies confirms that the velocity uniformity of the optimised wood-like grain profile melts presents a significant improvement in each sub-region at the exit of the co-extrusion die. Moreover, the distortion of composite profiles is decreased. The structural dimensions and performance of the composite profiles meet industrial demands.

Keywords: Wood-like grain profile; Co-extrusion die; Design variable; Numerical simulation; Optimisation design

1. INTRODUCTION

Wood-like grain profiles are a kind of wood-like grain composite polymer profile with a grain akin to that of natural wood. The production process is indicated as follows: wood grain materials are extruded into a white plastic profile production line by an extruder from the one side and converge in the internal channel of the co-extrusion die. Then the materials are plasticised asynchronously in the extruder by controlling the formula, processing temperature, and extrusion velocity of the PVC and its additives (e.g. stabiliser and lubricant) with a PVC master batch of different degrees of polymerisation (referred to as a wood-like grain material below). The new wood-like composite polymer profiles, with similar wood grain, are called wood-like profiles. Figure 1 shows the section of a push-pull window sash made of such a wood-like profile. They are generally used to produce doors and windows and widely used in the furniture, automobile, and electronics industries. This environmentally friendly product is being promoted in China owing to its favourable characteristics such as colourful appearance, thermal insulation, energy conservation, and raw material saving potential.

The co-extrusion die for this wood-like profile (Figure 2) is a key component of the co-extrusion production line. The design reasonability of this component determines the moulding quality of wood-like profiles and is thus a key goal in extrusion modelling design. However, due to the coexistence of two melts and the difference of the two melts in the co-extrusion die of a wood-like profile with regard to pressure, viscosity, and velocity, irregular and uneven fusion interfaces are easily formed. Moreover, attributed to the irregular shapes of the core sprue spreader, the co-extrusion die for a wood-like grain profile is provided with a more complex internal structure. The interface fusion of the two melts is difficult to control. Therefore, uniform, stable, interface fusion is a key difficulty facing co-extrusion moulding designer of PVC and wood grain materials. Current researches employ computer simulation to analyse the internal flow field in the die and provide theoretical guidance for the design and optimisation of the die1-6. In the co-extrusion moulding design of a wood-like profile, the velocity uniformity of the composite melt of PVC and wood grain material on the exit end surface of the die affect the quality of as-extruded profiles. The uneven polymer distribution in the wood-like co-extrusion die is the main reason for profile distortion. The key
for solving the distortion of wood-like materials lies in maximising velocity equality on the exit of the co-extrusion die. In the case of a fixed wood-like profile co-extrusion moulding process, the velocity equality of the co-extrusion melts in the exit depends on the structure and size of the runners in the composite co-extrusion die. In this regard, other researchers have made fruitful progress and improved the design of dies thereafter. Unfortunately, their studies are mostly based on simple profile sections (such as: T-, U-, and I-shaped sections) and simplifying hypotheses. They pay less attention to die flow analysis in profiles with complex, and hollow, sections and those with different wall thicknesses. In addition, researches have mostly concentrated on the PVC profile. However, few researchers investigate the internal flow field distribution, flow analysis, and design optimisation of the wood-like profile co-extrusion die with its complex, or hollow, sections and non-uniform wall thickness. This study is conducted based on the results of previous work and the results obtained by the author from the extrusion moulding of composite polymers through development, design, and research over many years. Moreover, with reference to the extrusion moulding die expert database established using CAD/CAE/ERP, a push-pull window sash made of surface wood-like profile polymer was used to optimise the design of the co-extrusion moulding of PVC and a composite wood grain profile.

2. Examples

2.1 Finite Element Analysis of the Co-extrusion Flow of a Wood-like Profile

2.1.1 Mathematical Model

In the extrusion process of the PVC and wood grain material, the channel in the co-extrusion die is irregular in shape. It changes from a circular shape at its entrance to whatever shapes is needed at the exit. Nevertheless, due to the rotational motion of the screw, the motions of melts of PVC and wood grain material are mainly three-dimensional at the entrance. The melts are provided with circumferential velocity, the flow velocity shows insignificant variations in the two directions of the melt section and along the flow direction. The co-extrusion melt flows three-dimensionally with a velocity represented by its components in three orthogonal directions. Inertia and gravity can be neglected. According to the creep flow characteristics of the incompressible viscous fluid, the mathematical model for the 3-D flow of a composite profile melt is as follows:

Continuity equation:
\[ \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \]  

Momentum equation:
\[ \frac{\partial p}{\partial x} = \eta \left( \frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right) \]  

\[ \frac{\partial p}{\partial y} = \eta \left( \frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2} \right) \]  

\[ \frac{\partial p}{\partial z} = \eta \left( \frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2} \right) \]

The constitutive equation of the material is:
\[ \tau = \eta \dot{\gamma} \]  

In Eqns (1) to (5), \( v_x, v_y, \) and \( v_z \) refer to the velocity components of the melts.
2.1.2 Boundary Conditions
The PVC melt has a density of 1120 kg/m³. The wood grain material has a density of approximately 1120 kg/m³. The two melts slide at velocity of 0.004 m/s in the straight extrusion section; the components of the velocity of the melts on other interfaces of the channel are set to zero; the two melts reach the entrance of the die with a velocity of 0.05 m/s. By using standard atmospheric pressure as a reference pressure, the pressure at the exit is zero (gauge); with reference to the thermodynamic temperature, the PVC and wood grain material are processed at temperatures of 463 K and 433 K respectively.

2.1.3 Target Function
The design optimisation of the wood-like profile is performed based on the analysis of the flow of the PVC and wood grain material. The purpose is to equalise the average flow velocity of the sub-channels or the sub-regions in the composite profile section upon reaching the exit of the die as the polymer melt flows through the die runner. In addition, it aims to maintain an even distribution of the melts of PVC and wood grain materials, and the uniformity of the physico-mechanical performance of products, and tendency to reduce the internal residual stress therein. In cases using a fixed extrusion process, the structural parameters of the co-extrusion die should be optimised to satisfy these aims. Therefore, the optimisation goal can be expressed by the mean square error of the average velocity of the sub-regions at the exit from the composite profile co-extrusion die relative to the average velocity in the exit section. The mathematical model is expressed as:

$$\min f(\varphi) = \left(\frac{v_{i,j}(\varphi)}{V} - 1\right)^2$$

$$\sum_{i=1}^{N} \left(\frac{v_{i}(\varphi)}{V} - 1\right)^2$$

where, \( f(\varphi) \) is the target function for wood-like profiles. \( V_i \) refers to the velocity of the \( j^{th} \) node of the exit section of the co-extrusion die section for a wood-like profile. \( V \) is the average velocity of the wood-like profile melt in the exit section of the die.

2.1.4 Finite Element Analysis of the Extrusion Flow
According to the 3-d FLOTRAN 142 element in ANSYS, and the stepped element division of a channel model, as shown in Figure 3, the physical parameters, process parameters of both PVC and wood grain materials, as well as the applied initial conditions and boundary conditions were input to simulate the flow process of the melts in the co-extrusion die. By numerical calculation, corresponding post-treatment was conducted according to the output data to obtain the velocity of the polymer melt at different positions. Figure 4 shows the fluid velocity distribution at the exit of the co-extrusion die: the melt rate was maximised at the intersection.
and minimised in the internal reinforcement. The unbalanced melt flow and uneven melt rate distribution in the exit of the co-extrusion die would result in distortion of composite profile products. Therefore, optimisation of the structural parameters of the channel is essential for the extrusion moulding design of composite profiles as it can equalise the flow velocity of the melts at the exit of the co-extrusion mould1.

2.2 Design optimisation of the extrusion moulding of a wood-like profile

2.2.1 Design Optimisation of the Extrusion Moulding of a PVC Profile

To achieve a reasonable computation time and ideal optimisation analysis results, the solution space should be reasonable yet as small as possible. In the moulding design of PVC profiles, it is essential to allow a reasonable design variable for definition of the problem domain. According to previous results, and based on the die design expert CAD/CAE/ERP network database, it was determined that the flow balance of melts was most greatly affected by the structural parameters of the compression section of the die runner. Therefore, the gaps in the compression sections were taken as design variables in this study. As shown in Figure 5, the PVC was divided into nine regions. To avoid an over-fast flow of the PVC melt in the intersections in Figure 4, the flow-limit reinforcements of A, B, C, D, and E were set on intersections 1, 2, 6, and 7. The wood-like profile presented in Figure 1 has a non-uniform wall thickness, with an internal reinforcement wall thicknesses of 1.2 mm and a main wall thickness of 2.2 mm. By analysis of the channel model, numerical simulation of the melt flow processes, and corresponding post-processing, it is found that the melts flow more slowly in the internal reinforcement with its thinner wall. Therefore, the channel structure needed to be optimised. The cavity in the sub-flow section is shown at Point 9 in

**Figure 5.** The gap in the cavity is 3.5 to 4.2 times the exit gap width, that is, it exerts a compression ratio of 3.5 to 4.2. The internal reinforcement gap uses the upper limit, while the outer wall gap takes the lower limit. The gaps are designed as independent feed cavities to improve the PVC flow velocity. The longitudinal runners are shown as the core and insert in Figure 2. Through the aforementioned optimisation, and die trial verification, even extrusion of the PVC melts through the exit of the extrusion die was possible.

2.2.2 Design Optimisation of the Extrusion Moulding of an Imitation Grain Material

The literature15 indicates that, the closer the mean degree of polymerisation of the wood-like profile to that of the PVC resin, the better the moulding process. Therefore, the mean degree of polymerisation of wood-like profile was selected to be close to that of the base PVC resin, as was also the case for the consistency coefficient, power law index, and solubility parameter (SP value). Therefore, the optimisation method for the design of a die channel for a wood-like profile was also similar to that for a PVC profile. The extrusion of the wood-like profile shown in Figure 1 also entails flow division, compression, and moulding, as shown in Figure 2. The gap in the compression sections is used as the design variable, with regional division along direction B, as shown in Figure 6. Compared to the gap in the compression sections of the PVC profile, that of the wood-like grain material presents a simpler structure, divided into 12 regions each of equal area. Since the wood-like

**Figure 5.** Dividing region for PVC flows

**Figure 6.** Dividing region for wood-like grain flows

Fig. 2—A partial enlargement
profile is coated on the outside of the PVC profile, the case is only 0.3 mm thick. When using the regional division method along direction B, defects, such as underfeeding, non-uniformity, and distortion, may now be induced in the wood-like profile. Therefore, the feed cavity of the wood-like grain material needs further optimisation. The key for its optimisation lies in keeping the uniform extrusion of the wood-like profile from its surroundings, maintaining uniformity and stability, while fusing the extrusion moulding interface with the PVC, and determining the manner of the combination of the wood-like grain material therewith (on exiting the die, or in the extrusion die). The literature describes flow conditions of these two incompatible polymer melts in the co-extrusion runner. According to previous research and the extrusion moulding die expert database built on the CAD/CAE/ERP network system, it is known that feed discharge also requires a uniform gap, a uniform transition on the matching surface, smooth runners, and the absence of steps, as shown in Figures 2 and 6. The feed cavity for the wood-like grain material entrance of die plate I in Figure 2 was expanded to overcome the defects in the wood-like profile (see C in Figure 6). Moreover, the melts of wood-like grain material and PVC converge on a position approximately 22 mm from the exit of die plate I. Through this optimisation design, and die trial validation, equal velocities in the exit of the die are achieved. Meanwhile, the optimisation also realises flow uniformity and stability. Combination of the surface co-extrusion composite interfaces of wood-like grain material and PVC with uniform and stable extrusion at equal velocities can thus be realised.

3. RESULTS AND DISCUSSION

Figure 7 illustrates the optimised velocity distribution of the melts in the co-extrusion die exit. Table 1 shows the average velocities that correspond to each sub-zone at the co-extrusion die exit before and after optimisation in Figure 5. The calculation results indicate that the objective functions (F) before and after optimisation are 3.0679 and 0.1259 respectively. Results apparently indicate that the optimised velocity of each sub-zone in the wood-like profile section at the exit from the co-extrusion die is shown uniform distribution and flows in a more balance way.

To validate the correctness and efficacy of the optimised design, the pressure on the composite melt in the co-extrusion die was measured using a pressure sensor. Bernoulli’s equation for the energy of the fluids per unit volume is:

$$\frac{1}{2} \rho v^2 + \rho g z + P = \text{constant}$$

(7)

The pressure in the fluid is related to its velocity, inter alia. Therefore, the pressure test holes were set at 15 mm from the co-extrusion die (A, B, C, D, and E in Figure 1). Moreover, pressure sensors were installed in this test hole, as shown in Figure 2. Table 1 lists the measured and simulated pressures.

![Figure 7. Melt rate distribution at co-extrusion die exit](image)

Table 1. Average velocity of sub-zones at die exit

<table>
<thead>
<tr>
<th>Sub-zones in Figure 5</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average velocity</td>
<td>0.0925</td>
<td>0.0913</td>
<td>0.0623</td>
<td>0.0615</td>
<td>0.0817</td>
<td>0.0931</td>
<td>0.0913</td>
<td>0.0613</td>
</tr>
<tr>
<td>before optimisation (m/s)</td>
<td>0.0711</td>
<td>0.0705</td>
<td>0.069</td>
<td>0.068</td>
<td>0.0721</td>
<td>0.0713</td>
<td>0.0717</td>
<td>0.071</td>
</tr>
<tr>
<td>Average velocity</td>
<td>0.0711</td>
<td>0.0705</td>
<td>0.069</td>
<td>0.068</td>
<td>0.0721</td>
<td>0.0713</td>
<td>0.0717</td>
<td>0.071</td>
</tr>
<tr>
<td>optimised (m/s)</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-zones</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Average velocity</td>
<td>0.0524</td>
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<td>before optimisation (m/s)</td>
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<td></td>
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<tr>
<td>optimised (m/s)</td>
<td>0.067</td>
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As suggested by Table 2, measured and simulated values were close. Owing to the sensor accuracy, the overall error was lower than 6%. This outcome proved the high accuracy of the optimisation method.

Optimisation of the design of the co-extrusion moulding of the surface wood-like profile reveals that, since the flow and velocity distribution are non-uniform in the exit of the co-extrusion die, the wood-like profile is prone to distortion. To overcome this defect, the optimisation objective becomes the equalisation of the flow velocities in the sub-regions of the wood-like profile section at the exit from the co-extrusion die. Moreover, the gap in the compression section, which exerts a significant influence on flow uniformity, is taken as the design variable. Using finite element numerical simulation and the co-extrusion die expert database, the uniform extrusion of the sub-region melts of wood-like grain material and PVC in the exit of the die is achieved by limiting the flow in the co-extrusion channel and increasing the feed cavity width. Meanwhile, through optimisation of the channel structure at the point of convergence of the melts of the wood-like grain material and PVC, the interfaces of the two melts fuse stably and uniformly and the two melts are extruded at uniform velocity. This optimisation was carried out based on the example of a wood-like composite push-pull window sash for house-building purposes. This method provides a reference for the co-extrusion moulding of composite profiles of wood-like grain and PVC with similar applications. Moreover, it can guide the co-extrusion moulding design of complex hollow profiles, such as window frames, window levers, etc. which are made of composites of wood-like grain with PVC surfaces.

4. CONCLUSIONS

1. The gap in the compression section exerted a significant influence on the flow balance and, as such, was set as the design variable. Using co-extrusion finite element analysis software and a polymer extrusion moulding expert database built in CAD/CAE/ERP, a reasonable feed cavity was designed, with a compression ratio of 3.5 to 4.2. The optimisation realised the uniform extrusion of the melt of the wood-like profile base and PVC resin in the exit of the co-extrusion die.

2. With reference to previous studies and the CAD/CAE/ERP polymer co-extrusion moulding expert database, the melt of the wood-like and PVC converged at a point 22 mm from the exit of die plate I through the optimisation of the channel structure around the confluence site of the two melts. The interface of the two melts fused uniformly and stably and the melts were extruded at equal velocities.

3. The distortion of wood-like profiles was overcome. The structural sizes and performance of the wood-like profiles were in full compliance with industry application-specific requirements.

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