Rheological properties of wood polymer composites and their role in extrusion

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Abstract. The influence of the rheological behaviour of PP based wood plastic composites (WPC) has been investigated in this research by means of a high pressure capillary rheometer incorporating dies having different geometries. The rheological experiments were performed using slit and round dies. The influence of moisture content on the flow properties of the WPC has been investigated as well. It was observed that higher moisture contents lead to wall slippage effect. Furthermore, measured viscosity data have been used in flow simulation of an extrusion profile die. Also, the influence of different rheological models on the simulation results is demonstrated. This research work presents a theoretical and experimental study on the measurement and prediction of the die pressure in the extrusion process of wood-plastic composite (WPC).

Keywords: Wood Plastic Composites, Rheology, Slit Die, Wall Slippage, Extrusion Profile Die

1. Introduction
Wood plastic composites (WPC) are an important and growing part of the plastic industry. In recent years WPC have evolved the considerable possibilities of design and functionality of the end product. The most common method for manufacturing WPC is either profile or sheet extrusion. WPC products cover a wide range of composites including polyethylene, polypropylene, and polyvinyl chloride (PVC) as the polymeric matrix and sawdust or wood fibres as the filler. Most of the commercial WPC products have a wood content in the range of 40 – 60 wt%. Although WPC is not yet a highly common material, its usage is intensively growing [2].

Predicting the required die profile to achieve good products is a very complex task and requires detailed knowledge of material properties and extensive experience with extrusion processing. Design of the dies for extrusion of products having complicated cross sectional shapes is still an art rather than a science. In many cases costly experiments and in-plant trials could be replaced by numerical simulation [16]. The flow behaviour of WPCs is strongly dependent on the wood filler content and on the moisture content of the wood particles. However, due to different flow behaviour of filler and polymer and the complex interaction between the two phases, the rheological behaviour of the WPC is

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complex. Several researchers have investigated the rheological behaviour of WPC e.g. 4, 5, 6, 9, 11, 12, 13, 14, 15. A better understanding of the rheological behaviour of the WPC and accurate rheological data are the prerequisite for the process optimization and the accuracy of simulation of extrusion of a WPC. These prerequisites for WPC are mostly not available.

2. Materials and methods

2.1. Material
The rheological experiments were performed using two PP based WPC, 70 wt% and 50 wt% soft wood particles (pine and firewood). Wood particles have an average length of approximately 500 µm. The measurements were done on undried material (relative moisture 3.1 - 3.8 %) and vacuum dried material (relative moisture 0.5 %).

2.2. Rheometry
The shear viscosity was measured at 190 °C on a commercial high pressure capillary rheometer Rheograph 2002 (GÖTTFERT Werkstoff-Prüfmaschinen GmbH) using round dies with a diameter of 2 mm, L/D 10, 20 and 30 and 180° entry angle and slit dies with different gap heights (1 mm, 1.5 mm, 2 mm and 2.5 mm). The width of the flow channel is 10 mm. The pressure gradient in the slit die is measured by using flush mounted pressure transducers along the length of the slit (figure 2). The figures 1 and 2 show a schematic view of measurement configurations.

The volumetric flow rate \( V \) is calculated by using the following equation
\[
\dot{V} = \frac{\pi \cdot D_p}{4} \cdot v_p
\]
(1).
Where: \( D_p \) - diameter of the cylinder/piston, \( v_p \) - piston velocity.

For a capillary of radius \( R \) the volumetric flow rate causes an apparent (Newtonian) wall shear rate \( \dot{\gamma}_{ap} \) of
\[
\dot{\gamma}_{ap} = \frac{4 \cdot \dot{V}}{\pi \cdot R^2}
\]
(2).

The wall shear stress \( \tau_w \) follows from the measured extrusion pressure \( p_v \), Bagley ends correction \( p_c \) [1] and the length over radius ratio \( L/R \)
\[ \tau_w = \frac{p - p_c}{2 \cdot L/R} \]  
(3).

The conversion from apparent to true wall shear rate \( \dot{\gamma}_w \) is given by the Weissenberg-Rabinowitsch correction [8]

\[ \dot{\gamma}_w = \frac{\dot{\gamma}_{ap}}{4} \left( 3 + \frac{d \log \tau_w}{d \log \dot{\gamma}_{ap}} \right) \]  
(4).

Finally the true viscosity is calculated as

\[ \eta = \frac{\tau_w}{\dot{\gamma}_w} \]  
(5).

In the case of the slit die, with the help of shape factor \( F_p \) [17] the corrected volumetric flow rate is given by the following equation

\[ \dot{V}_{H,\text{corr}} = \dot{V} \cdot \frac{1}{F_p} \]  
(6).

The shape factor accounts the width influence in the rectangular flow channel.

The apparent shear rate for the slit die is expressed as

\[ \dot{\gamma}_{H,\text{ap}} = \frac{6 \cdot \dot{V}_{H,\text{cor}}}{B \cdot H^2} \]  
(7).

Where: \( B \) - width of the slit, \( H \) - height of slit gap.

The true shear rate \( \dot{\gamma}_w \) is determined by applying the Weissenberg-Rabinowitsch correction [8]

\[ \dot{\gamma}_{H,w} = \frac{\dot{\gamma}_{H,\text{ap}}}{3} \left( 2 + \frac{d \log \tau_w}{d \log \dot{\gamma}_{ap}} \right) \]  
(8).

The pressure drop \( \Delta p \) can be determined by taking the difference of two pressures measured along the flow length and the corresponding distance \( \Delta L \) between the pressure transducers. When the ratio of width to thickness of the flow channel is smaller than 20 the wall shear stress is given by

\[ \tau_{H,\text{w}} = \frac{\Delta p}{2 \cdot \Delta L} \cdot \left( \frac{B \cdot H}{B + H} \right) \]  
(9).

After correction, the true viscosity can be obtained by dividing the wall shear stress by true shear rate. This calculated true viscosity is used for further analysis.

In case of wall adhesion (shear flow) the velocity in the slit die \( (v_s) \) has a parabolic profile and the velocity is maximum in the middle and at the walls zero (figure 3, left). According to Mooney [10] and Knappe [7] the reduced volumetric flow rate \( \dot{V}_{\text{red}} \) vs. wall shear stress curve for different slit heights \( H \) should be identical and lie over each other (figure 3, right). \( \dot{V}_{\text{red}} \) is a function of wall shear stress and can be well described as

\[ \dot{V}_{\text{red}} = \frac{\dot{V}}{B \cdot H^2} \]  
(10).

In case of wall slippage (ideal plug flow) the velocity profile of the flowing fluid is constant across the channel height (figure 4, left). The reduced volumetric flow rate curves lie apart from each other and cannot be represented as geometry independent parameter (figure 4, middle). In such case the slip velocity curves \( (v_G \text{ vs. } \tau_w) \) for different slit heights lie over each other forming a master curve (figure 4, right). The slip velocity \( v_G \) is a function of wall shear stress and can be well described as

\[ v_G = \frac{\dot{V}}{B \cdot H} \]  
(11).
2.3. Profile extrusion

In the present work, extrusion trials were carried out on the twin screw extruder Konos 38 (battenfeld-cincinnati Austria GmbH) using a rectangular hollow profile die (figure 5) in the melt throughput range between 10 and 50 kg/h. The profile die with installed measurement sensors is shown in figure 6.
2.4. Calculation of pressure drop

In order to predict the pressure drop along the die, two approaches were adopted. As a first attempt, a 2-dimensional finite-difference method (FDM) was incorporated to capture the response of the material at two flow extremes, i.e. shear and plug flow. Later, 3-dimensional simulations of the die were performed with a finite-element method (FEM) scheme utilizing ANSYS Polyflow software (v. 14.0.0). This approach enables us to calculate the pressure drop by considering the flow as a combination of both shear and plug flows. The results are discussed in section 3.2.

For FDM calculations, the profile die was discretized into smaller parts consisting of 4 cylindrical and 5 rectangular sections, wherein each length of the sections is divided into thousand subdivisions. The pressure drops were calculated on the cylindrical sections. For the rectangular sections we had to balance the flow between the four sides of the profile so that the axial pressure drop is equal on each side. The sum of the individual pressure drops equals the needed pressure for the whole die. These calculations scheme could be used either for a shear flow with a power-law viscosity model, or a plug flow with the Navier’s slip law:

\[ \tau = k \cdot v_G^n \]  

(12)

In the case of FEM, a triangular meshing was applied with 77 094 nodes and 387 862 elements. Two approaches were adopted; first, considering the flow as a shear type with the power-law viscosity model and second, considering the flow as the combination of shear and plug flow.

While the slippage coefficients are derived according to the well-known indirect gap-dependency method, one cannot apply the traditional viscosity measurement methods in the presence of wall slippage phenomenon. Therefore, the viscosity value was optimized to obtain valid material data for the simulation of the profile die. It was found that a very high viscosity value in the order of 1e6 Pa·s could best represent the material behaviour in the simulations. Such a high viscosity value induces a higher portion of plug flow in combination with the shear flow which can describe the pressure drop with a reasonable accuracy.
3. Results and discussion

3.1. Flow behaviour

Figure 8 shows measured viscosity curves of predried (0.5 % moisture) WPC with 70 wt% wood using the slit and the round die. It can be seen that the viscosity measured with the slit die is 20 % lower than the viscosity measured using the slit die. The main cause for this effect is that the pressure in the round die system is measured using the pressure hole. Due to poor pressure transmission through the pressure hole onto the pressure transducer diaphragm the measured pressure is lower. The wood fibres are accumulating in the pressure hole which has a diameter of 1 mm and constrict a good pressure measurement. This pressure hole effect can be avoided by using the slit die instead of round die. By implementing flush mounted pressure transducer, the pressure fluctuation can be minimized.

Figure 9 illustrates the reduced volumetric flow rate as function of the wall shear stress of vacuum dried WPC with 70 wt% wood for different slit heights. It can be seen that the flow curves produce a master curve independent of the slit height, which is indicative of wall adhesion and therefore shear flow. In case of WPC with higher moisture content 3.8 %, the curves do not produce such a master curve, which is an indication of wall slip.
WPC with 50 wt% and 3.1 % moisture content provide the similar results. As can be seen in figure 10, the flow curves measured using different slit heights show the dependence upon the slit height which proves the existence of wall slip.

Figure 11 shows the wall slip velocity curves. As explained before, in case of pure wall slip, the slip velocity curves for different slit die heights coincide to a single curve.

3.2. Simulation results and their analyses
Pressure drop along the profile die for the WPC with 50 wt% wood and a moisture content of 3.1 % was measured at different flow rates (figure 12). A 2D-FDM calculation was performed in order to calculate the pressure drop for either a complete wall adhering (shear) or a complete wall slipping (plug) flow type. According to figure 12, the pressure drops for the fully shear flow (2D-FDM shear flow) is observed to be quite lower than the measurement data while the predictions for the fully plug flow (2D-FDM, wall slip) are higher than the measurements especially at lower flow rates. This suggests that a flow type comprised of a combination of shear and plug flows should be dominant in the WPC extrusion through the profile die.
Using the viscosity model (figure 8) for wall adhesion (shear flow), in the 3D-FEM calculation, as material data, one can clearly observe that the calculated values are lower than the measurements and very close to the 2D FDM which was expected as it is indeed a shear flow simulation. The deviation between the FDM and the FEM calculations can be explained by the used methods, as in the 2D calculations the radii in the corners and other features as the spider legs are neglected.

By introducing Navier’s slip law into the calculations, it was possible to add the plug flow in combination with the shear flow (figure 8). The data are found to be well in tally with the measurements. From the results presented here, one can safely conclude that not only is it necessary to incorporate the wall slippage coefficients in the simulations, but also the shear flow component is important to be included to give best results.

![Figure 12. Resulting pressure drops against mass flow rate measured values, 3D simulation and 2D FDM results.](image)

### 4. Conclusion

In the present work, the flow behaviour of two WPC with different contents of wood particles has been investigated utilizing high pressure capillary rheometer with two different die geometries. It was proven that an increase in moisture content of WPC leads to wall slippage effect. It was founded that the slit die system equipped with the flush mounted pressure transducers along the flow channel is the most appropriate choice for the viscosity measurements of WPCs and the characterization of wall slippage behaviour.

Simulation results show that a combination of shear and plug flow should be used to describe the material behaviour in the presence of wall slippage. An optimized viscosity value was found to best describe the WPC flow in addition to the wall slippage coefficients of the Navier’s slip law determined from the gap-dependency experiments of the slit die setup. The coefficients for the simulations of the profile die where approximated using the experimental data and simulating the slit die. Based on the results presented here, it can be stated that a careful interpretation of flow behaviour is crucial to achieve good prediction results independent of the numerical methods.

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