A Die Rotating System for Moderations of Extrusion Load and Pressure Drop Profiles for Molten PP and Wood/Polypropylene Composites in Extrusion Processes

Naret Intawong,[1] Chatchawan Kantala,[2] Watit Lotaisong,[2] Narongrit Sombatsompop[2]

[1]*Department of Industrial Engineering, Faculty of Engineering, Rajamangala University of Technology Lanna, (RMUTL), Chiang Mai, 50300, Thailand*
[2]*Polymer Processing and Flow (P-PROF) Group, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi (KMUTT), Thongkru, Bangmod, Bangkok 10140, Thailand*

Received 16 June 2010; accepted 16 August 2010
DOI 10.1002/app.33209
Published online 8 November 2010 in Wiley Online Library (wileyonlinelibrary.com).

ABSTRACT: A die-rotating system was proposed in this work for moderations of extrusion forces and entrance pressure drop for molten polypropylene (PP) and wood/polypropylene (WPP) composites in a capillary rheometer and a single screw extruder. The effects of processing conditions and wood loading in PP were of our interests. The extrusion force and entrance pressure drop with and without the die rotating system were monitored in real-time. This was the first time that the die-rotating system was used for processing of highly viscous wood/polymer composite materials. It was found that the flow properties of the molten PP and WPP composites obeyed pseudoplastic non-Newtonian behavior. The behavior was more obvious at wood contents of above 6 wt % and in the capillary rheometer. The rotation of the die could moderate the extrusion load by 60% and entrance pressure drop by 20% in the capillary rheometer, and the entrance pressure drop by 30% in the single screw extruder, especially at the conditions where the viscosities of the WPP and the extrusion rate were high. Greater fluctuations in entrance pressure drop caused by die rotation were observed in the single screw extruder. © 2010 Wiley Periodicals, Inc. J Appl Polym Sci 120: 1006–1016, 2011

Key words: wood polymer composites; extrusion; polypropylene; processing

INTRODUCTION

Wood polymer composites (WPCs) have attracted scientists and engineers because of their cost savings, good mechanical properties, better dimension stability, environmentally friendly products and low density, as compared with synthetic fibers/plastic composites. The applications for WPC products are limited to decorative or nonstructural applications which include decking, exterior window and door profiles, automobile paneling, panel inserts, and flower pots, due to the limitations in their mechanical properties as compared with solid or natural woods. Recently, a number of methods have been proposed to make use of WPC materials for structural and engineering properties, these including chemical and physical surface treatments,[1–3] additions of synthetic fibers[4,5] and nano-particles,[6] selections of appropriate processing techniques[7–10] and design of product-shaping components.[11] De Albuquerque et al.[1] found greater mechanical properties of jute roving reinforced polyester composites could be obtained by an improved adhesion and mechanical locking between the treated-fiber and the polyester matrix using NaOH treatment. Sombatsompop et al.[2] suggested that the 2% MAH-*g*-PP agent with 11% impact modifier was sufficient for improving the overall mechanical properties of the composites while Me'ndez et al.[3] claimed that the MAPP coupling agent of 6% would be required for improving the wood and PP adhesion. Tungjitpornkull et al.[4] found that at low glass fiber contents (10–20%) the concentration of carbonyl groups to form chemical interaction with WPVC composites was important whereas the effect of final length of glass fiber after final processing became the dominant factor at high glass fiber loading (30%). A considerable improvement in tensile properties of wood/HDPE could be obtained by introducing 5 wt % glass fiber[5] or by incorporating nanoclay[6] into the wood/HDPE composites.

Processing techniques and their processing variables have significant effects on the properties of natural fiber/polymer composites. Liu et al.[7] measured

Correspondence to: N. Sombatsompop (narongrit.som@kmutt.ac.th).

Contract grant sponsor: Thailand Research Fund (TRF Research Senior Scholar; contract grant number: RTA5280008 and V.P. Wood Co., Ltd (Thailand).

Contract grant sponsors: Office of the Higher Education Commission (OHEC, under Postdoctoral grant and the National Research University Program).

the impact strength of kenaf fiber reinforced soy-based bio-composites using different manufacturing processes, and found that the compression molding could produce the composites with higher impact strength. The results were in line with those of Tungjitpornkul et al.[4] Practical views for reducing the void volume using small wood particles, and high compaction pressure were presented by Wolcott and Englund.[8] Xu et al.[9] studied life cycle assessment of PP and wood/PP using a compression molding technique, and also demonstrated a term called "material service density," defined as the volume of material satisfying a specific strength requirement. Migneault et al.[10] examined the effect of processing method on mechanical properties of three chemi-thermomechanical pulp (CTMP)/HDPE composites. They found that the physical and mechanical properties of the composites from injection molding process was better than those from extrusion process due to better fiber orientation and less fiber breakage were obtained from the injection molding process. Most recent work by Sombatsompop et al.[11,12] studied flexural, creep and fatigue properties of wood/PVC composite beams under a wide rage of die designs and testing conditions. Profile dies with low number of hollow cores with thick flanges and webs were recommended for the composites with higher mechanical properties.

The engineers and scientists have realized that, during processing the addition of wood particles or wood fibers into polymer materials causes a considerable increase in composite melt viscosity, especially when introducing secondary synthetic glass fiber and other property promoting agents. These will then make the processing become much more difficult as a result of high pressure drop built up during processing. This would eventually lead to a number of flow instabilities and finally physical distortions of WPC final products. Such behavior was supported by Maiti et al.[13] who investigated the melt rheological behavior of wood/isotactic polypropylene (i-PP/WF), and found that the apparent melt viscosity increased about 70% with increasing wood content. There have been a few attempts to ease the processabilities of metallic and nonmetallic materials in extrusion processes through the die design. Rawal and Davies[14] used a rotating square die to produce polyethylene net structure from an extrusion process, and found that the shape of the extruded PE filament using the rotating die deviated from its corresponding die at the die exit. Ma et al.[15,16] experimentally and theoretically investigated a forward extrusion of pure lead using rotating conical dies, and suggested that the extrusion load was reduced by die rotation. The molten lead exhibited a twisted flow at a finite distance from the punch, and the twisting level became larger and deeper by increasing the die rotating speed. Such works were further developed for the effects of steady and cyclic die rotations on the compression of aluminum.[17] A rotating die system was previously proposed by Intawong et al.[18] for studying the rheological properties, flow patterns, and extrudate swell of natural rubber (NR) compound in a capillary rheometer and found that the rotating die extrusion could reduce the extrusion load and finally resulted in decreases in NR extrudate swelling.

Recent literatures have indicated that methods to ease the process-abilities of wood/polymer composites are very rare and still open for wide discussion. This is because most studies have focused on mechanical, thermal, and morphological properties of the WPC composites whereas very few works have investigated the flow properties of wood/polymer composites, probably due to difficulties in viscosity control, limits of processing window, and incompatibilities of the wood and thermoplastic composites. Overcoming these processing problems, therefore, became our interests. In this work, a constant-rate capillary rheometer coupled with an in-house-developed rotating-die system, as similar to that proposed in our previous work,[18] was constructed and used to measure the viscous behavior in terms of applied forces, entrance pressure drop for highly viscous wood/polypropylene composite (WPP) melts. The study covered the effects of wood content, shear rate or volumetric flow rate, and die rotation speed. The extrusion processes used in this work were a constant-rate capillary rheometer and a single screw extruder, the differences in the experimental results obtained by these two extrusion processes being compared and discussed. The explanations for the differences in the flow behavior and changes in the extrusion load and die entrance pressure drop for molten PP and WPP composites due to die rotating effect were given in connection with flow visualization of molten PP developed in the rotating die, which was achieved through use of a color banding technique. It was hoped that die rotating technique proposed in this work could widen the processing window and reduce the composite viscosity for facilitating the processing of the WPC materials.

EXPERIMENTAL

Raw materials

1. Low molecular weight of polypropylene (PP Grade 1100NK) in granule form with a melt flow rate (MFR) of 9.8 was used and supplied by IRPC Public Co., Ltd (Bangkok Thailand).
2. Wood particles used in this work was obtained from carpentry and wood-working processes

and supplied by V.P. Wood Co., Ltd. (Bangkok Thailand) and had the average size of 250 μm. Wood particles must be dried to a constant weight. The maximum moisture content allowed was less than 5%, this being achieved using an oven at 80°C.[19] It should also be noted that it was not necessary to incorporate a coupling agent for wood treatment in this work since the chemical reaction between the coupling agent and the polymer dynamically changed during the extrusion (molten state). In addition, based on previous work by Sombatsompop and Chaochanchaikul,[20] the changes in rheological properties due to the addition of silane coupling agents were relatively small (less than 10%) as compared with those in mechanical properties of wood/thermoplastic composites.

Preparation of WPP composites

The dried wood particles were then dry-blended with the PP using a high speed mixer before melt-blending in a twin-screw extruder (Haake Polylab-Rheomex CTW100P, Germany). The wood content used was varied from 0 to 30% weight (wt %) of the PP, depending on the type of extrusion process used. The blending temperature profiles on the twin-screw extruder were 160, 170, 180, and 190°C from hopper to die zones and a screw rotating speed used was 50 rpm. A three-strand die having a diameter of 3 mm for each strand coupled with a palletizing unit was used to produce the WPP composite pellets, and then held in an oven for 24 h at 80°C for redrying the WPP composites ready for further flow property measurements in a capillary rheometer and a single screw extruder. This experimental procedure was to ensure that the starting mixing qualities of the WPP in the rheometer and the single screw extruder were very similar.

Extrusion processes for PP and WPP composites

In this work, the molten neat PP and WPP composites were processed using two different extrusion processes which included a capillary rheometer and a single screw extruder, and their flow properties were evaluated during the extrusions. In the capillary rheometer the PP and WPP composite melt was left about 20 min in the barrel until the melt temperature across the barrel diameter (40 mm) was uniform before starting the flow. But, the PP and WPP composite melts in the single screw extruder were produced and extruded through the die continuously, the temperature of the melts being nonuniform at the starting point of extrusion and during the flow.

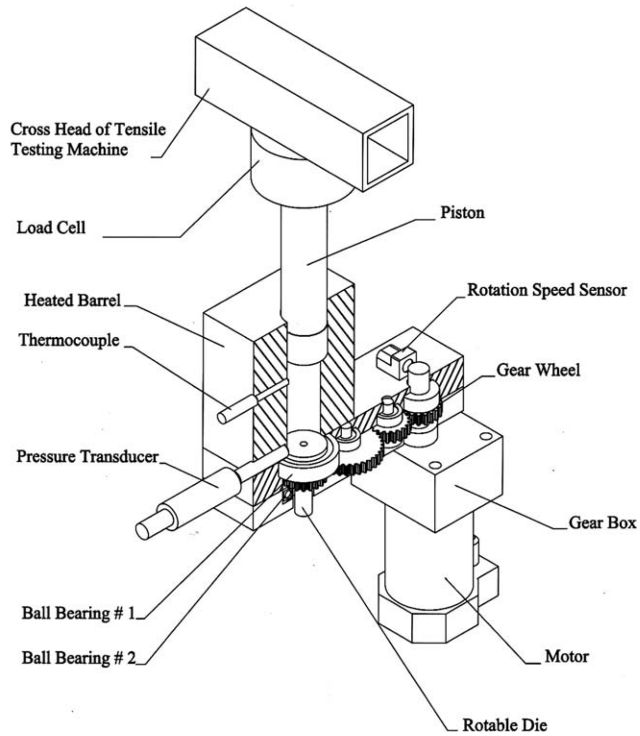

Figure 1 An experimental arrangement for flow property measurements of PP and WPP composite melts in a capillary rheometer.

Capillary rheometer

Figure 1 shows an experimental arrangement for flow property measurements of PP and WPP composite melts in an in-house-designed piston driven capillary rheometer coupled with a rotating die system. This experimental apparatus was a modification from that proposed in our previous work.[18] Thus, a brief description of the experimental rig was given. The barrel size of the rheometer used was 40 mm in diameter and 150 mm in length. A large circular die with 5 mm in diameter and 65 mm in length was located at the bottom of the barrel. The Ball Bearing#1 was to keep the alignment of the die during the rotation, and to lessen the friction of the die radius. Ball Bearing#2 at the bottom of the die base was used to lessen the friction on the axis which was in the same direction with piston movement. Four gear wheels were connected to the bottom part of the die base to transfer power from DC motor source to rotate the die system in the barrel. The rotation speed of the die can be adjusted in the range of 0–70 rpm which was measured using a speed sensor installed on the driving axis of the motor. This gear wheel set had a speed ration of 1/1; hence, the die rotation speed was the same as the speed of the motor axis. The barrel and die temperatures used in this work were 190°C. The piston speed was varied to obtain a wide range of shear rates. The apparent shear rates were calculated

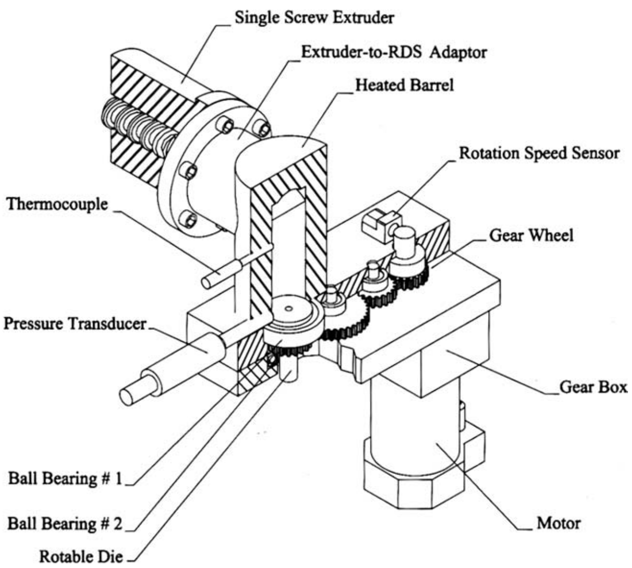

Figure 2 An experimental arrangement for flow property measurements of PP and WPP composite melts in a single screw extruder.

based on the information of piston speed used and the known barrel diameter. The apparatus temperature was controlled using a DD6 temperature controller. The entrance pressure drop was measured using a pressure sensor (Dynisco, Model PT460E-2CB-6, Franklin, MA) which was situated at the base of the barrel just above the die face.

Single screw extruder

The rotating die equipment as described in the capillary rheometer was used and connected at the end of a single screw extruder using a specially-constructed adaptor (RMUTL SE001 MUSHIKING Poly-Lab supplied by RMUTL, Chiang Mai, Thailand) shown in Figure 2. The exact length-to-diameter (*L*/*D*) ratio of the barrel was 600/25 mm/mm, and the temperature profiles on the extruder were 170, 180, 190, and 190°C from hopper to die zones, and the screw rotating speed was varied to obtain a wide range of shear rates in the experiment. It should be noted that the temperature profiles along the barrel length for screw extrusion process are usually non-uniform, but tended to be given for melting and homogenizing the PP and WPP materials without degradation. The temperature reported in this work was "die temperature" which was carefully controlled by DD6 temperature controller, and the die temperatures in the capillary rheometer and the screw extruder are equal (190°C) for result comparison. The entrance pressure drop was measured using a pressure sensor (Dynisco, Model PT460E-2CB-6, Franklin, MA) which was situated at the base of the barrel just above the die face.

Measurements of flow properties of PP and WPP composites

The flow properties of the PP and WPP composite melts were evaluated during extrusion from the barrel through the rotating die both in the capillary rheometer and the single screw extruder. In the capillary rheometer, the prepared PP and WPP were fed into the barrel and left about 20 min until the melt had a uniform temperature before the piston started to push the polymer down the barrel. The extrusion force exerted at the piston during the flow and the entrance pressure drop were then measured and recorded in real time (or piston displacement) using a high speed data-logging system having a scanning speed of 20 data/s. The piston speed and the barrel diameter were used for the apparent shear rate calculations, and the pressure drop at the die entrance was measured for the shear stress calculations.[18] In the screw extruder, the apparent shear rates were varied by varying screw rotation speeds and calculated based on the mass flow rate and melt density of the melt extruded from the die. Therefore, only entrance pressure drop as a function of extrusion time was of interest. It should be noted that Bagley's and Rabinowitsch corrections were not applied to the shear stress and shear rate data generated in this work due to two reasons. First, the shear stress and shear rate data were used solely for comparative reasons to illustrate the magnitude of the changes observed in the flow characteristics of the materials as a function of the die rotating speed and the wood content. Second, the die dimensions used were constant throughout this work which implies that the Bagley's corrections could be neglected in this case.

In both extrusion processes, the shear rates and the shear stress values were used to establish flow curves which were used to identify the flow behavior of the PP and WPP composites. Apart from the flow curves, the main experimental results reported in this work were the extrusion force and entrance pressure drop profiles during the real time extrusion by varying die rotating speeds from 0 to 70 rpm. It should also be noted that the PP and WPP composite melts extruded from the rotating die in this work did not experience any sharkskin, fractures or distortion, or oscillation at the die exit. This was because the large die size (low shear rate range) was used for appropriate range of die rotating speeds after a number of trial and error tests.

RESULTS AND DISCUSSION

Capillary rheometer

Figure 3 shows the extrusion force changes and Figure 4 shows the entrance pressure drop profiles as a function of extrusion time and die rotating speed for neat PP and WPP (WPP) composite melts at various

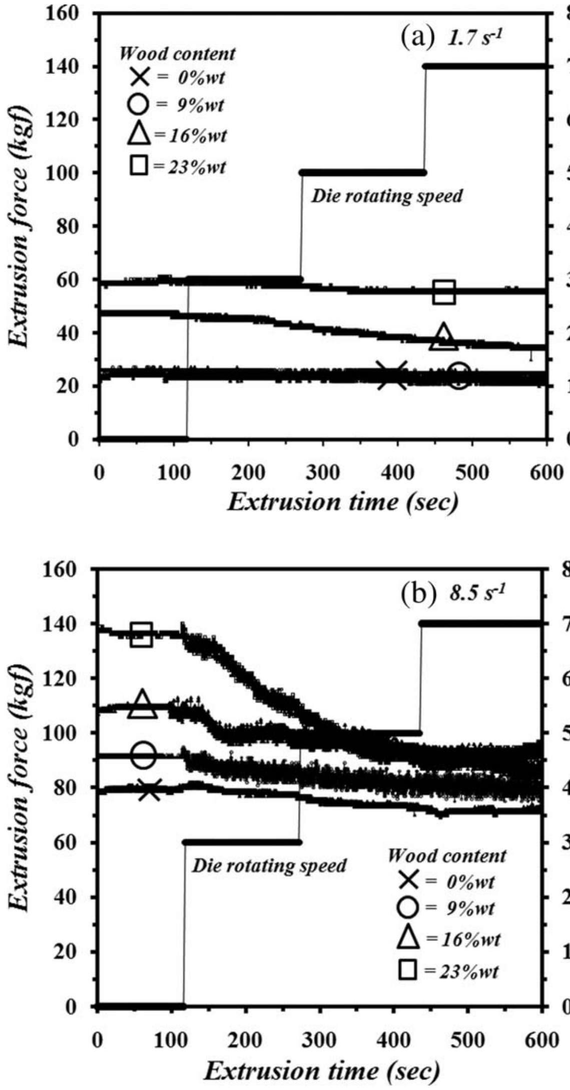

Figure 3 Extrusion force VS time for WPP composite melts for different wood contents. (a) 1.7 s^{-1} (b) 8.5 s^{-1}.

wood contents at apparent shear rates of 1.7 [Figs. 3(a) and 4(a)] and 8.5 s^{-1} [Figs. 3(b) and 4(b)]. All the data were recorded in real time using a high speed data logger. It should be noted that the shear rates used in this work were relative low due to the large diameter of the die used. Therefore, the recorded extrusion force and entrance pressure drop were relatively low. The extrusion force and entrance pressure drop were measured while the die rotation speed was increased in a stepladder manner. It was observed for low apparent shear rate (1.7 s^{-1}) that the extrusion force [Fig. 3(a)] and entrance pressure drop [Fig. 4(a)] did not change with increasing die rotating speed. However, at higher apparent shear rate (8.5 s^{-1}) the extrusion forces decreased from 140 to 90 kgf (by ~ 60% reduction) for 23 wt % wood content used, and the entrance pressure dropped from 10×10^5 to 8×10^5 Pa (by 20% reduction) for 23 wt % wood content used by increasing die rotating speed from 0 to 70 rpm. This behavior was similar to the work by Ma et al.[15,16] who found the extrusion load reduction of pure lead by using rotating conical dies. The fluctuations in the entrance pressure drop during the measurements were probably caused by the flow of the composite melt which was continuously developing in the barrel as the piston moved down the barrel. The decreasing effects of the extrusion force and entrance pressure drop of the PP and its composites due to increasing die rotating speed were much more significant at the higher wood contents. This was because the addition of wood particles into PP would result in an increase in bulk viscosity of the composite melts, and this could generate more shearing stresses during the flow by the action of die rotation.

The viscosity changes due to the addition of wood particles could be substantiated by the results of

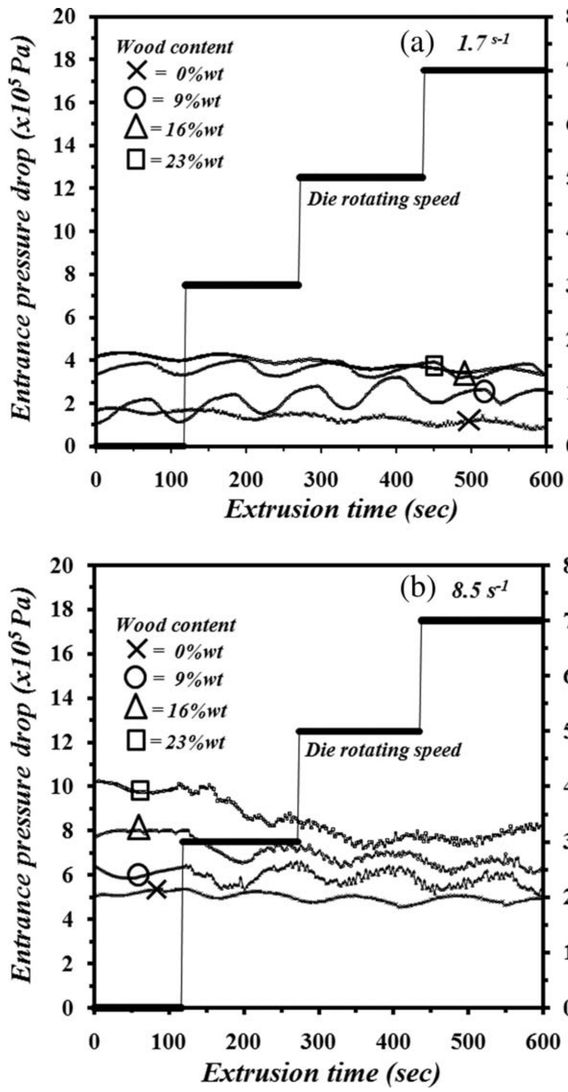

Figure 4 Entrance pressure drop VS time for WPP composite melts for different wood contents. (a) 1.7 s^{-1} (b) 8.5 s^{-1}.

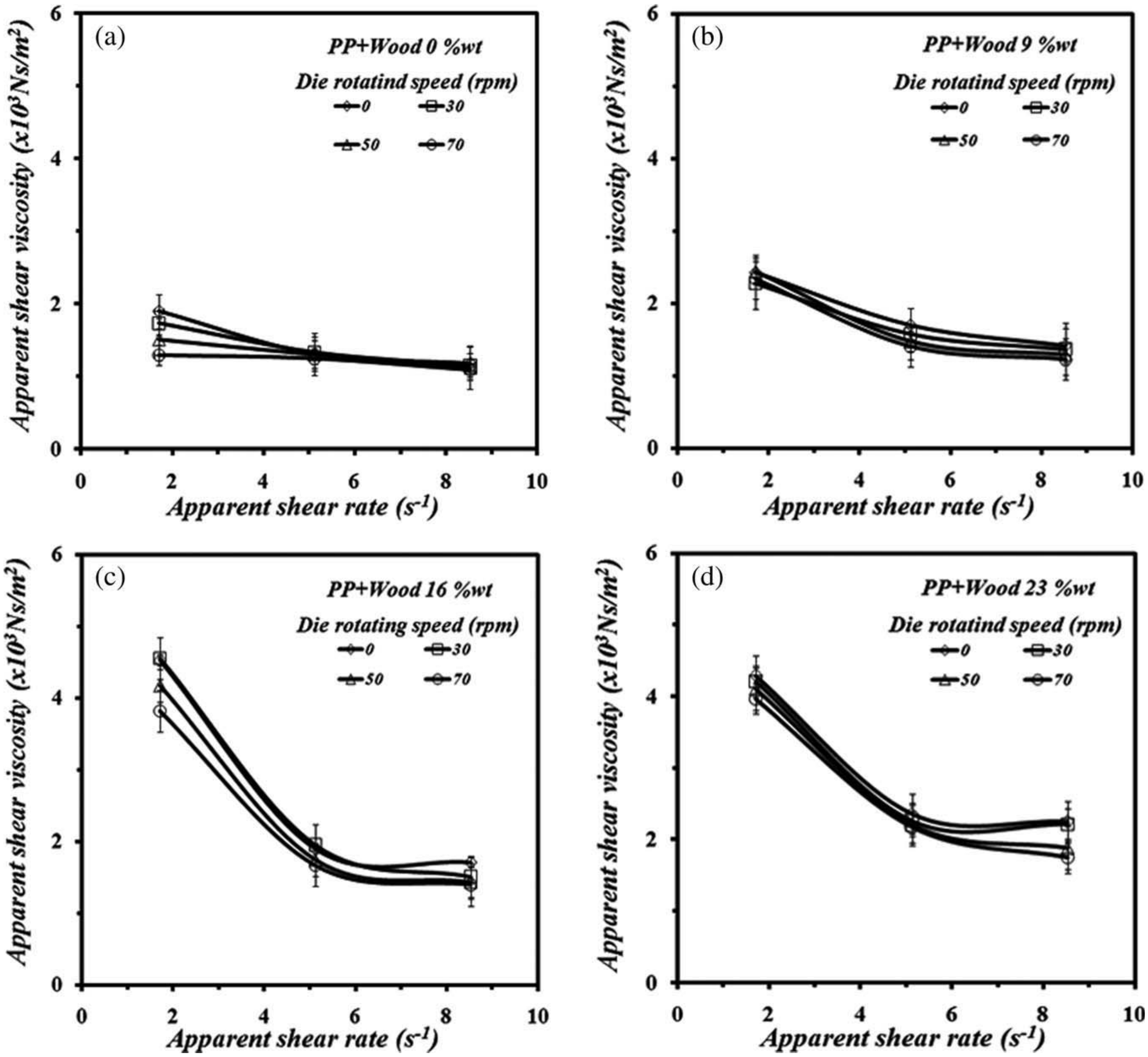

Figure 5 Flow curves for neat PP and WPP composites measured in the capillary rheometer at 190°C. (a) 0 wt % (b) 9 wt % (c) 16 wt %, and (d) 23 wt %.

flow curves which were referred to as relationship between apparent shear viscosity and apparent shear rate for neat PP and WPP composites measured in the capillary rheometer given in Figure 5. It was found that the apparent shear viscosity decreased with increasing apparent shear rates, and this suggests a pseudoplastic non-Newtonian flow behavior. As expected, the viscosity of the PP melt increased with increasing wood content. This was supported by Maiti et al.[13] who found that the apparent melt viscosity of PP increased about 70% with increasing wood content. It was interesting to note that the decreasing magnitude of shear viscosity with increasing apparent shear rate was more obvious with the WPP composite melt with high wood contents (16 and 23wt %). It was observed that the die rotating speed had no effect on the viscosity changes for PP and WPP composite melts although in some cases the viscosity slightly decreased with increasing the die rotating speed. However, the viscosity

TABLE I
Flow Properties for PP Melt with and without Red-24 Pigment Tested in a Capillary Rheometer

Apparent shear rate (s^{-1})	Apparent shear viscosity ($\times 10^3$ Ns/m^2)	
	Uncolored PP	Colored PP
6.22	1.56	1.73
12.44	1.00	1.02
18.66	0.74	0.75
31.10	0.50	0.50

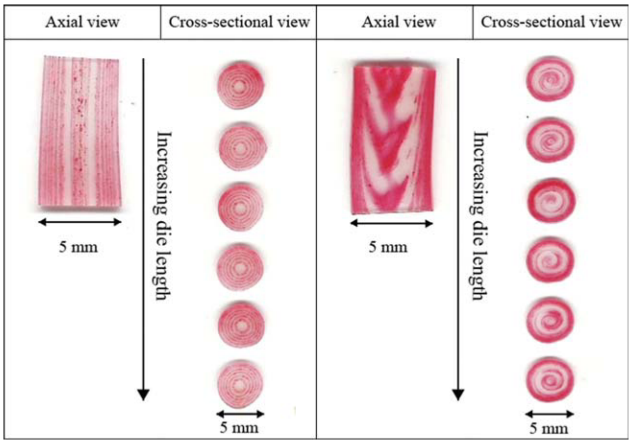

Figure 6 Flow visulizations of PP melt in the capillary rheometer at axial and cross-sectional views at apparent shear rate of 8.5 s^{-1}. (a) Stationary die and (b) Rotating die. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

changes were probably within the experimental errors (±5%). This implies that the reductions in extrusion load (Fig. 3) and entrance pressure drop (Fig. 4) were not caused only by the viscosity changes as a result of die rotation.

Changes in extrusion force and entrance pressure drop are usually in a direct relationship, i.e., the higher the extrusion force the greater the pressure drop developed at the die entrance. Therefore, the reductions in these two parameters found in this work practically indicate that higher extrusion outputs or productivities could be achieved either by increasing piston speed in piston-driven rheometers or by increasing screw rotation speed in single screw extruders. It was observed from the results in Figure 4 that the effect of entrance pressure reduction was higher at higher extrusion time or higher die-rotating speed when piston went closer to the capillary die entrance. In other words, when piston tip was far away from the capillary die entrance the effect of rotation on the pressure was negligible at low extrusion time or low die-rotating speed. This was probably due to contribution of capillary rotation. It was postulated that the decreases in extrusion force and entrance pressure drop were associated with flow development in the rotating die.

To support our reasons, flow visualizations for PP under the same testing conditions (PP material, die temperature, and apparent shear rates with and without die rotation) were performed. In this section, the same PP granules were used but made in two different colors for better resolutions by addition of 1.0 wt red-pigment (CI solvent Red-24 supplied by Orient Chemical Industries Co., Ltd, Osaka, Japan) for pigmentation of PP sample. The PP granules were dried in an oven at 75°C for 60 min to avoid any possible air traps and bubbles during solidification. The flow property results in Table I shows that the addition of Red-24 pigment in the PP had no effect on the flow properties of the melt, indicating that the changes in the flow properties of PP did not result from the pigmentation process. The flow visualization experiment was carried out by preparing the uncolored and colored PP sample sheet with 3-mm-thick using a hydraulic press with a mold temperature of 210°C under a hydraulic pressure of 150 kg/cm^2 before cooling the molded sample to room temperature. The PP sheet was then cut into disks having 40 mm in diameter and 3 mm in thickness. The sample disks were then loaded into the heated barrel in color alternating sample disks. The piston was then mounted and slowly compressed the PP disks to ensure that there was no air trapped in the barrel. All the PP disks were left about 10 min under 190°C barrel and die temperatures until fully molten before being extruded for the required piston displacement (80 mm down the barrel in this case), this being achieved using a metal plate to block the die at the exit. After that the PP melt in the barrel was left to solidify using a rapid air cooling to avoid any voids and bubbles within the PP sample before unloading the PP sample rod, then sectioned in half, and the flow visualization was investigated. This experiment was then repeated for the maximum die rotating speed used in this work (referred to as 70 rpm), the die rotating during the extrusion of the PP melt for any required piston displacement.

Figure 6 shows the flow visualization of solidified PP at the axial (left) and cross-sectional (right) views of PP melt flowing along the die length using the stationary die and the rotating die in the capillary rheometer. It should be noted that different magnifications for axial and cross-sectional views were used to ease the resolution of the flow visualizations of PP melt. It can be seen that for the stationary die [Fig. 6(a)], the PP layers flowing in the stationary die were independent of one another indicating that each flow layer flowed along its flow path from the barrel into the die in a laminar form. In the case of die rotating system (Fig. 6b), each PP melt layer exhibited a continuous and twisting flow around and along the die length. The flow patterns of the PP melt observed in this work were very similar to those found for natural rubber compound in our previous work.[18] The twisting of the flow layers suggested a helical or spiral flow occurring in the rotating die and this was believed to produce torsional shear strain within the die. At higher shear rates or high composite viscosities, the torsional shear strain would be even higher, and this could lead to a circumferential slippage between the molten PP and the die wall during the flow in the rotating die and possibly additional shear heating to the PP and WPP

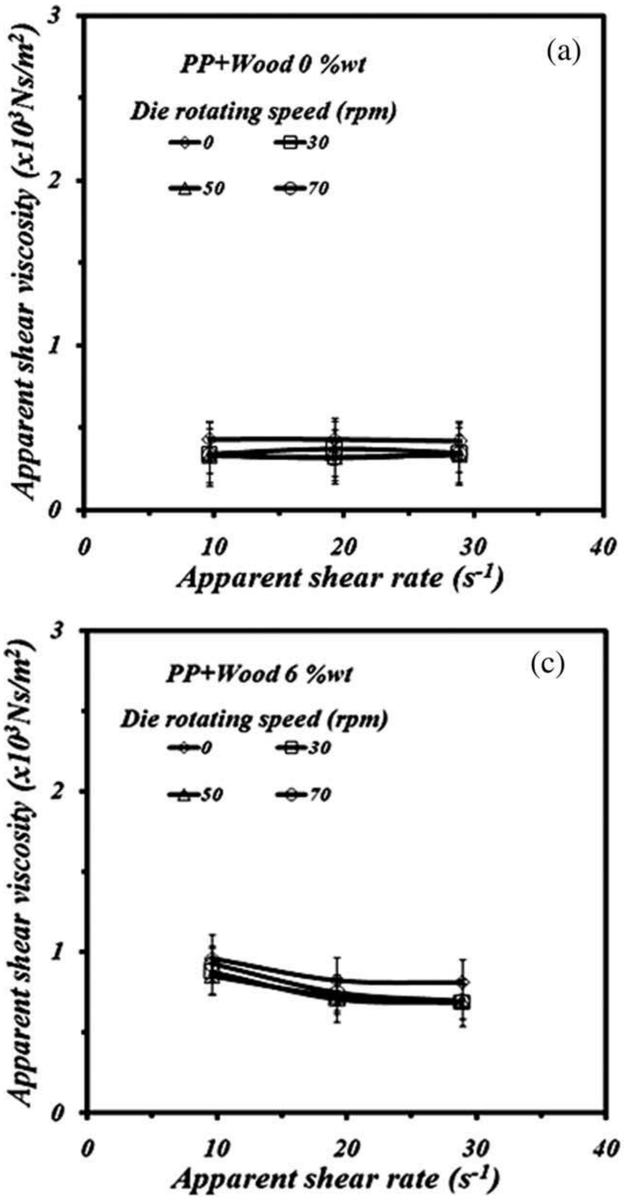

Figure 7 Flow curves for neat PP and WPP composites measured in the single screw extruder at a die temperature of 190°C. (a) 0 wt %, (b) 3 wt %, (c) 6 wt %, and (d) 9 wt %.

melts.[21] These effects caused the reductions of extrusion load and entrance pressure drop observed in Figures 3 and 4. The torsional shear strain effect was supported by the works of Ma et al.[15,16] extruded the molten lead using rotating conical dies, and found that the extrusion load was reduced by die rotation as a result of circumferential flows during extrusion equipped with a rotating die system.

Single screw extruder

It should be rementioned that it was not possible to obtain the extrusion force in a single screw extruder. This was because the neat PP and WPP composite materials were melted and pushed by the action of screw rotation simultaneously. It should be noted that the motor amperage from in the screw extruder includes all the exerted forces (torques) to process the PP and WPP in various states (solid to fluid from feed to metering zones along the screw length) whereas the extrusion force for processing the polymer in the molten state was only required for direction comparison with those in the capillary rheometer (whose PP and WPP were was fully molten). Therefore, only pressure drop at the die entrance was recorded and examined. To prevent an overloading of the extruder, the wood content used for this case was reduced and varied from 2.9 to 9.0 wt %. Figure 7 shows the flow properties of neat PP and WPP composites in the single screw extruder in form of apparent shear viscosity VS apparent shear rate. It was interesting to note that the viscosities of

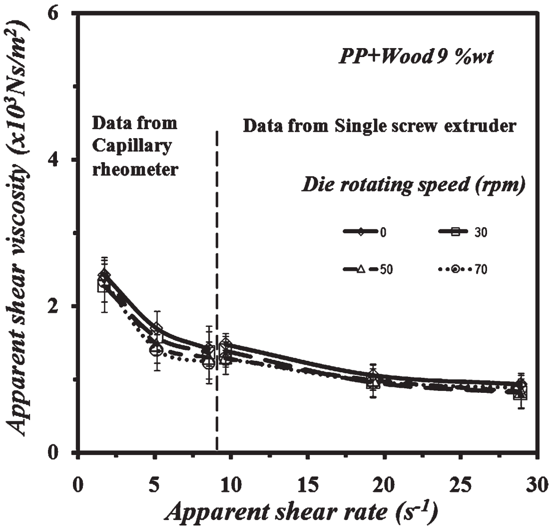

Figure 8 Viscosity data comparison for WPP composites containing 9 wt % wood from capillary rheometer and single screw extruder using a die temperature of 190°C.

neat PP and WPP with 3 wt % wood in the extruder did not change with shear rate. This may be due to low molecular weight of neat PP (as already mentioned by MFR value in Experimental section) and low shear rates used for screw extrusion process. However, the flow properties of WPP composites with higher wood contents (6 and 9 wt %) tended to follow shear-thinning non-Newtonian behavior. Similar to the results in the capillary rheometer, the viscosities for PP and WPP composite melts were unaffected by the die rotating speed, the variations in the viscosity data within the experimental errors (±5%).

It was interesting to compare the viscosity values of the molten PP and WPP composites in the capillary rheometer (Fig. 5) and the single-screw extruder (Fig. 7) although they were measured in different apparent shear rates. For general comparison, it was found that the changes in viscosity of PP and WPP in both extrusion machines obeyed pseudoplastic non-Newtonian behavior, especially when high wood contents were used. For more specific comparison, the viscosity data from the capillary rheometer and the screw extruder were merged and replotted in the same graph, allowing the flow properties of the melt in a wide range of apparent shear rates to be observed. An example of the merged viscosity data from the two extrusion machines was given only for the WPP composite with 9.0 wt % wood content and the result are shown in Figure 8. It was interesting to note that due to the differences in apparent wall shear rates used in the rheometer and the screw extruder, the viscosity of the WPP composite in the capillary rhemoter was higher than that in the screw extruder as one would expect since higher shear rates in the screw extruder would lower the melt viscosities. This observation clearly confirmed the shear thinning behavior of the WPP composite melt as stated earlier. By combining the viscosity data of WPP composite from the capillary rheometer and the screw extruder in Figure 8, one could evidently say that the flow properties of the WPP composite was more dependent on the apparent shear rate than the extrusion design used.

Figure 9 shows the changes in entrance pressure drop against extrusion time at different apparent shear rates, wood contents, and die rotating speeds. It was found that the greater the apparent shear rates the higher the entrance pressure drops as one would expect. Increasing apparent shear rates from 9.6 to 28.9 s^{-1} resulted in the increase in entrance pressure drop about 6–7 $\times$ 10^5 Pa. For a given apparent shear rate, the entrance pressure drop increased about 6 $\times$ 10^5 Pa with increasing wood contents from 0 to 9 wt %. This was due to the increases in the bulk viscosity of the composite melt, similar to the case for the capillary rheometer. For the effect of die rotating speed, the experimental results suggested that the entrance pressure drop decreased with die rotating speed of 30 rpm, and then leveled off or slightly increased in some cases for higher die rotating speeds of 50 and 70 rpm. The most obvious change in the entrance pressure drop was the case where the wood content and the shear rate were high [Fig. 9(c,d)], the pressure drop reduction being up to 4 $\times$ 10^5 Pa (about 30% reduction). The changes in the entrance pressure drop occurring in the single screw extruder as a result of increasing die rotating speeds could also be explained in the same way as those in the capillary rheometer.

Comparative and supplemental comments

This section was intended to illustrate a comparison of flow properties for PP and WPP melts flowing in the capillary rheometer and the single screw extruder. First, the flow curves (apparent shear viscosity VS apparent shear rates) of the PP and WPP melts obtained were similar in the two extrusion processes, showing the shear-thinning now-Newtonian behavior. Second, the percentage reductions in the entrance pressure drop found in the capillary rheometer (20% reduction) in Figure 3(b) were slightly smaller than those occurring in the screw extruder (30% reduction) in Figure 9. This was probably due to differences in the initial shear rates and wood contents added into the PP. Finally, it was observed that the fluctuations or data scatterings in entrance pressure drop with increasing die rotating speed in the single screw extruder were more apparent than those in the capillary rheometer. This was associated with differences in the velocity profiles and the temperature profiles of the molten polymer composites across and along the flow channel occurring in these two extrusion processes. It has been

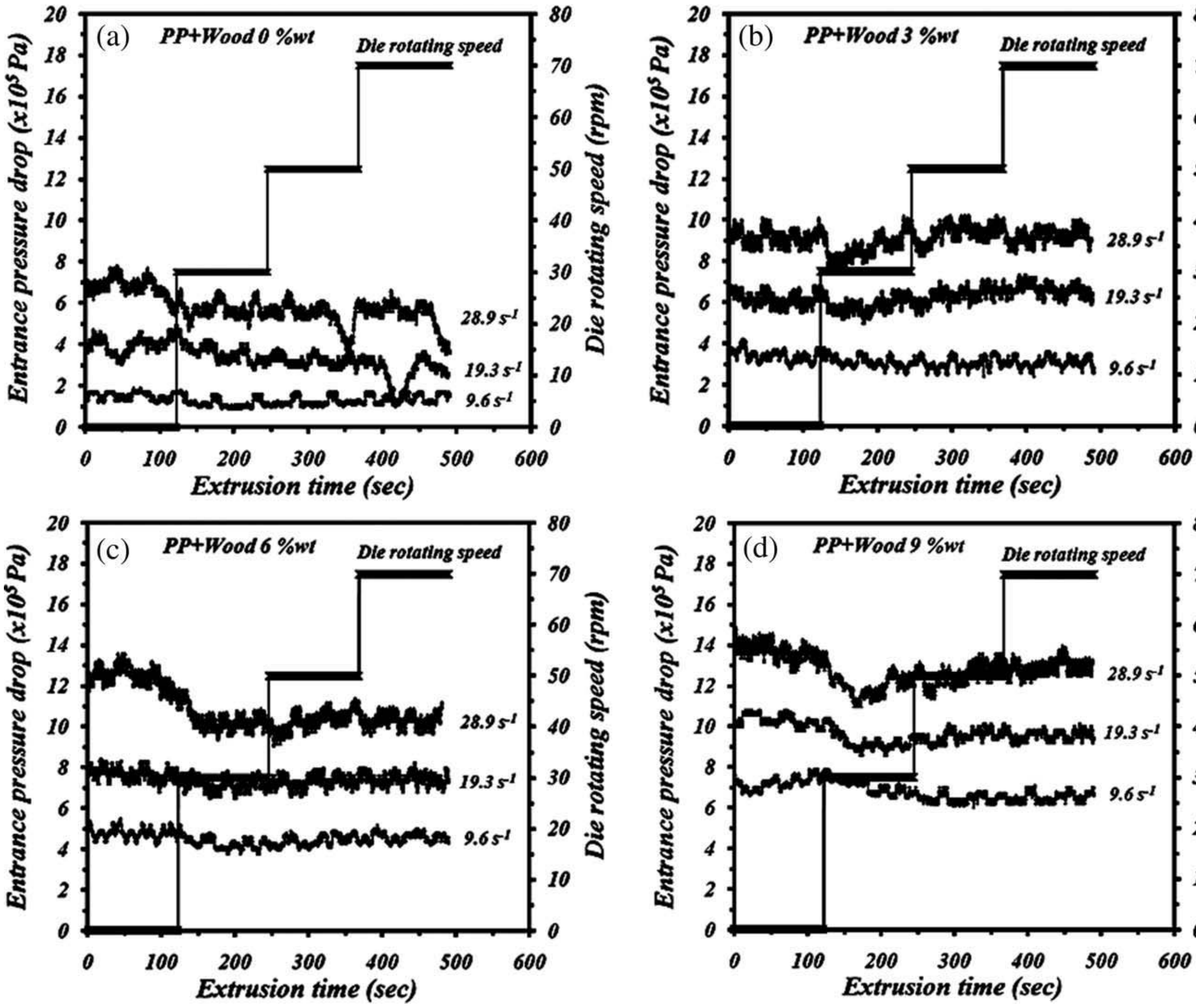

Figure 9 Entrance pressure drop for WPP composite melts for different wall shear rates and wood contents. (a) 0 wt %, (b) 3 wt %, (c) 6 wt %, and (d) 9 wt %.

known that the flows in the single- or twin-screw extruder combine between the drag flow and the pressure driven flow components whereas those in the piston-driven capillary rheometer is mainly the pressure flow. As a consequence, more melt temperature fluctuations with unstable velocity profiles of polymer melts were expected in the single screw extruder. This statement could be supported by previous studies on measurements of temperature gradients and velocity profiles of flowing thermoplastic melts in a capillary rheometer[22] and a screw extruder.[23]

In supplemental remark, it could be said that this was the first time that the die-rotating technique was applied for processing of wood/polymer composite (WPC) materials and their flow properties were discussed in association with the flow visualization. According to the experimental results, the die-rotating technique was relatively simple and suitable for reductions of extrusion loads and pressure built up in the extrusion processes, especially for the situations where the shear rates and material viscosities (like WPC materials in this work) are high. It was also hoped that the die-rotating technique could be used to remedy some flow defects like sharkskin and melt distortions since it could reduce the pressure drop along the shaping die, probably with assistance of some lubricants. As stated earlier that the reductions of extrusion load and pressure build-up could practically increase extrusion outputs or productivities either by increasing piston speed in piston-driven rheometers or by increasing screw rotation speed in screw extruders. However, the use of die-rotating technique has one obvious limitation. That was, the technique can so far be used only for symmetry dies, such as circular or annular dies.

CONCLUSIONS

The results suggested that a proposed die-rotating system was possible and successful for moderating the extrusion force and entrance pressure drop for PP and WPP composite melts in the capillary rheometer and the single screw extruder. The flow properties of the molten PP and WPP composites exhibited a shear-thinning character, the effect being obvious for the melt with high wood contents. The effect of die rotating speed was more pronounced for the WPP composite melts having high wood content and higher shear rate used in this work. The rotation of the die could reduce the extrusion load by 60% and entrance pressure drop by 20% in the capillary rheometer, and the entrance pressure drop by 30% in the single screw extruder for the WPP composites. The helical shearing flows and torsional shear strain developed as a result of die-rotation were responsible for the decreases in the extrusion force and the entrance pressure drop. The changes in the entrance pressure drop due to die rotation in the single screw extruder showed more fluctuation than those in the capillary rheometer. The flow properties of the WPP composite were more dependent on the apparent shear rates than the extrusion modes used.

Special thanks are expressed to Mr. Wanlop Harnnarongchai, Mr. Watcharin Sithicharoen and Mr. Chatchai Wongchaleo for their assistances in flow visualization work.

References

1. De Albuquerque, A. C.; Joseph, K.; De Carvalho, L. H.; D'Almeida, J. R. M. Compos Sci Technol 2000, 60, 833.
2. Sombatsompop, N.; Yotinwattanakumtorn, C.; Thongpin, C. J Appl Polym Sci 2005, 97, 475.
3. Mendez, J. A.; Vilaseca, F.; Pelach, M. A.; Lopez, J. P.; Barbera, L.; Turon, X.; Girones, J.; Mutje, P. J Appl Polym Sci 2007, 105, 3588.
4. Tungjitpornkull, S.; Chaochanchaikul, K.; Sombatsompop, N. J Thermo Compos Mater 2007, 20, 535.
5. Rizvi, G. M.; Semeralul, H. J Vinyl Addit Technol 2008, 14, 39.
6. Faruk, O.; Matuana, L. M. Compos Sci Technol 2008, 68, 2073.
7. Liu, W.; Drzal, L. T.; Mohanty, A. K.; Misra, M. Composites B 2007, 38, 352.
8. Wolcott, M. P.; Englund, K. In Proceedings of 33rd International Particleboard/Composite Materials.Washington State University, WA, 1999.
9. Xu, X.; Jayaraman, K.; Morin, C.; Pecqueux, N. J Mater Process Technol 2008, 198, 168.
10. Migneault, S.; Koubaa, A.; Erchiqui, F.; Chaala, A.; Englund, K.; Wolcott, M. Compos A, 2009, 40, 80.
11. Sombatsompop, N.; Prapruit, W.; Chaochanchaikul, K.; Pulngern, T.; Rosarpitak, V. J Vinyl Addit Technol 2010, 16, 33.
12. Pulngern, T.; Choocheepsakul, S.; Padyenchean, C.; Rosarpitak, V.; Prapruit, W.; Chaochanchaikul, K.; Sombatsompop, N. J Vinyl Addit Technol 2010, 16, 42.
13. Maiti, S. N.; Subbarao, R.; Ibrahim, M. N. J Appl Polym Sci 2004, 91, 644.
14. Rawal, A.; Davies, P. J. Plast Rubber Compos 2005, 34, 47.
15. Ma, X.; Barnett, M. R.; Kim, Y. H. Intl J Mechan Sci 2004, 46, 449.
16. Ma, X.; Barnett, M. R.; Kim, Y. H. Intl J Mechan Sci 2004, 46, 465.
17. Ma, X.; Barnett, M. R. Mater Sci Eng A, 2008, 483–484, 444.
18. Intawong, N.-T.; Wongchaleo, C.; Sombatsompop, N. Polym Eng Sci 2008, 48, 1191.
19. Sombatsompop, N.; Chaochanchaikul, K. Polym Intl 2004, 53, 1210.
20. Sombatsompop, N.; Chaochanchaikul, K. J Appl Polym Sci 2005, 96, 213.
21. Wapperom, P.; Hassager, O. Polym Eng Sci 1999, 39, 2007.
22. Sombatsompop, N.; Patcharaphun, S. Polym J 2001, 33, 491.
23. Sombatsompop, N.; Chaiwattanapipat, W.; Panapoy, M. Mater Res Innovat 2000, 3, 271.