Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Melt rheology and extrude swell properties of talc filled polyethylene compounds

Adib Kalantar Mehrjerdi [*], Tariq Bashir, Mikael Skrifvars

Swedish Centre for Resource Recovery, University of Borås, 501 90 Borås, Sweden

ABSTRACT

An experimental study of high-density polyethylene (HDPE) composites filled with talc (0–15 wt.%) was carried out to investigate the rheological properties. The apparent melt viscosity, melt density, and die-swell ratio (B) of the composites were measured at constant shear stress and constant shear rate by using a melt flow indexer and capillary rheometer. The experimental conditions were set to a temperature range from 190 to 220 °C for both apparatuses whereas a load range from 5 to 12.16 kg was selected for melt flow indexer and shear rate range from 1 to 10000 s^{-1} for capillary rheometer. The initial study showed that the talc particulates did not influence the melt viscosity compared with the neat HDPE but decreased the elasticity of the polymer system. The HDPE/talc systems obeyed power-law model in shear stress–shear rate variations and were shear thinning, meanwhile, the die-swell increased with an increased wall shear rate and shear stress. The melt density of the composites increased linearly with an increase of the filler weight fraction and decreased with the increase of the testing temperature. The talc-HDPE composites showed compressible in the molten state.

1. Introduction

Polymers and polymer composites are used extensively in technical applications by the industry and by consumers in daily life applications. Their popularity is due to their versatile properties, which are dependent on the polymer type, the presence of additives and fillers, as well as various modification methods. Post-polymerization modification results in polymer materials with an interesting range of properties and characteristics, such as enhanced mechanical properties, improved electrical conductivity, and better heat transfer properties [1, 2]. Most properties of the polymers can be enhanced using various reinforcing fibers, cellulose, particulates, and fillers to meet material requirements in a wide range of applications [3].

Moreover, the addition of fillers to a polymer brings changes in the process conditions and the rheological properties of the polymer. Rheological and melt flow properties are important indications of the polymer processing behavior and might impact all stages of material use, from formulation development, post polymerization and compounding to processing and product performance. Since rheological measurements are quite sensitive to detecting changes in the molecular architecture, several researches have dealt with this subject in the recent years.

Polymer materials exhibit both viscous and elastic behaviors when subject to force. The elastic component is related to the ability of the material to store and release the energy to become an initial state when the stress causing deformation is removed, while the viscous component is associated with the loss of the energy and converted into heat from the applied force. Melt polymer characteristics such as viscoelastic and melt density are extremely important properties in the field of polymer processing like rotational molding, compression molding, extrusion, blow molding, injection molding, fiber melt extrusion, 3D-printing, and many more [4].

Melt rheology governs the processability, including how a melt is transferred, final shape, and also many defects associated with the final products [5].

Rheological characteristics are dictated by the molecular architecture of the polymer, which is formed during the polymerization. Therefore, rheology plays an important role in creating a relationship between a given polymer structure, the processing properties, and the final quality and properties for a given polymer product.

The viscous properties for polyethylene (PE) melts have extensively been investigated [6]; it was documented that the zero shear-rate viscosity (η_0) is strongly dependent on the weight average molecular weight ($\overline{M}_w$) but is unaffected by the molecular weight distribution (MWD). The

---

onset of the shear-thinning is not sensitive to the $\overline{M}_w$, but it is connected to the polymer polydispersity index ($\overline{M}_w/\overline{M}_n$, where $\overline{M}_n$ is the number of the average molecular weight) [7, 8, 9]. According to the literature [8, 10], a broader MWD leads to a faster shear-thinning effect so the MWD can modify the viscosity function. In addition, it was observed that the long-chain branches lead to a stronger shear-thinning; therefore, the Newtonian shear viscosity-regime becomes smaller. For some polymer processing techniques, knowledge of the elongational viscosity is essential; therefore, there have been studies on the Trouton's ratio for which the extensional viscosity (μ_0) over the zero shear-rate viscosity (η_0) is 3. This ratio is valid for many melt polymers such as Newtonian fluids [11, 12, 13]. As mentioned earlier, the elasticity is the property of the polymer to contract and expand. Die swell, also named in the literature as extrudate swell, Barus effect, or post-extrusion swelling is one of the important manifestations for melt elasticity. When molten polymers are forced by shear stress through a die, the extrudate expands and becomes larger than the die size. In polymer processing, this phenomena has practical implications such as shark skin, stick slip, and melt fracture; accordingly, many researches have been attempted to show that the reason for these flow instabilities is due to the melt elasticity [14, 15]. For example, to extrude a pipe from the polyethylene at a specific output rate, the pipe surface starts to lose its glossy appearance; instead, a matte surface appears and, at higher output rates, periodic distortions are formed on the surface known as shark skin or surface melt fracture. Consequently, the phenomena is not only an attractive academic research topic, it is also quiet relevant to the plastic industry, as the phenomena contribute to limitations in the throughput in the processing operations as well as the quality variations. Liang et al. have reported a linearly increasing extrudate swell with an increasing shear stress for the PE blends, while it decreased with an increase of the die length/diameter ratio (L/D) and with a rise of temperature [16]. Die swell is affected by many factors such as the fundamental properties of the polymer like the molecular weight, molecular weight distribution, degree of branching, polydispersity, as well as processing conditions such as shear rate, shear stress, capillary dimension, and melt temperature. The presence of fillers also has a reported effect on the die swell [14, 17, 18, 19, 20].

The melt density (ρ_m) is an important control parameter during the polymer processing, especially in injection molding and extrusion. The polymer volume changes a lot due to solid transitions, melting, glass transition, temperature, pressure, among others. In the industry, there has always been great interest to simulate the process conditions, the final product shape, and to predict the polymer shrinkage. The melt density (or inversely specific volume) as a function of the thermal and pressure history is often essential for the different design processes, such as in the design of an extruder screw, a runner, gate size, and gate position, of an injection mold, or prediction of the shrinkage during the solidification in the mold, etc. [21, 22].

In recent years a variety of inorganic materials have been used as fillers in polymers for improving their properties, and studies of the preparation of plastic composites have advanced. Previous works suggested that the HDPE/talc composites have a great potential in industrial applications [1, 23, 24], however, very few reports have documented the melt flow properties of the talc/high density polyethylene (HDPE) composites [1, 25]. At the same time, their flow behavior, viscoelastic properties, and other melt flow properties are important indication of polymer processing behaviors. Therefore, the objective of this paper was to investigate the influence of the experimental conditions on the melt rheology properties of the talc/HDPE composites by means of a melt flow indexer and capillary rheometer. The aim therefore, is to report results about the melt rheology and Barus effect, obtained from the low shear rate measurements of the talc/HDPE composites done in a melt flow indexer. A completely randomized and balanced experimental design was conducted for three fixed factors: particle concentration at four levels (0–15 wt. %), loads at three levels (5, 10.1, and 12.16 kg), and three temperatures (190, 200, and 220 °C).

2. Experimental

2.1. Material

High-density polyethylene (HDPE) was supplied by Unipetrol RPA, Czech-Republic. This HDPE is commercially used in the extruded pipes application, and it has a melt flow rate (190/5) of 0.4 g/10 min, $\overline{M}_w$ of 185,000 g/mol, a polydispersity of 11, and a density of 0.952 g/cm^3, according to the supplier specifications. Talc powder supplied by Bassermann, Germany was used as filler. The density of the material was 2.77 g/cm^3, and the median particle diameter (D50) was 2.3 μm, according to the supplier specifications.

2.2. Composite preparation

Both the HDPE and the talc were dried overnight to expel any moisture prior to the blending, first in a vacuum oven at 70 °C and then in an air circulation oven at 100 °C, respectively. The weighed materials (0, 5, 10, and 15 wt.% talc concentration) were loaded into a 15 cm^3 twin-screw micro-compounder (DSM Xplore, the Netherlands). The compounding was done at 200 °C and 50 rpm for 5 min. Argon gas was used to maintain an inert environment in the compounder. The extruded strand was cooled in air, pelletized by cutting, and kept in a glass desiccator before further analysis.

2.3. Rheological and die swell measurements

The melt rheology was studied in a Tinus Olsen MP1200 melt indexer (United Kingdom). The reservoir diameter (d_r) and length of the barrel were 9.550 ± 0.007 and 150 mm, respectively, while the ratio of the length-to-inner diameter (L/D) of the die was 3.82, and the die entry angle was 180°. The test equipment used, together with the dimensions is shown schematically in Figure 1. The pellets were loaded into the bore of the barrel, and the barrel was set to the testing temperature, at which temperature the samples were preheated for 360 s before the load was applied, by placing a weight on the piston. A three-factor randomized statistical design was used, involving three replicates at each level for all 108 experimental runs. The talc concentration, testing temperature, and piston load weight were the investigated variables. Table 1 gives the detailed information about the sample treatments and variable levels used in the design experiment. As the melted compound was extruded from the die, extrudate specimens were carefully cut, cooled without any disturbances, and collected before taking the measurements of their diameter and weight. For each set of experiment, six cut-offs, with a length of approximately 10 mm, were obtained from the extrudate and characterized. The diameter of the cut-off extrudate (D_e) was calculated as the average diameter, at least five positions, measured by a digital calliper. The die-swell ratio is defined as the percentage of the extrudate swell as follows:

$$\%B = \frac{(De - D) \times 100}{D} \tag{1}$$

here, D is the die diameter, which is 8 ± 0.025 mm. The apparent shear stress in kPa (τ_w) was calculated by [26].

$$\tau_w = \frac{\Delta p D}{4L} \tag{2}$$

where Δp is the total pressure drop during the extrusion, D and L are the diameter and length of the capillary, respectively. Since the load and geometry of the barrel are known, then Δp can be given by the quick calculation. The apparent shear rate ($\dot{\gamma}$) can be defined by [26].

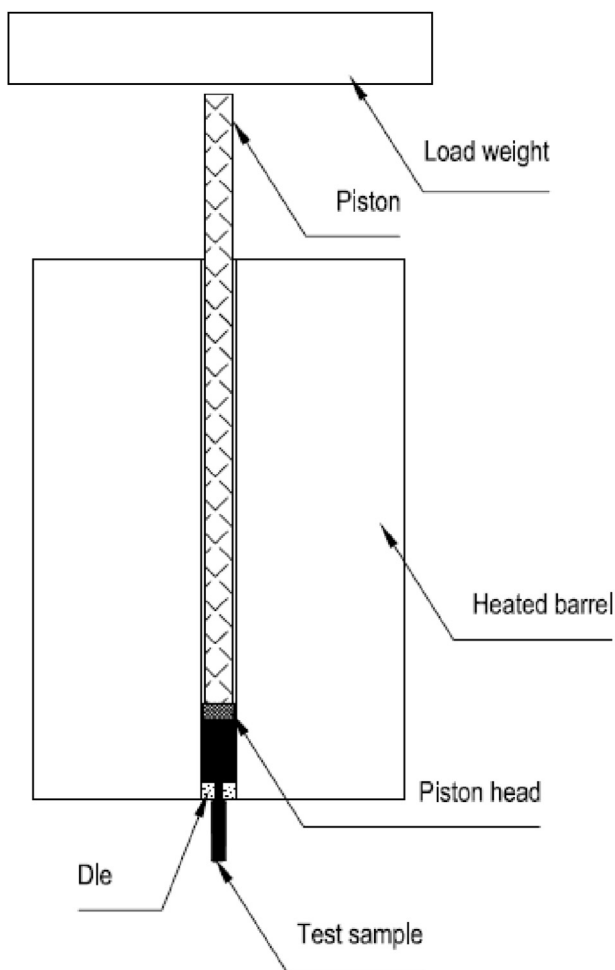$$\dot{\gamma} = \frac{32Q}{\pi D^3} \tag{3}$$

Figure 1. Schematic diagram of the test equipment.

where, Q represents the flow rate. According to Eqs. (2) and (3), the apparent shear viscosity can be expressed by [26].

$$\eta = \frac{\tau w}{\dot{\gamma}} \tag{4}$$

Melt density (ρ_m) is estimated by the measurement of extrudate mass and the corresponding decrease in the volume of the melt in the reservoir, which is given by:

$$\rho_m = \frac{4m}{\pi h d_r^2} \tag{5}$$

where m is the mass of the cut-off extrudate and h is the predetermined distance moved by the piston in the reservoir. These rheological parameters are termed apparent because the data measured were not corrected to absolute values at the orifice wall due to the fact that we wanted to detect the general trends for a comparative study. Images of cut-off extrudates were captured using a Nikon SMZ800 using a Nikon SMZ800 stereo microscope (Nikon Corporation, Tokyo, Japan). Since

some of the loaded talc filler might be lost during the compounding process, the filler content needed to be confirmed. This was done by thermogravimetric analysis in a TA instrument (TGA Q 500) supplied by Waters LLC, New Castle, U.S.A. Samples of 15 ± 3 mg weight were heated at a rate of 10 °C/min in an air purge stream, with a flow rate of 60 ml/min, from 30 °C to 700 °C, and then the weight change as a function time or temperature was recorded. One sample was run for each talc concentration.

Statistical analysis was performed by an analysis of variance (ANOVA) using a general linear model with level of significance $\alpha = 0.005$ or 95 % confidence. Data analysis was conducted using Minitab 17.1.

In the melt flow indexer, measurements are done in a constant shear stress rather than the constant shear rate, therefore in order to confirm data, the rheological characteristics of the neat HDPE and compound with 10 wt.% talc were reproduced using a capillary rheometer (Göttfert RG20, Göttfert, Buchen, Germany). In this instrument, the flow rate is imposed by a piston and the extrusion pressure monitored by a melt pressure transducer in the barrel with diameter of 15 mm. The barrel temperature was pre-set to 190 and 220 °C. The samples were heated for 300s in the barrel and then extruded through flat entrance die of 20 mm length and 1 mm diameter. The experiments were performed at increasing shear rates of 1, 10, 50, 100, 500, 1000, 2000, 5000 and 10000 s^{-1}. The pressure needed to extrude the materials through the orifice die at each shear rate was recorded when constant (less than 3% deviation) reading values were reached.

3. Results and discussions

The results from the thermogravimetric analysis after compounding are shown in Figure 2. The onset temperature of mass changes (T_5), the 50% loss temperature (T_{50}), and the percentage residues at 650 °C for the composites are listed in Table 2. It is confirmed that the residue values at 650 °C are in good agreement with the amount of the loaded talc, for each composition given in Table 1.

Figure 3 illustrates the dependence of the melt density on the testing temperature at the load of 5 kg and different talc concentrations. It can be noticed that the density of the melt decreases linearly with an increasing testing temperature, while added talc particulates have an increasing
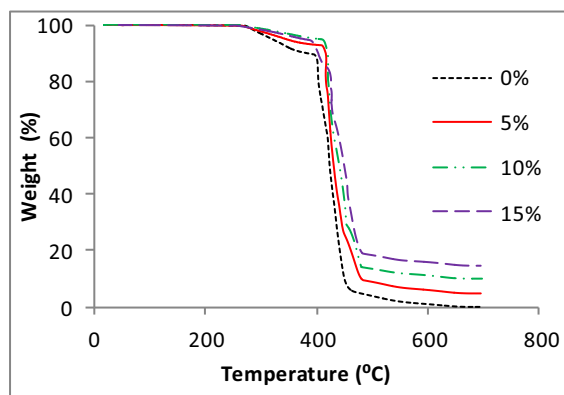

**Figure 2.** Thermogravimetric traces of the HDPE/talc composites.

Table 1. Factors and levels in the experimental design*.

| Treatment	Levels	Values			
Talc concentration (wt. %)	4	0	5	10	15
Temperature (°C)	3	190	200	220	–
Load (kg)	3	5	10.1	12.16	–

* Characterization data for all compounds and experimental details are tabled in Supporting Information Suppinfo1.

Table 2. Thermal degradation and residue for individual samples.

Property	HDPE/talc composite (wt.%)			
	HDPE	5	10	15
Temperature for 5% weight loss (°C)	320	345	404	377
Temperature for 50% weight loss (°C)	424	430	441	449
Residue at 650 °C (%)	0.16	4.99	10.15	14.88
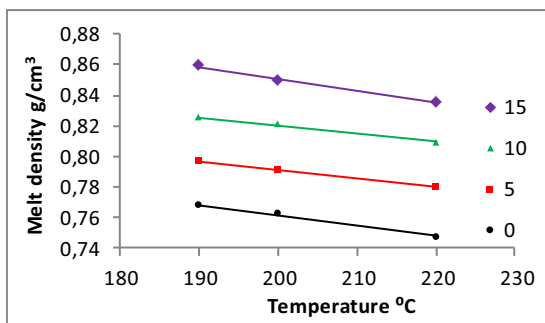
Figure 3. The relation between the melt density and the temperature in the HDPE/talc composites at 5kg load and different talc concentrations. Mean value of three measurements are shown.

effect on the melt density due to the fact that the density of the talc is higher than for the HDPE. The melt densities obtained for the neat HDPE show good agreement with the corresponding values in the literature [27]. Furthermore, when these values are compared to the density of the neat HDPE at room temperature, it can be realized that the volume of the material would be reduced by around 30% (shrinkage) due the temperature and phase changes. Figure 4 shows the melt density against the filler content under the test conditions at 5 kg and 10.1 kg load. From this graph, it can be seen that the melt density is linearly dependent on the filler content and slightly higher at a higher pressure. Similar observations for other polyolefins modified with particulates have been reported by other researchers [22, 28]. However, the values for the melt densities at the two pressures are very close to each other, thus, to prove the compressibility of the melt composites, the statistical analysis of ANOVA was used. The aim was to illustrate whether the means of the factor levels differ and are bigger than the errors. General linear model analysis of variance gives the p values maximum of 0.001, which are much less than the alpha (0.05). This indicates that the influence of all the factors on the response was significant. However, the p values (minimum of 0.103) for the interaction between the predictors suggest that there is no interaction of the factors that have an effect on the melt density. The practical outcome of this observation is that the polymer melt is compressible, although in many simulation models, it is ignored just because of the common simplifying [13]. Therefore, in polymer processing such as
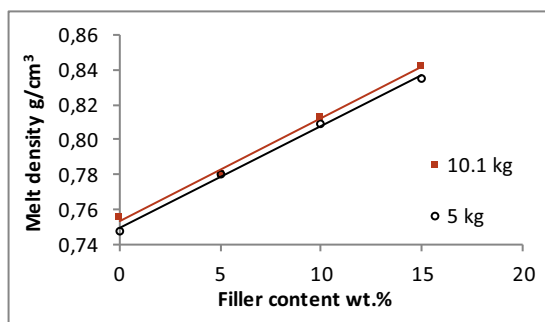
rotational molding, where the pressure and shear rates are rather low, the melt can be considered as an incompressible fluid. While in other processes, like injection molding where the pressure is high, the melt density at the desired pressures and temperatures should be carefully evaluated.
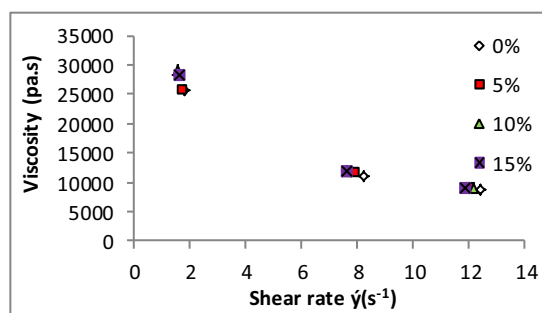
Figure 5 outlines the dependence of the apparent shear viscosity on the apparent shear rate for neat and talc filled PE at a temperature of 190 °C.

It can be seen that the shear viscosities decrease dramatically with an increasing shear rate, confirming the shear-thinning (pseudoplastic) behavior of the studied systems. A similar trend was observed at higher testing temperature. From the figure, it can also be inferred that the talc does not influence the shear viscosity in the temperature range of the experiment. This is interesting, as it is a well-known general behavior that adding particles to the polymers will increase the melt viscosity. Normally, the addition of the particulate fillers to the polymers restricts the molecular motion, thus, imposing a resistance to flow. As a result, it gives a higher viscosity value as the filler content increases. However, by adding the talc to the filled system, the viscosity was observed remaining constant with respect to its concentration up to 15%. Only a few disperse systems have been documented in the literature where the fillers do not have an influence on the shear viscosity [29]. This phenomenon might be attributed to the morphology of the talc particle. Talc is a mineral, composed of hydrated magnesium silicate, arranged in three disc-shape layers. The layers are attracted to each other by van der Waals forces and are able to slip over each other easily [1, 25, 30]. Therefore, by applying shear forces, the particles have the ability to slide past each other and have a lubricating function in the melt flow.

This observation can be explained the dependence of the shear viscosity against the talc content at the different testing temperature illustrated in Figure 6. In this figure, the effect of all three factors on the shear viscosity is shown. It can be seen that when the load is constant with an increase in the temperature, the viscosity decreases, while at the same time the effect of the load is the most dominant among other factors. The viscosity drops a lot when the load increases as it was shown earlier. Figure 6 also shows that the relationship between the apparent shear viscosity and the talc weight-fraction is linear and can be expressed by:

$$\eta = \beta_1 \times wt.\% + \beta_2 \qquad (6)$$

where, β_1 and β_2 are constants, which are related to the material properties and test conditions. Values for the coefficients β_1 and β_2 were calculated by linear regression and are summarized in Table 3. Data from

Figure 4. The dependence of the melt density on the weight fraction of the filler in the HDPE/talc composites at a temperature of 220 °C.

Figure 5. Apparent shear viscosity of the HDPE/talc composites as a function of the apparent shear rate at varying filler concentrations.
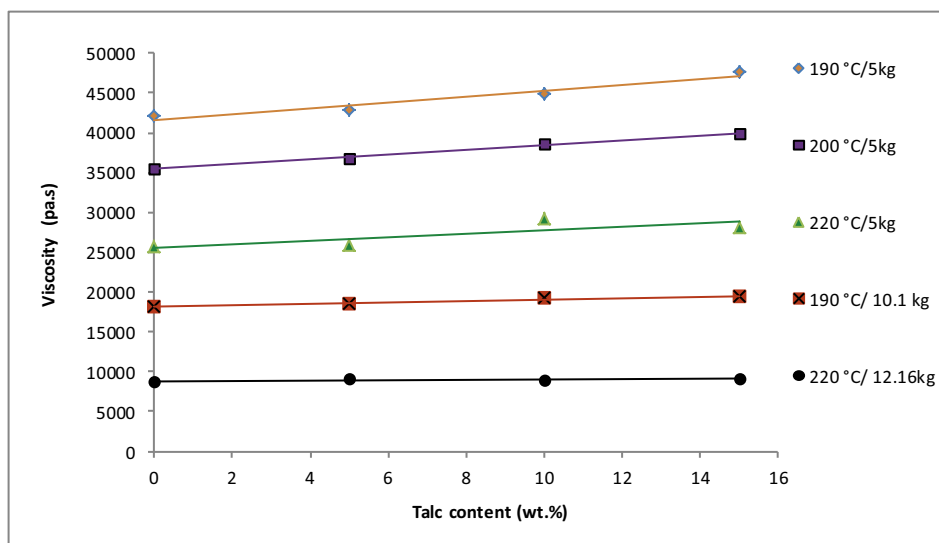
Figure 6. Apparent shear viscosity of the HDPE/talc composites as a function of the filler content at varying temperatures and loads.

Table 3 and Figure 6 indicate that the β_1 declines with a rise of the shear rate; this can be interpreted as less sensitivity of the shear viscosity on the talc load at a higher shear rate. This can be rationalized by the morphology and layer structure of the talc particle and shear stress. At a lower shear rate (like 1 s^{-1}), the shear stress is too weak to align the particles with the flow; therefore, the talc particles are distributed randomly in the melt. With increased filler content, there are more possibilities for the talc particle to orient itself perpendicularly to the flow direction. Thus, the randomized distribution of the particles might restrict the molecular motion in the matrix and slightly increase the melt viscosity; however, at a higher shear rate, there is enough shear stress in the system to align all the talc particles with the flow direction. In this structural arrangement, the talc layers can easily slip over each other and will therefore not influence the shear viscosity of the composite. Therefore, it is expected that the talc can have a different influence on the shear viscosity; at a very low shear rate (less than 1 s^{-1}), the talc gives an increased shear viscosity of the melt, while the talc does not affect the viscosity at a high shear rate.

Statistical analysis, based on the general linear model with the ANOVA at the 95% confidence level, was performed to test the effects of the factors and their interactions on the melt viscosity. The analysis confirmed that the most effective factors are load and then the temperature, meanwhile the P value for the talc was (0.08), which is bigger than the alpha, supporting that the talc content cannot significantly change the shear viscosity.

A similar observation was reported by Goel, D. C. et al. [29] for the shear viscosity of the PP/talc composites, which remain the same as for the neat polymer in the shear rates range of 100–900 s^{-1}. Another result has been documented by Chapman, F. M. et al. who worked with PP/talc composite [31]. They have reported that above a shear rate of 1.0 s^{-1}, the viscosity behavior of the PP/talc blends (40 wt.% talc loading) was the same as for neat PP. At a low shear rate (less than 0.1 s^{-1}), the melt viscosity of the talc/PP increased, compared to the melt viscosity of the

neat PP with increasing talc content. However, the results of our study contradict other reports where the melt viscosity of the polytrimethylene terephthalate/talc and PP/talc systems were examined and showed increased viscosities, compared to the neat polymers [32, 33].

Above discussions are based on the observation by the melt flow indexer that flow properties are compared in the constant shear stress (and not exactly the same shear rate), therefore, in this work the visco-elastic properties are investigated by means of a capillary rheometer, which operated at constant piston velocity. Figure 7 demonstrates apparent shear stress at the die wall versus shear rate at 190 and 220 °C for the 10wt.% talc-HDPE composite and neat HDPE by capillary rheometer in shear rate range of 1–10000 s^{-1}. It can be observed from Figure 7 that the melt shear stress generally increases linearly with the increase of apparent shear rate, for both the unfilled HDPE melt and the HDPE/talc composite melt at 190 and 220 °C in a logarithm coordinate system. Their relationship can be represented by the power law model as it is shown in the Figure 7. The value of the power-law index is less than unity (0.3033) implying pseudoplastic (shear-thinning) nature of the melt composites as it was shown earlier.

It may be noted that talc filler does not change the processability and the viscosity of the HDPE/talc composite behaves like the neat HPDE in the range of the experimental shear rate. These finding are in agreement with the melt indexer results discussed earlier. As it is expected, the overall viscosity for the higher processing temperature is respectively lower than that of at low processing temperature however the effect of shear rate is more dominate.

The elastic behavior of the system was investigated by die swell methods. Figure 8 displays the general photographs of two cut-offs of the post extrude samples with 15 wt.-% talc at 190 °C/5 kg load and neat HDPE at 220 °C/12.16 kg, respectively. From this picture, the strong effect of the talc particle on the reduction of the swelling is obvious. A general trend was observed, that is, the more the swelling, the more the tendency of bending in the extrudes. This behavior is related to the

Table 3. Values for the coefficients of β1, β2, and R squared of composites at different temperatures and loads.

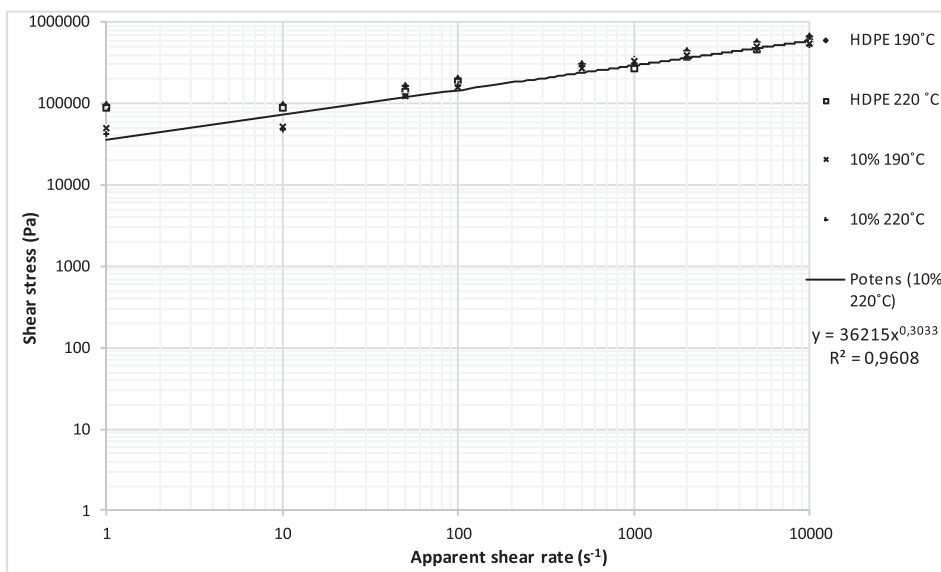| Treatment	Shear rate (s^{-1})	β_1 (Pa.s)	β_2 (Pa.s)	R-Sq.
5 kg/190 °C	1	366.2	41605	0.9313
5 kg/200 °C	1.2	303.8	35417	0.998
5 kg/220 °C	1.7	217.9	25573	0.6584
10.1 kg/190 °C	4.9	91	18168	0.9654
12.16 kg/220 °C	12.3	22	8829	0.6866

Figure 7. The comparison of shear stress and apparent shear rate of neat HDPE and HDPE/talc composite for 10 %wt. talc under 190 and 220 °C in logarithm scale.

Figure 8. General photograph of the post extrudate: left composite with 15 wt.% talc at 190 °C/5 kg load and right HDPE base material at 220 °C/12.16 kg load.

Figure 9. Effects of the filler concentration on the die swell at varying loads (190 °C).
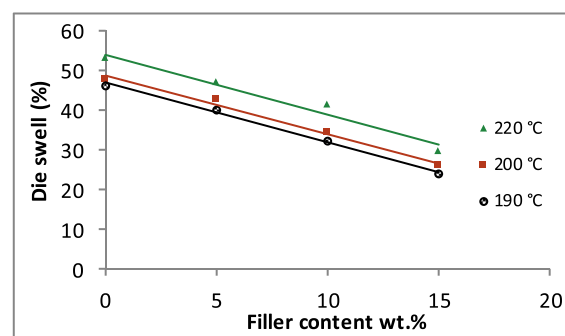
Figure 10. Effects of the filler content on the die swell at different temperatures (load 12.16 kg).

more elastic melt behavior and confirms that the extrudate swell has a significant effect on the quality of the final product.

The relationship between the die swell and the filler content is presented in Figures 9 and 10. As evident from these figures, the addition of talc has a strong dominant effect on the reduction of the elasticity of the melt composite. Such behavior may be explained as follows: generally, die swell is related to the recoverable elastic deformation formed during the flow through the die. In talc-filled polyethylene, the filler is distributed in an entangled polymer matrix, so with the increase of the talc particle loadings, the relative movement of the polymers in the melt is restricted; therefore, the elastic recovery of the shear deformation declines. Figure 9 also suggests that the die swell increases with a rise of the load (shear stress and also shear rate). When the shear stress in the barrel goes up (as a result of a rise in the load), the apparent shear rate
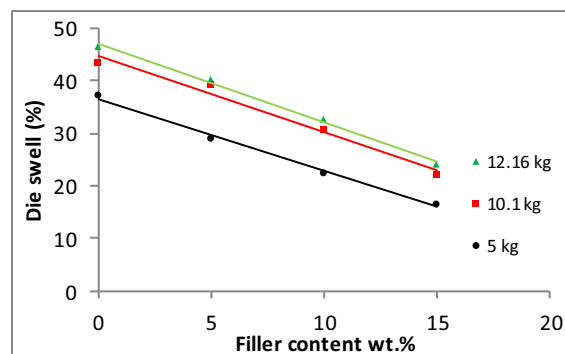
increases, making the polymer chains align in the flow direction. The deformation energy stored in the polymer melt increases, leading to a corresponding increased swelling of the extrudate. Moreover, when the shear stress intensifies, the residence time of the melt in the die will be reduced; consequently, the melt has less to time to relax, and it results in even more swelling.

Figure 10 outlines that the temperature has a positive effect on the die swell. The literature is not clear in establishing a relationship between the die-swelling behavior and the melt temperature. It has been reported
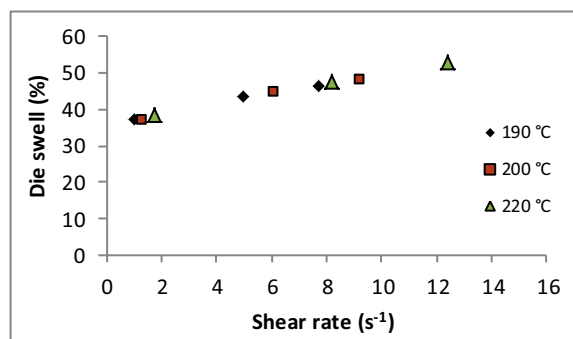
Figure 11. Effect of the shear rate on the post extrudate swell for the neat HDPE.

that the swelling increases with decreasing temperature [16, 34, 35]. In contrast, Mills et al. have reported the reverse situation for PE, and it has also been documented that in polyvinylchloride the degree of swelling increases with an increasing temperature [36, 37]. Of course, this discrepancy might be due to the differences in the polymer type or in the experimental set up. It should be noted that our study has been done under constant shear stress. In addition, from Table 3, it is obvious that when the shear stress (load) is constant the shear rate rises slightly with the temperature; therefore, the swelling can be a result of the different conflicting parameters. This interpretation is illustrated in Figure 11 where the dependence of the extrudate swell as a function of the shear rate is shown for the neat HDPE at different testing temperatures. Similar behavior is observed for the talc-filled HDPE composites (for simplicity, these results in this figure are excluded). The behavior shown in Figure 11 can be seen as that the die swell increases with a rise of shear rate, for example, the two samples with a set up condition of 190 °C/12.16 kg and 220 °C/10.1 kg had a similar swelling since they had the same shear rate (approximately 8 s^{-1}). Based on the results, it seems therefore that the die swelling is controlled by the shear rate rather than the shear stress or the testing temperature. These results are in accordance with other reports, which show that the swelling behaviors were independent of the extrusion temperature [19, 38].

Statistical analyses based on the general linear model with the ANOVA at the 95% confidence level show that all three factors (load, talc content, and temperature) have a significant effect on the die swell (P value was 0.000).

4. Conclusions

In this study, the melt flow and the viscoelastic properties, in terms of melt density, viscosity, and extrudate swell of the HDPE/talc composites have been investigated.

Shear stress–shear rate data in HDPE-talc composites obeyed power-law model in the shear rate range 1–10000 s^{-1} at talc concentrations 0–15 wt.% and at temperature range 190–220 °C. The power-law indexes were less than one, indicating pseudoplastic (shear-thinning) nature of the composites. Additionally, the experimental results indicate that the viscosity up to 15 wt. percent talc filled HDPE is independent of filler concentration, but the elasticity is decreased. The viscous characteristics of the HDPE/talc blends both at constant shear stress and shear rate, are governed by the neat melt polymer, while the talc filler loading shows negligible effect on the shear viscosity; however, the melt elasticity decreases significantly with an increase in the talc loading.

It was found that the melt composites are compressible, but this can be a negligible effect for low pressure manufacturing processes like rotational molding. Moreover, the melt densities decrease linearly with a rise in the testing temperature.

The observed viscoelastic properties in this system (reduction and increase in the post extrudate swell) are better explained on the basis of the talc particle morphology, and supported in the range of filler loadings

and processing parameters. It was found that the testing temperature has no direct effect on the die swelling; instead, the shear rate might be responsible for the control of the die swell.

References

[1] A.K. Mehrjerdi, B. Adl-Zarrabi, S.-W. Cho, M. Skrifvars, Mechanical and thermo-physical properties of high-density polyethylene modified with talc, J. Appl. Polym. Sci. 129 (4) (2013) 2128–2138.
[2] F. Yu, T. Liu, X. Zhao, X. Yu, A. Lu, J. Wang, Effects of talc on the mechanical and thermal properties of polylactide, J. Appl. Polym. Sci. 125 (S2) (2012) E99–E109.
[3] P.B.V. Scholten, M.B. Özen, Z. Söyler, J.-M. Thomassin, M. Wilhelm, C. Detrembleur, M.A.R. Meier, Rheological and mechanical properties of cellulose/LDPE composites using sustainable and fully renewable compatibilisers, J. Appl. Polym. Sci. (2020) 48744.
[4] M. Spoerk, C. Holzer, J. Gonzalez-Gutierrez, Material extrusion-based additive manufacturing of polypropylene: a review on how to improve dimensional inaccuracy and warpage, J. Appl. Polym. Sci. 137 (12) (2020) 48545.
[5] S. Moghaddamzadeh, D. Rodrigue, Rheological characterization of polyethylene/polyester recycled tire fibers/ground tire rubber composites, J. Appl. Polym. Sci. 135 (34) (2018) 46563.
[6] T. Wu, L. Yu, Y. Cao, F. Yang, M. Xiang, Effect of molecular weight distribution on rheological, crystallization and mechanical properties of polyethylene-100 pipe resins, J. Polym. Res. 20 (10) (2013) 271.
[7] P.M. Wood-Adams, J.M. Dealy, A.W. deGroot, O.D. Redwine, Effect of molecular structure on the linear viscoelastic behavior of polyethylene, Macromolecules 33 (20) (2000) 7489–7499.
[8] J.A. Resch, Elastic and Viscous Properties of Polyolefin Melts With Different Molecular Structures Investigated in Shear And Elongation, Ph. D. dissertation, Universität Erlangen-Nürnberg, Erlangen, 2010.
[9] C. Gabriel, H. Münstedt, Influence of long-chain branches in polyethylenes on linear viscoelastic flow properties in shear, Rheol. Acta 41 (3) (2002) 232–244.
[10] H.M. Laun, Orientation of macromolecules and elastic deformations in polymer melts. Influence of molecular structure on the reptation of molecules, in: Permanent and Transient Networks, Vol. 75, Steinkopff, 1987, pp. 111–136.
[11] D. Auhl, J. Stange, H. Münstedt, B. Krause, D. Voigt, A. Lederer, K. Lunkwitz, Long-chain branched polypropylenes by electron beam irradiation and their rheological properties, Macromolecules 37 (25) (2004) 9465–9472.
[12] H. Münstedt, S. Kurzbeck, L. Egersdörfer, Influence of molecular structure on rheological properties of polyethylenes, Rheol. Acta 37 (1) (1998) 21–29.
[13] Z. Tadmor, C.G. Gogos, Principles of Polymer Processing, Wiley, 2006.
[14] J.Z. Liang, Effects of extrusion conditions on die-swell behavior of polypropylene/diatomite composite melts, Polym. Test. 27 (8) (2008) 936–940.

[15] F. Cyriac, J. Covas, L. Hilliou, I. Vittorias, Predicting extrusion instabilities of commercial polyethylene from non-linear rheology measurements, Rheol. Acta 53 (10-11) (2014) 817–829.

[16] J.-Z. Liang, The elastic behaviour during capillary extrusion of LDPE/LLDPE blend melts, Polym. Test. 21 (1) (2002) 69–74.

[17] J.-Z. Liang, J. Yang, C.-Y. Tang, Die-swell behavior of PP/Al(OH)3/Mg(OH)2 flame retardant composite melts, Polym. Test. 29 (5) (2010) 624–628.

[18] I.B. Kazatchkov, S.G. Hatzikiriakos, N. Bohnet, S.K. Goyal, Influence of molecular structure on the rheological and processing behavior of polyethylene resins, Polym. Eng. Sci. 39 (4) (1999) 804–815.

[19] M.G. Rogers, Some studies on the swelling behavior of polyethylene, J. Appl. Polym. Sci. 14 (7) (1970) 1679–1689.

[20] M. Ansari, Y.W. Inn, A.M. Sukhadia, P.J. DesLauriers, S.G. Hatzikiriakos, Wall slip of HDPEs: molecular weight and molecular weight distribution effects, J. Rheol. 57 (3) (2013) 927–948.

[21] J.-Z. Liang, L. He, Melt flow properties and melt density of POM/EVA/HDPE nanocomposites, Polym. Plast. Technol. Eng. 50 (13) (2011) 1338–1343.

[22] J.-Z. Liang, C.-Y. Tang, L. Zhou, L. He, C.-P. Tsui, Melt density and flow property of PDLLA/nano-CaCO3 bio-composites, Compos. B Eng. 42 (7) (2011) 1897–1900.

[23] A.K. Mehrjerdi, B.A. Mengistu, D. Åkesson, M. Skrifvars, Effects of a titanate coupling agent on the mechanical and thermo-physical properties of talc-reinforced polyethylene compounds, J. Appl. Polym. Sci. 131 (13) (2014).

[24] A.K. Mehrjerdi, M. Skrifvars, Geothermal Pipe Collector: Google Patents, 2013.

[25] A.K. Mehrjerdi, B.A. Mengistu, D. Åkesson, M. Skrifvars, Effects of a titanate coupling agent on the mechanical and thermo-physical properties of talc-reinforced polyethylene compounds, J. Appl. Polym. Sci. 131 (13) (2014) n/a-n/a.

[26] M.T. Shaw, Introduction to Polymer Rheology, Wiley, 2012.

[27] D. Walsh, P. Zoller, Standard Pressure Volume Temperature Data for Polymers, Taylor & Francis, 1995.

[28] J.Z. Liang, C.Y. Tang, Y.J. Zhang, Melt density and volume flow rate of polypropylene/Al(OH)3/Mg(OH)2 flame retardant composites, J. Appl. Polym. Sci. 118 (1) (2010) 332–337.

[29] D.C. Goel, Effect of polymeric additives on the rheological properties of talc-filled polypropylene, Polym. Eng. Sci. 20 (3) (1980) 198–201.

[30] G. Wypych, Handbook of Fillers, 3e, ChemTec Publishing, 2009.

[31] F.M. Chapman, T.S. Lee, Effect of talc filler on melt rheology of polypropylene, SPE J. 26 (1) (1970) 37–&.

[32] Z. Lin, K. Mai, Effect of inorganic filler on the crystallization, mechanical properties and rheological behavior of poly(trimethylene terephthalate), Polym. Plast. Technol. Eng. 46 (4) (2007) 417–420.

[33] M.S.F. Samsudin, Rheological Behavior of Talc and Calcium Carbonate Filled Polypropylene Hybrid Composites [TA455. P58 S528 2008 F Rb], Universiti Sains Malaysia, 2008.

[34] J.C. Miller, Swelling behavior in extrusion, Spe Trans. 3 (2) (1963) 134–137.

[35] A. Ariffin, Z.M. Ariff, S.S. Jikan, Evaluation on extrudate swell and melt fracture of polypropylene/kaolin composites at high shear stress, J. Reinforc. Plast. Compos. 30 (7) (2011) 609–619.

[36] D.R. Mills, G.E. Moore, D.W. Pugh, The effect of molecular weight distribution on the flow properties of polyethylene, Spe Trans. 1 (1) (1961) 40–46.

[37] F.R. Eirich, Rheology: Theory and Applications, Elsevier Science, 2014.

[38] A.P. Metzger, J.D. Matlack, Comparative swelling behavior of various thermoplastic polymers, Polym. Eng. Sci. 8 (2) (1968) 110–115.