Determination of Apparent Viscosity as Function of Shear Rate and Fibres Fraction in Polypropylene

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Abstract—apparent viscosity of short fibre-reinforced plastics depends on the shear rate (because it is Non-Newtonian Fluid), melt temperature, fibre fraction etc.Therefore, it is very important to know their basic mathematical model. This paper presents examples of measuring apparent viscosity of the same polypropylene with different filler fraction (glass fibres in this case). From the viscosity of unfilled material and 10% filled material, we can calculate viscosity for other filled materials. This mathematical formula is discussed in this paper.

Index Terms—plastics, polypropylene, fillers, glass fibres, rheology, apparent viscosity.

I. INTRODUCTION

Recently, fibre-reinforced thermoplastic composites have found wide application in structural and non-structural applications because of their excellent mechanical properties. Structural parts a prepared by injection moulding, where moulds are manufactured by machining – milling and grinding. For this application currently new polymer composites are developed. [1]. However, the choice of proper processing conditions is dependent mainly on the rheological behaviour of composites. Integration of fillers in thermoplastics will increase the melt viscosity. Rheological properties of the pineapple [2] and sisal [3] fibres was observed, but not mathematically formulated. Apparent viscosity of the fibre-reinforced thermoplastics is influenced by the fibre weight ratio and fibre length more significantly at lower shear rate than at higher shear rate.

II. THEORY

Viscosity of a polymer melt depends on concentration and size (molecular weight) of the dissolved polymer. By measuring the solution viscosity, we should be able to get an idea about molecular weight. Fig. 1 shows a volume unit of liquid moving at a strain rate $\dot{\gamma}$ under the applied shear stress. Viscosity of the liquid is the ratio of the applied shear stress to the resulting strain rate (or equivalently, the ratio of the shear stress required to move the solution at a fixed strain rate to that strain rate). The shear strain [4] is:

$$\gamma = \frac{du}{dy} \tag{1}$$

Where u is displacement in the x direction. The strain rate is therefore:

$$\dot{\gamma} = \frac{d}{dt} \cdot \frac{du}{dy} = \frac{dv_x}{dy} \tag{2}$$

Where v_x is velocity in the x direction. The relations between viscosity (η), shear stress (τ), and shear rate ($\dot{\gamma}$) is:

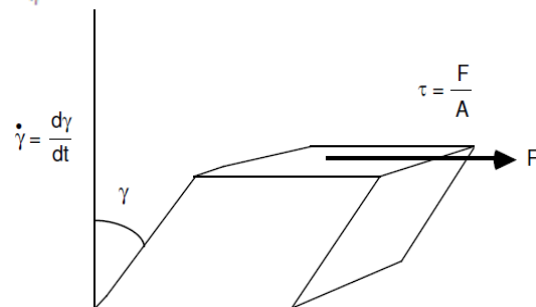$$\dot{\gamma} = \frac{\tau}{\eta} \tag{3}$$

Fig. 1 A volume unit of liquid moving at shear rate $\dot{\gamma}$ under the applied shear stress of τ

A Newtonian fluid is the one in which viscosity is independent of the shear rate. In other words, a plot of shear stress versus shear strain rate is linear with slope η. In Newtonian fluids, all the energy goes into the molecules sliding by each other. The fluids in which shear stress is not directly proportional to deformation rate are non-Newtonian flow. In non-Newtonian fluids; the shear stress/strain rate relation is not linear. Viscosity changes with shear rate. Apparent viscosity is always defined by the relationship between shear stress and shear rate. Typically, the viscosity drops at high shear rates; the phenomenon is known as shear thinning. Plots of shear force vs. shear rate for Newtonian and non-Newtonian fluids are given in Fig. 2.
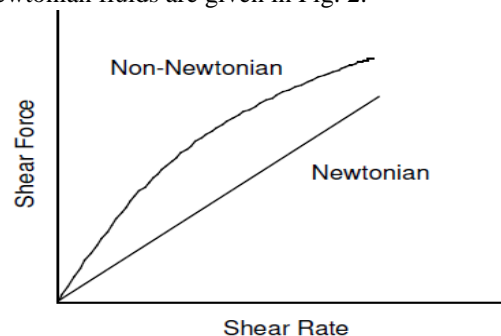

Fig. 2 Schematic plots of shear force vs. shear rate for Newtonian and non-Newtonian fluids

The higher the viscosity η of polymer is, the higher resistance to melt flow is generated. Otherwise, it means lower resistance. The viscosity curves of most thermoplastics exhibit the same dependence on shear rates as shown in Fig. 3.
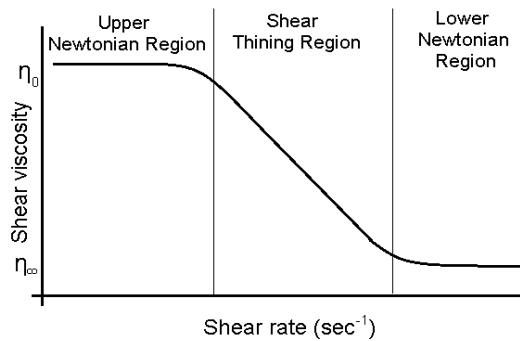
Fig. 3: Characteristic viscosity curve of thermoplastics (log-log plot)

At lower shear rates, viscosity is a nearly constant. This is the usually called as Upper Newtonian Region. Polymer chains are more uniformly aligned as the shear rate increases, so the viscosity decreases accordingly. This is called the Shear Thinning Region. When all polymeric chains are fully aligned, the shear viscosity becomes virtually insensitive to shear rate. This is called as Lower Newtonian Region. The Upper Newtonian Region and Shear Thinning Region can be observed in most polymers. The Lower Newtonian Region is, however, not as obvious in most thermoplastics as it occurs with molecular degradation at the ultra-high shear rates.

III. EXPERIMENT

In this case, polypropylene with different fibre ratio, namely 0, 10, 20, 30 and 40% was used. These thermoplastics were dried in Heraus T6 oven at 80°C for 4 hours. Measurements of the melt rheological properties were carried out at the Dynisco Capillary Rheometer model LCR7001 at different plunger speeds of 0.9 to 648mm.min-1. The sample was placed inside the barrel of the extrusion assembly and forced down into the nozzle with a plunger at the predetermined plunger speeds. Conditions of measurements were kept identical in all experiments, and shear viscosities at different shear rates were obtained from a single charge of material. The measurements were carried out at 230°C for each material.

The shear stresses at different plunger speeds were calculated using the equation:

$$\tau = \frac{F}{4A_F \left(l_c/d_c\right)} \tag{4}$$

Where F is the force of the plunger, A_p the cross-sectional area of the plunger and l_c and d_c are the length and diameter of the capillary.

IV. RESULTS AND DISCUSSIONS

Measured apparent viscosity vs. shear rate functionality of PP with different fraction of glass fibres at 230°C is shown in Figure 4. These curves are typical for pseudo plastic materials. They show a decrease in viscosity with increasing shear rate. Behaviour of the measured curves can be described by the power law relationship:

$$\eta = \eta_0 \cdot (\dot{\gamma})^{n-1} \tag{5}$$

Where n is the power law index and η_0 zero-shear rate. The Power-law model neglects the Upper Newtonian Region. The

viscosity depending on shear rate can be simplified as a simple power-law equation. This is a three-parameter model that reflects the observation that the viscosity function at medium-high shear rates is nearly a straight line in log-log plots. Many analytical design equations for polymer processing were derived from this model. The incorporation of fibres into polymer systems increases the viscosity and keeps increasing with the fibre content. The increase in viscosity is found to be more predominant at lower shear rates where the fibre and polymer molecules are not completely oriented. The results of measuring by capillary rheometry were obtained in order to discuss the rheological behaviour of the blends. The study showed that viscosity of the glass-fibre-reinforced polypropylene in molten state is dependent of shear rate as well as of the different weight content of fibres. The analysis of the charts proves that the raw PP is less viscous than the reinforced polypropylene. The results in Fig. 4 showed that the viscosity of reinforced PP increases significant with the content of fibres.
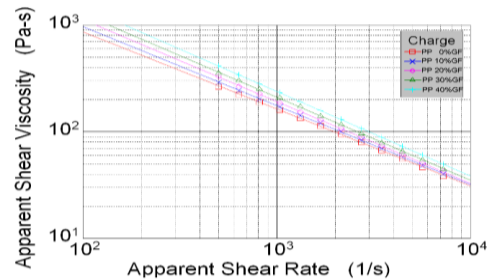

Fig. 4 Graphical comparison of measured viscosity and regression viscosity curves at 230°C

Effect of particular fillers on the viscosity is given in the following mathematical formula:

$$\eta = \eta_M + (C \cdot \psi + 1) \tag{6}$$

η-Viscosity of reinforced composite
η_M-Viscosity of matrix of polymer (0% fillers)
C-Constant- value depends on the structure and orientation of fillers
ψ- Fibre weight fraction
In Power-Law case:

$$\eta = \eta_0 \cdot \dot{\gamma}^{n-1} + (C \cdot \psi + 1) \tag{7}$$

In our case:

$$\eta = 23650.6286 \cdot \dot{\gamma}^{-0.7225} + (0.01 \cdot \psi + 1) \tag{8}$$

Values n and $\dot{\gamma}$ were calculated by the first and last points of unfilled material by Power-law equation. Variable ψ takes the values 0, 10, 20, 30 and 40 in our case.

Tables 1 to 5 show measured viscosity, calculated viscosity by equation 8 and ratio of these viscosities.

Table 1 Measured and calculated viscosity of composites at 0% glass fibres

Point	Sh.rate (1/sec)	Apparent viscosity (Pa·s)		Different of viscosities
		Measured	Calculated	
1	500	265.33	265.33	0.00%
2	637.5	224.82	222.61	+0.99%
3	812.8	190.06	186.78	+1.76%
4	1036.3	160.37	156.71	+2.34%
5	1321.3	135.2	131.48	+2.83%
6	1684.7	113.74	110.31	+3.11%

7	2147.9	95.44	92.56	+3.12%
8	2738.6	79.97	77.65	+2.98%
9	3491.7	66.87	65.15	+2.64%
10	4451.9	55.86	54.66	+2.19%
11	5676.2	46.51	45.86	+1.41%
12	7237.1	38.48	38.48	0.00%

Table 2 Measured and calculated viscosity of composites at 10% glass fibres

| Point | Sh.rate (1/sec) | Apparent viscosity (Pa·s) | | Different of viscosities |
		Measured	Calculated	
1	500	291.96	291.86	+0.03%
2	637.5	245.46	244.88	+0.24%
3	812.8	204.42	205.46	-0.50%
4	1036.3	171.71	172.38	-0.39%
5	1321.3	143.03	144.63	-1.11%
6	1684.7	121.95	121.34	+0.50%
7	2147.9	100.88	101.81	-0.91%
8	2738.6	84.08	85.42	-1.57%
9	3491.7	69.94	71.67	-2.41%
10	4451.9	58.02	60.13	-3.51%
11	5676.2	48.25	50.45	-4.36%
12	7237.1	40.25	42.33	-4.91%

Table 3 Measured and calculated viscosity of composites at 20% glass fibres

| Point | Sh.rate (1/sec) | Apparent viscosity (Pa·s) | | Different of viscosities |
		Measured	Calculated	
1	500	333.17	318.40	+4.64%
2	637.5	267.7	267.14	+0.21%
3	812.8	226.78	224.13	+1.18%
4	1036.3	187.88	188.05	-0.09%
5	1321.3	154.32	157.78	-2.19%
6	1684.7	129.41	132.37	-2.24%
7	2147.9	107.57	111.07	-3.15%
8	2738.6	89.29	93.18	-4.18%
9	3491.7	74.26	78.18	-5.02%
10	4451.9	61.32	65.60	-6.52%
11	5676.2	50.63	55.04	-8.01%
12	7237.1	42.8	46.18	-7.31%

Table 4 Measured and calculated viscosity of composites at 30% glass fibres

| Point | Sh.rate (1/sec) | Apparent viscosity (Pa·s) | | Different of viscosities |
		Measured	Calculated	
1	500	355.18	344.93	+2.97%
2	637.5	301.19	289.40	+4.07%
3	812.8	250.78	242.81	+3.28%
4	1036.3	209.13	203.72	+2.65%
5	1321.3	171.99	170.92	+0.62%
6	1684.7	140.69	143.40	-1.89%
7	2147.9	117.27	120.32	-2.54%
8	2738.6	96.08	100.95	-4.82%
9	3491.7	78.92	84.70	-6.82%

10	4451.9	65.13	71.06	-8.35%
11	5676.2	54.45	59.62	-8.68%
12	7237.1	45.15	50.02	-9.74%

Table 5 Measured and calculated viscosity of composites at 40% glass fibres

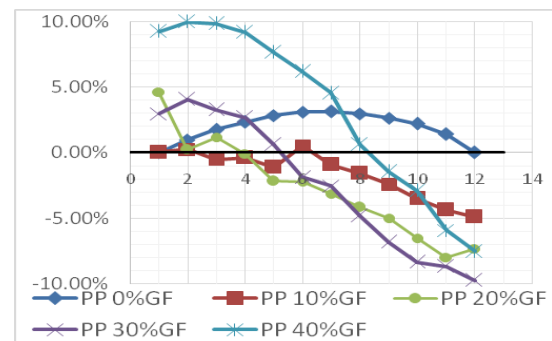| Point | Sh.rate (1/sec) | Apparent viscosity (Pa·s) | | Different of viscosities |
		Measured	Calculated	
1	500	405.8	371.46	+9.24%
2	637.5	342.72	311.66	+9.97%
3	812.8	287.18	261.49	+9.82%
4	1036.3	239.55	219.39	+9.19%
5	1321.3	198.14	184.07	+7.64%
6	1684.7	164.01	154.44	+6.20%
7	2147.9	135.47	129.58	+4.55%
8	2738.6	109.37	108.72	+0.60%
9	3491.7	89.9	91.21	-1.44%
10	4451.9	74.3	76.53	-2.91%
11	5676.2	60.4	64.21	-5.93%
12	7237.1	49.81	53.87	-7.54%

Fig. 5 Comparison of ratio measured and calculated viscosity at different materials

V. CONCLUSION

The experiments described in this paper demonstrated that mathematical model can be used for calculating apparent viscosity from shear rate and fibre fraction. All results were obtained from Dynisco LCR 7001capillary rheometer. Coefficients n a η_0 were calculated from unfilled material using the Power-Law. C was calculated from the filling material coefficient.. This enabled to construct the function of the calculation using shear rate and fibre weight fraction. The measured and calculated viscosities were compared for all materials. Their mutual ratio is shown in Figure 5. This implies that all the values differ by less than ±10%.

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