The Influence of Screw Geometry on the Extrusion of Soft PVC

ANTTI SAVOLAINEN and RAUL KARLING, *Tampere University of Technology, Department of Mechanical Engineering, Chemistry, P.O. Box 527, SF-33101 Tampere, Finland*

Synopsis

This article summarizes studies on the single screw extrusion of three soft PVC materials of different K values. The results are analyzed as a function of screw geometry. The operation of the screws as functions of output, economy, plasticating effect, and melt homogeneity was studied. The Maddock mixing screw with no treads after the mixing section performed well, and, especially, its melt homogeneity was excelllent.

INTRODUCTION

The state of a plastic melt is set when the thermodynamic and rheological states are fixed. The total homogeneity of the melt is determined by the stable thermodynamic and rheological state.[1] The mixing capacity of a common three zone screw with a 2.5:1 compression is inadequate in the extrusion of soft PVC materials. The decrease of channel depth in the metering section increases the mixing effect; however, it also decreases the output as well as increases the extrusion temperature, which, in turn, increases depolymerization.[2] In addition, the homogeneity of the melt increases when a thick sieve[3] or a static mixer is used.[4] Static mixers can only be used in continuous processes, and, therefore, the dynamic mixers play a major role in this field. A turbulent flow in the material is obtained by using different types of plug and groove screws. Using this type of screw geometry results in the appearance of burned mass on the mixing rings.[5]

In addition, a billow screw, with a continuous change of shear rate,[6] and a DIS screw, which combines the benefits of a static and dynamic mixing section, have been studied.

An inhomogeneous melt in the extrusion is one reason for a poor product. The homogeneity of the mass can be observed for the changes in temperature and pressure, i.e., the stability of the thermodynamic state as the molten mass is moving through the machine. The rheological state, depending on the thermodynamic state, can be observed, for example, with an ultrasonic method. The ultrasonic velocity has a good correlation with both temperature and pressure as well as viscosity when the shear rate is constant.[1]

The aim of this work has been to study the influence of different mixing screws on the homogeneity of the melt in the extrusion of soft PVC materials that have different K values.

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EXPERIMENTAL

Equipment and Screws

A Nokia MP40-24D extruder equipped with a special measuring head was used in the experiments (see Fig. 1). The dimensions of the die were as follows: $L = 120$ mm, w = 14 mm, h = 1.6 mm, and the distance between p_1 and p_2 (pressure gradient) 60 mm.

The different screw geometry designs are presented in Table I. The PVC experiment screw was equipped with different mixing sections. In the back flow mixing section the mixing effect is based on an increasing helix angle of the screw combined with an increasing flight clearance [Fig. 2(a)]. The increasing back flow over the flight makes the melt homogeneous in this mixing section. The flow can be made turbulent with a back flow screw modification [Fig. 2(b)], in which the screw channel is equipped with five mixing plug rings. Experiments were also done on modifying the conventional Maddock screw [Fig. 2(c)–(d)]. One of the experiments included a mixing section with an opposite direction flow in the shearing gap [Fig. 2(d)].

Raw Materials

The experiments were done with the soft PVC compounds of Pekema Oy, a Finnish chemical company. The base compound was a Pekevic 295/70 REM which corresponds to the production brand Pekevic 295/00 PE. This lead-stabilized compound contains 22% DOP. The specification of the Pekevic 295/00 PE is given in Table II. The Pekevic 295/00 is especially aimed for use as cable insulation. The K values of the compounds were 64, 68, and 70 and the brands are, correspondingly, known as Pekevic 295/64 REM, 295/68 REM, and 295/70 REM which, in turn, correspond to $\overline{M}_v$ values of 71.000, 83.000, and 89.000, respectively.

Experiments

The following quantities were measured in the experiments: the mass temperature in the middle of the flow; the mass temperature on the surface of the flow; the barrel pressure; the pressure p_1 in the die (see Fig. 1); the pressure gradient p_1–p_2 (see Fig. 1); the current of the motor; the output; the ultrasonic travel time; the ultrasonic amplitude; the temperature of the

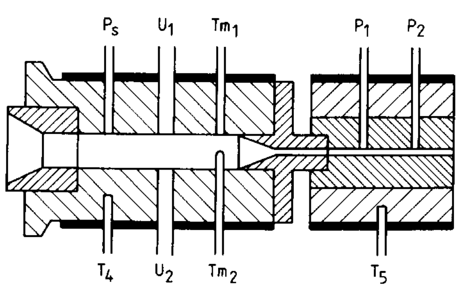

Fig. 1. The adapter, the die, and the measuring techniques schematically.

TABLE I
Screw Geometries

Screw	Feed L/D	Feed h (mm)	Comp. L/D	Homog. L/D	Homog. h (mm)	Mixing section
Basic screw	5	6.2	10	9	2.6	—
Back flow screw	4	7.0	7.5	8.75	2.6	Back flow mixing section at the end of the screw
Back flow screw with mixing plug rings	4	7.0	7.5	8.75	2.6	Back flow mixing section with 6 mixing plug rings at the end of the screw
Shearing screw	4	7.0	7.5	8.75	2.6	Maddock type shearing at the end of the screw
Polyethene screw	5	6.75	3	12	2.65	Maddock type shearing section and $L/D = 2$ $h = 2.9$ mm at the end of the screw
Shearing screw, flow direction same as the rotation direction in the shearing gap	4	7.0	7.5	8.75	2.6	Maddock type shearing section at the end of the screw; the flow direction same as the rotation direction in the shearing gap

ultrasonic gauges. The temperature (°C) profiles of the extruder and the die were as follows:

	Barrel			Die	
1.	150	160	170	170	170
2.	160	170	180	180	180
3.	170	180	190	190	190
4.	180	190	200	200	200

The used screw speeds were 60, 80, 100, 120, and 140 min^{-1}. The following quantities were calculated from the results: the ultrasonic velocity; the ultrasonic amplitude variation; the volume flow; the apparent viscosity; the apparent shear rate; the energy consumption per plastized material.

RESULTS AND DISCUSSION

Screw Geometry and Output

The influence of the screw geometry on output is shown in Figure 3. The best output of mass was produced by the basic screw while the opposite flow Maddock screw produced the least. The difference in the outputs of

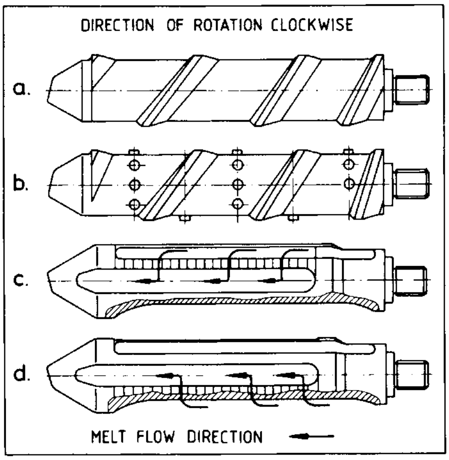

Fig. 2. Mixing sections schematically.

the abovementioned screws was 15%. The output capacity of the screws in decreasing order was: (1) the basic screw; (2) the LDPE screw and the Maddock screw; (4) the back flow screw; (5) the back flow screw with plug rings; (6) the Maddock screw with the opposite flow section.

The conventional basic screw is "continuous," i.e., its feed zone is very long and the channel depth decreases steadily during a relatively long compression zone ($10 \times D$). No dramatic changes occurred in the pressure gradient, which resulted in the best output capacity.

Screw Geometry and Economy

The energy consumption of the mixing screws was greater than that of the basic PVC screw (see Fig. 4). This is understandable because the screws equipped with the Maddock mixing section are cramped, the flow over the mixing barrier is partly restrained, and the screw has to work harder to achieve the same output as the loose running screws do. The stearing pins hinder the melt flow in the screw channel of other mixing screws thereby increasing energy consumption.

The economy performance of the screws in decreasing order is as follows: (1) the basic screw; (2) the LDPE screw; (3) the back flow screw, the Maddock

TABLE II
The Production Brand of Pekevic 295/00 PE Which Corresponds to the Pekevic 295/70 REM is a Semirigid, Opaque, Lead Stabilized PVC Compound for Cable Applications

Property		
Density	ASTM D 1505	1.32 g/cm^2
Shore A hardness	ISO R 868	95
Tensile strength	ISO R 527	25.0 MPa
Break resistance	ISO R 527	250%
Tension at 100% elongation	ISO R 527	21.2 MPa
Cold short	ASTM D 746	−20°C
Volume resistivity	ASTM D 257-66	2.9×10^{13} Ω · m

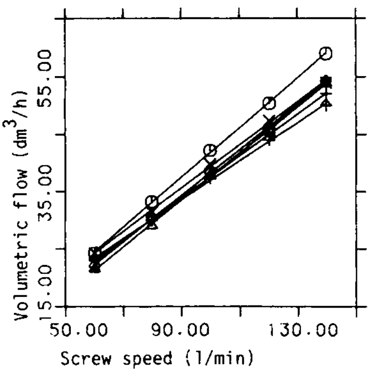

Fig. 3. The volumetric flow as a function of the screw speed: (Ⓓ) basic screw; (△) back flow screw; (+) back flow screw with mixing plug rings; (×) shearing screw; (△) polyethene screw; (ϯ) shearing screw, flow direction the same as the rotation direction in the shearing gap. Temperature profile 170–190°C. Material Pekevic 295/70 REM.

screw, and the back flow screw with the plug rings; (6) the Maddock screw with the opposite direction flow.

Plasticating Efficiency of the Screws

The plasticating efficiency of the screw was measured by the attenuation of the amplitude of the ultrasonic pulse. The ultrasonic variation increases by increasing screw speed and by decreasing the melt temperature (Fig. 5 and 6). These changes are very sudden with the basic screw because of the increasing amount of unplastized particles throughout the melt flow in the CM direction. An interesting exception is the decreased intensity variation with increasing screw speed of the Maddock screw. This indicates that the plasticating effect of the screw increases with increasing screw speeds. This is mainly caused by the increased shear rate in the mixing barrier of the Maddock mixing section. However, the position of the mixing section of the Maddock screw is not without aim. The UC-polyethene screw contains threads the length of $2 \times D$ after the mixing section, and this causes a

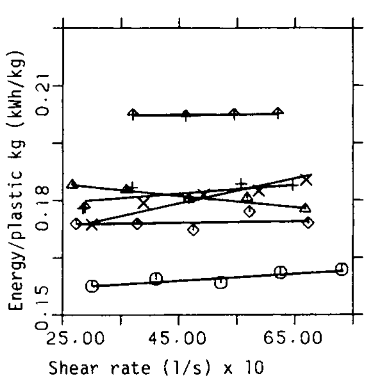

Fig. 4. The energy consumption per plastizised material as a function of screw speed (see symbols in Fig. 3). Temperature profile 170–190°C. Material Pekevic 295/70 REM.

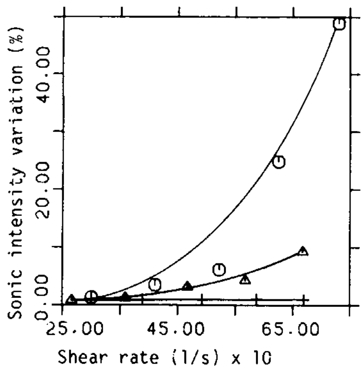

Fig. 5. The ultrasonic intensity variation as a function of screw speed: (⏀) basic screw; (△) back flow screw; (+) shearing screw. Temperature profile 170–190°C. Material Pekevic 295–70 REM.

greater variation in the ultrasonic intensity compared to that of the Maddock screw.

Screw Geometry vs. Ultrasonic Velocity. Melt Homogeneity

It has been shown that the total homogeneity, i.e., the thermodynamic and the rheological stability, is a function of the ultrasonic velocity.[1] By presenting the ultrasonic velocity as a function of the viscosity, the linearity in the graphs will also pinpoint a rheological homogeneity. Therefore, it is obvious that the basic screw is suitable only for the high molecular weight PVC, the Pekevic 295/70 REM ($\overline{M}_v = 89 \times 10^3$). The counterpressure caused by the tool will decrease with decreased molecular weight and viscosity of the material and, as a result, the plasticating effect diminishes (Figs. 7–9). The lower molecular weight materials, the Pekevic 295/64 REM ($\overline{M}_v = 83 \times 10^3$) and the Pekevic 295/68 REM ($\overline{M}_v = 71 \times 10^3$) can be processed with all of the screws used in this study. Furthermore, the processing instability showed that the only screw reasonably capable of satisfactory processing of the Pekevic 295/64 REM is the mixing screw.

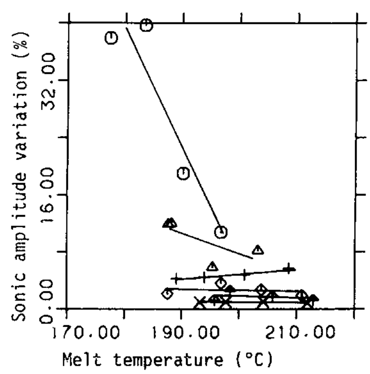

Fig. 6. The ultrasonic intensity variation as a function of melt temperature (for symbols, see caption to Fig. 3). Shear rate 600 s^{-1}. Material Pekevic 295/70 REM.

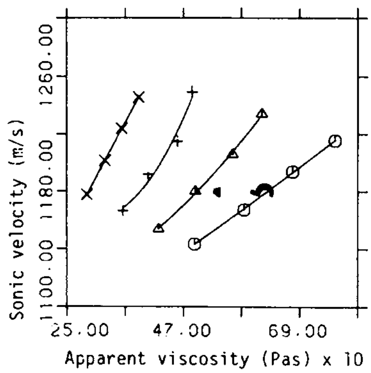

Fig. 7. The ultrasonic velocity as a function of apparent viscosity for Pekevic 295/70 REM; shear rates (s^{-1}): (⌽) 250; (△) 400; (+) 550; (×) 700. Basic screw.

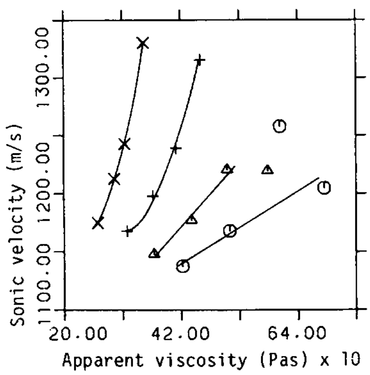

Fig. 8. The ultrasonic velocity as a function of apparent viscosity for Pekevic 295/68 REM (for symbols, see caption to Fig. 7). Basic screw.

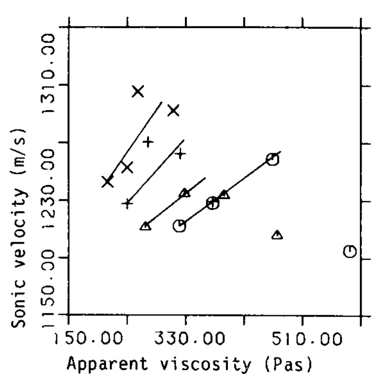

Fig. 9. The ultrasonic velocity as a function of apparent viscosity for Pekevic 295/64 REM (for symbols, see caption to Fig. 7). Basic screw.

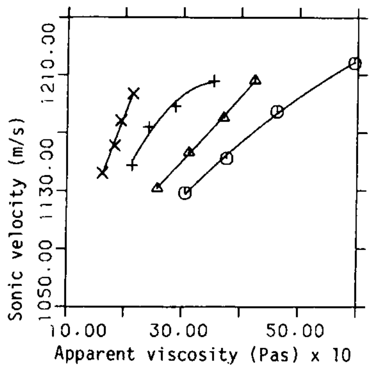

Fig. 10. The ultrasonic velocity as a function of apparent viscosity for Pekevic 295/64 REM (for symbols, see caption to Fig. 7). Shearing screw.

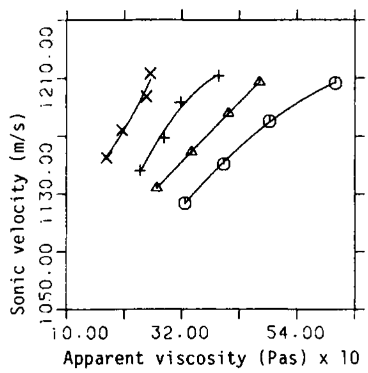

Fig. 11. The ultrasonic velocity as a function of apparent viscosity for Pekevic 295/64 REM (for symbols, see caption to Fig. 7). Back flow screw.

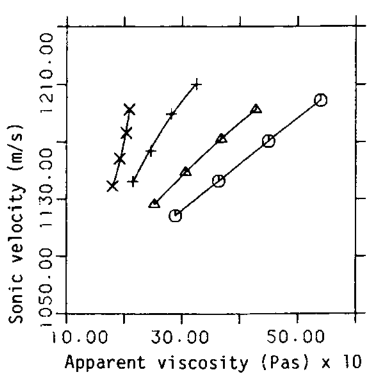

Fig. 12. The ultrasonic velocity as a function of apparent viscosity for Pekevic 295/64 REM (for symbols, see caption to Fig. 7). Back flow screw with mixing plug rings.

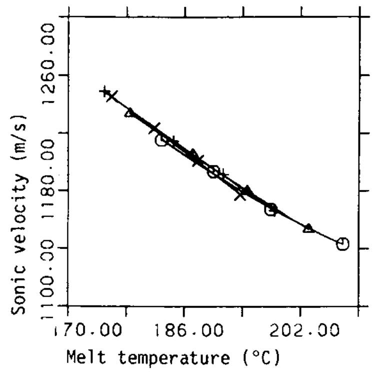

Fig. 13. The ultrasonic velocity as a function of melt temperature (for symbols, see caption to Fig. 7). Basic screw. Pekevic 295/70 REM.

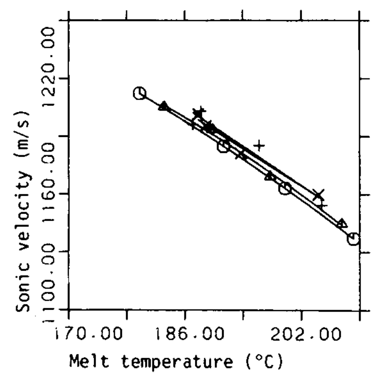

Fig. 14. The ultrasonic velocity as a function of melt temperature (for symbols, see caption to Fig. 7). Back flow screw. Pekevic 295/70 REM.

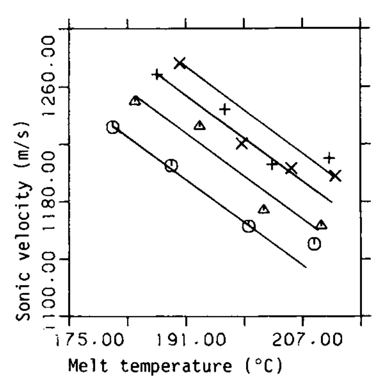

Fig. 15. The ultrasonic velocity as a function of melt temperature (for symbols, see caption to Fig. 7). Polyethene screw. Pekevic 295/70 REM.

By increasing mixing screw speeds, i.e., by processing with high shear rates, a state of constant apparent viscosity may be reached. At this state, the change in ultrasonic velocity depends only on changes in the melt temperatures (Figs. 10–12).

The basic screw and the back flow screw have a slight mixing effect. This can be seen in Figures 13 and 14, where the ultrasonic velocity is linearily depended on the melt temperature and the influence of pressure and viscosity are very small.

The increased mixing effect increases the influence of pressure. The maximum benefits in this respect are obtained with the polyethene screw (Fig. 15).

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