Jurnal Teknologi, 39(A) Keluaran Khas. Dis. 2003: 149–163

PROCESS PARAMETERS DEPENDENCE OF ACRYLONITRILE BUTADIENE STYRENE (ABS) FLOW PATTERNS INSIDE A CAPILLARY RHEOMETER BARREL

ZULKIFLI M. ARIFF[1], AZHAR A. BAKAR[2] AND M. NASIR Z. ARIF[3]

Abstract. Flow patterns of ABS melt inside a constant-stress capillary rheometer barrel was investigated. The effects of variations in process parameters such as temperature, pressure and plunger displacement towards the flow patterns were studied. Temperature and plunger displacements were found to have prominent influences on the flow patterns where changes in pigmented layer thickness and complex flow were observed respectively. No significant effect was displayed on the flow patterns when extrusion pressure was increased exceeding pressure limit of melt fracture occurrence. Velocity profiles were measured from the flow patterns using an image analyser and it was discovered that some deviations existed between experimental measured velocity profiles and that of theoretically calculated valves using an established non-Newtonian fluid flow equation. These deviations reduced with extrusion temperature but become relatively complicated when large plunger displacement was applied.

Keywords: Flow patterns, capillary rheometer, Acrylonitrile-Butadiene-Styrene (ABS)

Abstrak. Corak aliran leburan ABS di dalam barel rheometer kapilari tegasan-malar telah dikaji. Kesan perubahan parameter pemprosesan seperti suhu, tekanan dan sesaran penolak terhadap corak aliran diselidik. Suhu and sesaran penolak didapati mempunyai pengaruh yang ketara ke atas corak aliran. Ini diperhatikan melalui perubahan terhadap ketebalan lapisan berwarna dan kemunculan bentuk aliran yang kompleks. Tiada perubahan corak aliran yang besar dipamerkan apabila tekanan pengekstrudan ditingkatkan melebihi had tekanan bagi berlakunya rekahan leburan. Profil halaju diukur daripada corak aliran menggunakan penganalisis imej dan keputusan ujian menunjukkan bahawa terdapat sedikit penyimpangan antara profil halaju yang diukur melalui ujikaji dengan profil yang di perolehi secara pengiraan teori menggunakan persamaan aliran bendalir tak-Newtonan yang telah terbukti keberkesanan penggunaannya. Sisihan tersebut berkurangan sekiranya suhu pengekstrudan ditingkatkan namun menjadi agak rumit secara relatifnya apabila sesaran penolak yang lebih besar digunakan.

Kata kunci: Corak aliran, rheometer kapilari, Akrilonitril-Butadiena-Stirena (ABS)

1.0 INTRODUCTION

One area in rheology that interests many researchers over the years is flow visualisation. Not only it is used to visualise and record the actual flow, it also serves the purpose as a benchmark in developing analytical and numerical tools required to solve flow

[1,2] School of Material & Mineral Resources Engineering, Engineering Campus Universiti Sains Malaysia, 14300 Nibong Tebal, SPS, Pulau Pinang. E-mail: 1) z_ariff@hotmail.com 2) azhar@eng.usm.my
[3] Universiti Industri Selangor, Jln. Zirkon A 7/A, Seksyen 7, 40000 Shah Alam, Selangor D.E.

problems [1]. Examples of these tools are Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) and Finite Difference (FD) software for fluids. These tools evolved from classical and modified theory of fluid mechanics combined with extensive experimental evaluations over the century. Although these tools make things easier for rheologist in predicting complex flow such as in polymer melts, the reliance on experimental flow visualisation is still important in confirming all the predictions since many extravagant effects of viscoelasticity can only be captured with this technique.

The analysis of the flow patterns and velocity profiles of flowing polymer melts appears complex not only because of the significant frictional heat generation but also because of the highly temperature sensitive and non-Newtonian rheological character of the fluid [2]. In pursuing the objective of capturing or recording the actual flow patterns or profiles of polymer melts, a number of methods or techniques have been utilised by many workers [3-7]. Most of these investigations concentrate in visualisations of capillary flow. Generally, these methods and techniques can be categorised into four categories [8]:

(a) Pigmented banding
A test specimen made from a sequence of layers of unpigmented and pigmented materials is prepared in a transparent apparatus. The movement of layers is observed and recorded while the test specimen is being deformed. If the test apparatus is not transparent, the test specimen can be cooled, removed, sectioned and investigated.

(b) Dye injection
This technique can be considered equivalent to the first technique. The difference is, it is only suitable for transparent liquids. A suitable dye is injected into the test liquid at one or more locations and the flow patterns are observed [7].

(c) Particle injection or streak photography
This method is quite similar to dye injection technique. Small tracer particles with appreciative optical properties and able to be suspended and carried by the fluid without settling out, are injected into the fluid and photographed at intervals. Velocities of the fluid elements correspond to the velocities of the particles, which can be determined from the knowledge of the exposure time and distance moved by the particles [3].

(d) Laser Doppler Velocimetry
This technique involves the use of laser beam. The flowing fluid needs to be seeded first with very fine particles that can scatter light, this scattered light is then collected by a photomultiplier. The frequency of the scattered

light is compared with the incident light. The differences in frequency depend on the velocity of the passing particles [3,9].

There are few other techniques which are not listed here such as birefringence technique [10], Nuclear Magnetic Resonance (NMR) imaging [11] and Cooled-Stainless Tube technique proposed by Sombatsompop and Wood [8] recently. All these techniques have their own advantages and disadvantages in the sense of practicality, suitability, ease of fabrication and for the more advance techniques, there is always the cost factor. It is up to the researchers to decide which one is suitable bearing in mind all those factors.

In this work, flow visualisation of ABS polymer melt in a constant stress capillary rheometer was observed using the first technique mentioned above, i.e. pigmented banding. The influence of test conditions such as temperature, pressure and plunger displacements on flow profiles of molten ABS polymer were investigated. The objective of this study is to compare velocity profile measurements obtained from experimental procedure with that determined from calculation of an established non-Newtonian flow equation for polymer melts. Any deviation from the theoretical calculations will show that experimental confirmation of flow visualisation is needed in studying and explaining the complex flow of polymer melts.

2.0 EXPERIMENTAL PROCEDURE

2.1 Raw Material

An injection-moulding grade of ABS, Toyolac 250-X10, was used throughout this study. This resin was a yellowish granular solid having density of 1.05 g cm^{-3} and melt flow index of 48 g/10 min which was determined at 220°C with a 10 kg load in accordance with ISO 1133 [12].

2.2 Flow Visualisation Specimen Preparation

Before the flow visualisation experiment can be conducted, an amount of the supplied ABS resin has to be coloured. This was done by adding 3.0 g of suitable pigment (in powder form) to 300 g of ABS granules. In order to disperse the pigment, the mixture was manually tumbled for 5 minutes in a tumbler. Melt compounding of the mixture was affected using a Betol single screw extruder having temperature setting as folows:

Extruder zone	Feeding	Compression	Metering	Die
Temperature (°C)	170	190	180	170

Unpigmented resin was also extruded using the same condition in order to ensure same thermal history was affected and comparison can be made with the compounded

pigmented resin. The extrudates from this procedure were pelletised before the moulding process. Then, both unpigmented and pigmented resins were compression moulded into disc-shaped specimens having a dimension of 14.0 mm in diameter and 5.2 mm thick using a customised stainless steel mould. It should be noted that ABS is quite hygroscopic. So, prior to any experimental procedure, the resin was dried in a circulating air oven at 80°C for 4 hours.

2.3. Flow Visualisation Apparatus and Experimental Procedure

The apparatus used in this work was a High Shear Viscometer manufactured by Davenport Limited. It can be classified as a constant stress compressed gas driven capillary rheometer. More detailed description of the rheometer features have been discussed elsewhere [13,14]. A flat-entry capillary die was used throughout the experiment. The die has a dimension of 1.5 mm in diameter and 6.0 mm in length making a length-to-diameter (L/D) ratio of 4.

This technique was actually adapted from Sombatsompop *et al.* [4,5]. In their investigation, they used natural rubber, which is a thermoset and utilised a constant rate rheometer, which was equipped with a piston-type plunger. In contrast, a thermoplastic ABS polymer and a rheometer with steel-ball plunger were used in this work hence making the experimental slightly different and challenging. The challenge was to establish a method of removing the test specimen after the experiment has ended. Wood *et al.* [4] designed a barrel that can be opened up into two halves in order to remove the test specimen. In this study, no modification was made to the barrel but piston-plunger mechanism was devised to assist test specimen removal. Details of the mechanism can be found elsewhere.

In this investigation, the influence of three process parameters, i.e. temperature, pressure and plunger displacement towards flow patterns of ABS melt was studied. The overall test condition used is tabulated in Table 1.

Table 1 Process parameter variables used in the experiment

Process parameter	Variables
Temperature (°C)	180, 200 and 220
Pressure (kg/cm^2)	30, 50 ,70 and 107
Plunger travel time (constant stress rheometer) (second)	30, 60, 90 and 120

The rheometer temperature was set to the desired test temperature. When this has been achieved, coloured and uncoloured disk was loaded in predetermined sequence. Thickness of each layer depends on the numbers of disc loaded. Here, each layer consists of three discs and the barrel was loaded with eight alternating layers. Then, the die exit is blocked and the polymer was allowed to heat up to test temperature for

10 min. During this pre-heating period, a loaded piston applied pressure to the discs in order to consolidate them and remove any trapped air. After that, the piston was removed and the steel-ball plunger was loaded. Then, the rheometer system was sealed and extrusion initiated. The extent of extrusion process (i.e. extrusion time) varies according to the variables studied. The principle of determining the extrusion time was based on displacing the same amount of volume during extrusion and was applied only when the temperature and pressure variables were investigated. Calculation on the amount of volume that should be displaced being described elsewhere [15]. The extrusion was stopped after the desired volume of polymer has been displaced. The applied pressure was then reduced to a value that was enough to hold the flow patterns inside the barrel and not to extrude anymore polymer out of the die. For extra preventive measure, the die exit was blocked to prevent any polymer being extruded out.

Removal of the test specimen also requires ABS polymer glass transition, T_g, information that was obtained prior to the experiment. In thermoset, solidification was affected by curing the material at predetermined curing temperature. However, thermoplastic solidification was achieved by cooling the material below their glass transition temperature, T_g. So, in removing ABS test specimen after the experiment has ended, the apparatus was cooled down and temperature of the barrel was monitored. As barrel temperature reached around 70–80°C, the barrel was unsealed and the plunger mechanism was placed inside the barrel. The retainer plate at the bottom of the barrel, which was holding the die in place, was also removed. A container of silicone oil was placed at the bottom of the barrel to cool down the polymer further and prevent distortion of the test specimen.

Slowly, the test specimen was pushed out of the barrel into the silicone oil container. After the polymer has cooled, silicone oil was wiped off from the test specimen and 1/3 of the cooled rod of ABS polymer diameter was removed using a band saw. In order to evaluate the flow patterns correctly, the rod diameter has to be reduced into half. This diameter reduction was conducted carefully using a series of coarse-to-fine wet sandpaper and frequent monitoring of the thickness was done using a Venier calliper.

2.4 Die Entrance Velocity Profiles Study

For investigation of velocity profiles of ABS polymer inside the barrel, an image analyser was used. The analyser was equipped with a digital camera for acquiring images of the test specimens and Image-Pro Plus(r) software that was able to perform measurements on the specimens. Before acquiring any image of the specimens, a thin layer of silicone oil was wiped onto the cut surface to improve optical quality. Layer displacement and radial position due to the extrusion process was determined by measuring directly the XY coordinates of pre-selected layer(s) from the specimens. In order to make correct measurements the image analyser was calibrated using a scale reference. An example of such scale reference is shown in Fiqure 1.

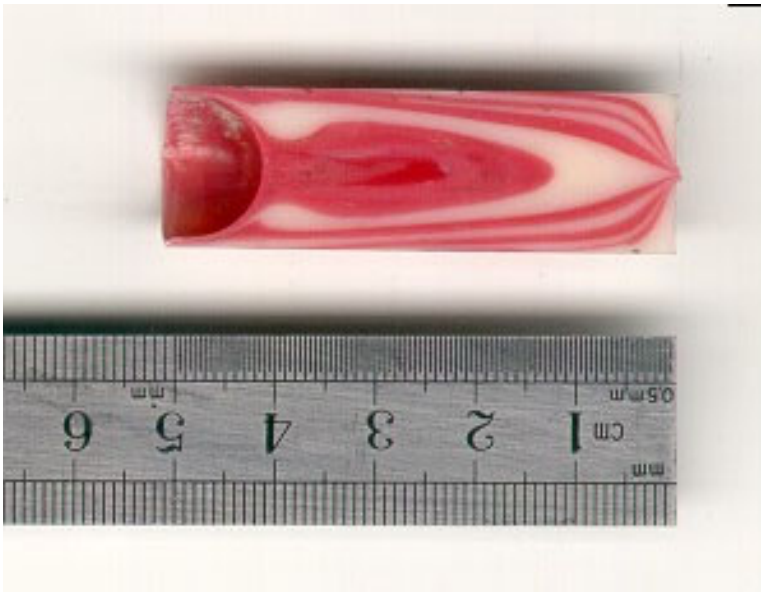

Figure 1 Calibration of specimen image with a reference scale (ruler)

After the displacements have been measured, it has to be corrected since the specimen images did not reveal all information. This is because each individual layer has its own starting position in the barrel which may or may not appear in the image depending on the extent of the extrusion process. If the position did not appear, the starting point of the selected layer has to be manually calculated with the knowledge of volume of each layer and added to the measured displacement. Only then the correct velocities (corresponding to radial position) can be determined with information of the extrusion time and the following equation was used.

$$\text{Velocity}, V_{\text{exptal}}, (\text{m/s}) = \frac{\text{Corrected Linear Displacement of Selected Layer (m)}}{\text{Extrusion Time (s)}} \quad (1)$$

Theoretically, each layer should have the same velocity profile since they are in the same system. Measuring velocity profiles of two or more layers in the same system can confirm the validity of calculations.

A comparative theoretical velocity profile for a fully developed flow can be calculated using the following equation [16].

$$V(r) = \overline{v}\frac{(3n+1)}{(n+1)}\left[1-(r/R)^{(n+1)/n}\right] \quad (2)$$

in which $V(r)$, velocity at radial position r, was assumed to be zero taking into consideration of no slippage occurrence at the die wall, $\overline{v}$ is the average velocity of the

fluid, n is the power law index and R is the radius of the tube or in this case is the barrel.
Rearranging Eq. 2 gives,

$$\frac{V(r)}{\bar{v}} = \frac{(3n+1)}{(n+1)}\left[1-(r/R)^{(n+1)/n}\right] \tag{3}$$

Eq. 3 was arranged in a manner that relates velocity ratio to the reduced radius (r/R). For the experimental velocities, a mathematical treatment was employed in order to obtain the average velocity, $\overline{v_{exptal}}$ The mathematical expression was derived and discussed in detail by McKelvey [16] and is given by the following equation,

$$\overline{v_{exptal}} = \left(\frac{n+1}{3n+1}\right)v_o \tag{4}$$

where, v_o is the maximum velocity (corresponds to maximum displacement in the image) and usually represents the velocity at the centre of the barrel. The experimental average velocity was calculated. Dividing the measured local velocity (from Eq. 1) to the average velocity yielded the experimental local velocity ratios with respect to the reduced radius (r/R) of the barrel.

$$\text{Experimental velocity rations} = \frac{V_{exptal}{}^{(r)}}{\overline{v_{exptal}}} \tag{5}$$

3.0 RESULTS AND DISCUSSION

3.1 Validity of measured flow profiles

As mentioned in the experimental procedure, flow profiles, which were measured in the same system, should give similar velocity profiles. Measuring velocity profiles of two or more layers in the same system can confirm the validity of the measured flow profiles. Figures 2(a), 2(b) and 2(c) are plotted flow profiles taken from two different layers in the same system. The overlapping nature of the profiles confirms that velocity measurements were valid and can be used further to investigate influence of extrusion parameters towards flow profiles regardless of which layer is chosen for measurement.

3.2 Influence of temperature

Increase in temperature will result in higher flow rate due to decrease in viscosity. If a flow curve was to be considered, one may observe that the slope of the curve would

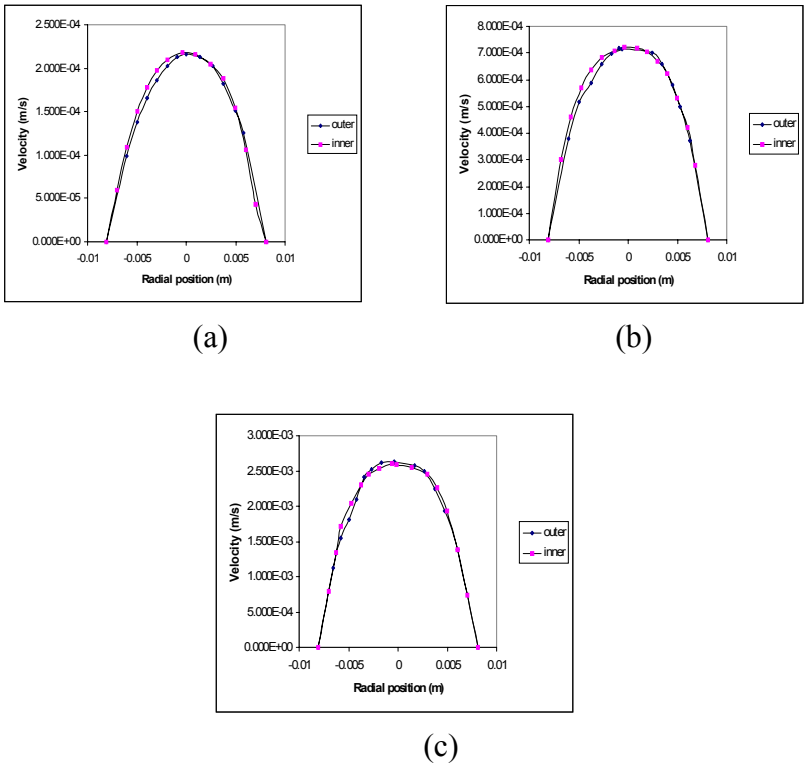

Figure 2 Plotted velocity profiles of ABS taken from two different layers (2nd. red layer: refer Figure 3) at extrusion temperature of: a) 180°C, (b) 200°C and (c) 220°C. Notes: Extrusion pressure = 30 kg/cm^2 and $L/D = 4$

become steeper with respect to temperature. This was indicated by the increase in power law index, n, value. The determination of power law index for this study has been discussed previously [13] and was used here to calculate the theoretical velocity profile inside the barrel (refer Equations 3 and 4). Table 2 tabulates the power law index change with temperature.

Table 2 Dependence of power law indices towards temperature

Temperature (°C)	180	200	220
Power law index	0.431	0.455	0.508

The changes of power law indices indicate changes in ABS melt flow behaviour and subsequently suggest changes in flow patterns inside the barrel. Figure 3 depict the flow patterns of ABS melt inside the barrel with respect to temperature. Displacement measurement was made and plotted into a graph in order to make

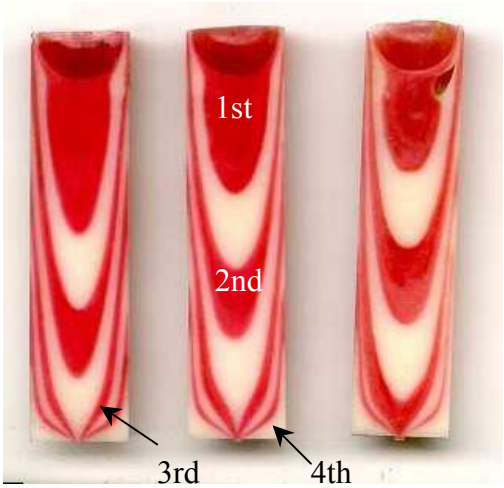

Figure 3 Effect of extrusion temperature on flow patterns inside capillary rheometer barrel – (a) 180°C, (b) 200°C and (c) 220°C Notes: Extrusion pressure = 30 kg/cm^2 and L/D = 4

comparison easier (Figure 4). Figure 4 yielded from measurements made on the inner part of the second red layer from the top of the image (see Figure 3).

As clearly shown in these figures, flow patterns at 180°C have the furthest layer displacement. This was followed by patterns at 200°C and subsequently patterns at 220°C. As extrusion temperature was increased, the shape of the patterns becomes more blunt or rounded. Image in Figure 3 shows that melt flow at 180°C concentrate in the centre of the barrel. It seems that polymer melts at this location are more drawn or pushed towards the die entrance.

As the temperature increases, the tip of the layer investigated becomes broader and ABS melt looks to be pushed aside towards the wall rather than be drawn towards the entrance. It is also interesting to mention that changes occurred in third and fourth red layer of the flow patterns. The third layer seems to become wider with temperature while the fourth showing the opposite trend.

Changes in the fourth layer give the indication that as temperature increases more displacement of polymer melts occurs within this layer. Extrusion at 220°C displaced more polymer melts, which are near to the die entrance first and leaving the third layer wider compared with that of in 180 and 200°C. This happened due to the fact that as temperature rises, polymer melts, which were in contact with the die and/or barrel surfaces become less viscous. So, molten polymer near to the barrel wall will be pushed to the side while near the die entrance, it will be displaced out through the die. Since the flat-entry die serves as an abrupt contraction, more polymer melts in the

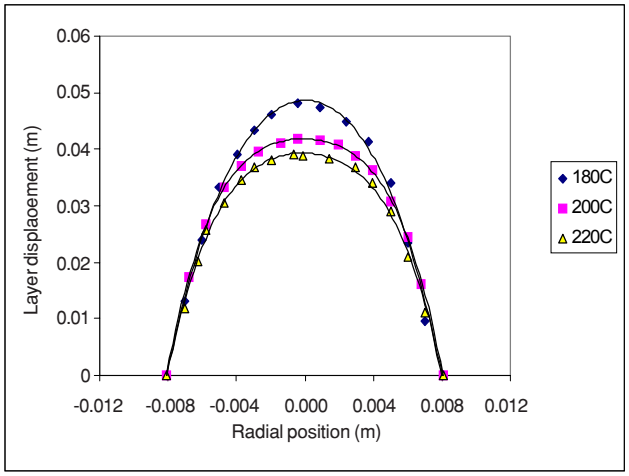

Figure 4 Effect of extrusion temperature on flow patterns inside capillary rheometer barrel plotted in a graph of layer displacement versus barrel radial position

system were pushed to the side towards the wall making the flow pattern tip become rounded with respect to extrusion temperature.

Sombatsompop *et al.* [4] made similar investigation for natural rubber and concluded that the flow patterns show no changes with temperature. The study reviewed flow patterns that were obtained after large displacement of the plunger whereby flow patterns had become too complex to be assessed. The conclusion was made based on qualitative nature of the flow patterns and no quantitative measurement was conducted. However in this study, the flow patterns were not allowed to become too complex (low plunger displacement) in order to make measurement possible.

Layer displacement was not a good representation for evaluating flow profiles in this study. It does not take into account the extrusion time, which was different depending with the extrusion temperature. There were two variables (i.e. temperature and time) making the flow profile incomparable if velocity of the melt was to be considered. Referring to Eq. (3), (4) and (5), a better evaluation was to take velocity ratios into consideration, which enables comparison of flow profiles to be made with theoretical prediction. Figures 5(a), 5(b) and 5(c) display comparative study of velocity profile obtained from the experiment with that of theoretical calculation.

Significant deviation of experimental velocity profiles with that of calculated from the theory was observed especially at 180°C. The deviation seems to decrease with temperature and as at the extrusion temperature of 220°C, both experimental and theoretical velocity profiles overlapped each other. At 180°C, flow of ABS melt was very slow near the wall and concentrated in the middle of the barrel. Figure 5(a) depicts that deviation tends to reduce in the middle of the barrel and supports the above statement.

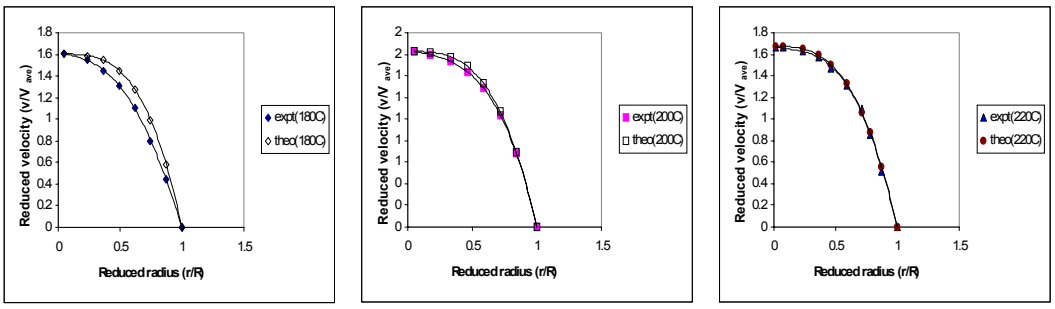

Figure 5 Comparative evaluation of velocity profiles of ABS polymer obtained from experimental with calculated theoretical velocity profiles at extrusion temperature of: a) 180°C, (b) 200°C and (c) 220°C. Notes: Extrusion pressure = 30 kg/cm^2 and L/D=4

Another factor that may contribute to the deviation is overestimation of the theoretical velocity profiles due to the power law index, *n*, used. The value of *n* used in the calculation was obtained from the flow curve which uses the shear rate inside the capillary die and not inside the barrel. Mitsoulis [17] numerically calculated shear rate in both die and barrel in his study on entry flow of LDPE melt. He reported that the wall shear rate of a fully developed flow in the reservoir (or barrel) is lower than that of the die. At very low shear rate and far below the power law region (0.01^{-1} s^{-1}), *n* value is significantly higher as reported previously [13]. Higher *n* value is estimated to reduce the rounded and broader tip shape of the theoretical velocity profiles making it closer to the experimental one. Temperature increment will shift the flow curve more towards the power law region (10–103 s^{-1}) where n value is less sensitive to shear rate giving less deviation from the theoretical velocity profiles at 200 and 220°C.

3.3 Influence of pressure

Changing extrusion pressure in a constant stress capillary rheometer is equivalent to changing extrusion rate in constant rate capillary rheometer as increase in rate results in pressure increment, which was measured by a pressure transducer in the latter system. Figures 6 and 7 show barrel velocity profiles of ABS polymer extruded at different extrusion pressure.

Both image and plotted measurement did not show any significant influence of pressure towards velocity profiles. Sombatsompop *et al.* [4] also reported similar finding with natural rubber and highlighted the absence of vortex formation at near die entrance. Similarly in this study, although a pressure value of 107 kg/cm^2 which exceed pressure value that initiate rippling melt fracture was used [13], no vortex formation was observed. This indicates that the generation of a vortex is not the cause of melt fracture and suggests that the vortex formation is related to the viscous nature of the

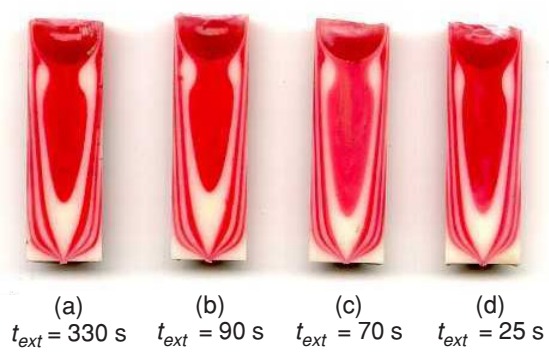

Figure 6 Effect of extrusion pressure on flow patterns inside capillary rheometer barrel (a) 30 kg/cm^2, (b) 50 kg/cm^2, (c) 70 kg/cm^2 and (d) 107 kg/cm^2. Notes: Extrusion temperature = 180°C and L/D = 4

fluid, the higher the viscosity of the fluid, the less likely vortex formation will be observed [4].

It is has been mentioned in literatures [2,18,19] that melt behaviour of polymer is dependent on pressure. However, it is not the case for the velocity profiles obtained from this experiment. Small influence may exist but was not significant enough to be detected due to low extrusion temperature with regards to ABS polymer. More significant influence may be discovered at higher temperature but unfortunately, it was not possible due to high and uncontrollable extrusion rate that limits the study.

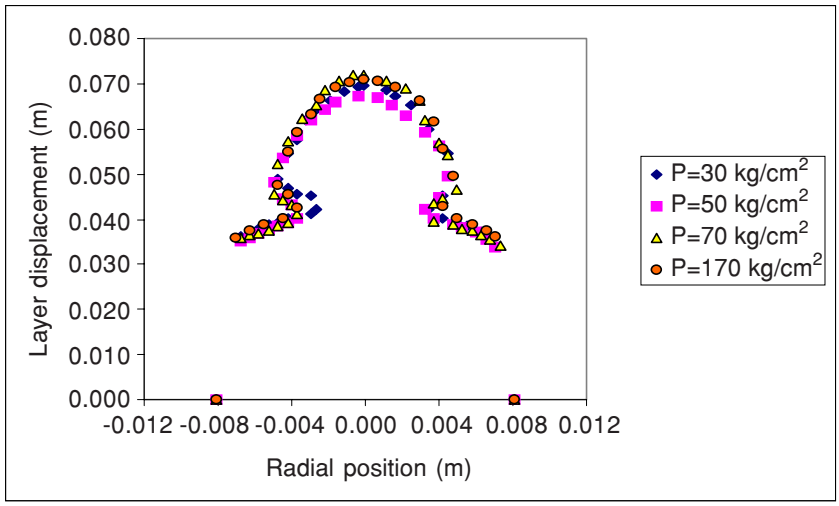

Figure 7 Effect of extrusion pressure on flow patterns inside capillary rheometer barrel plotted in a graph of layer displacement versus barrel radial position

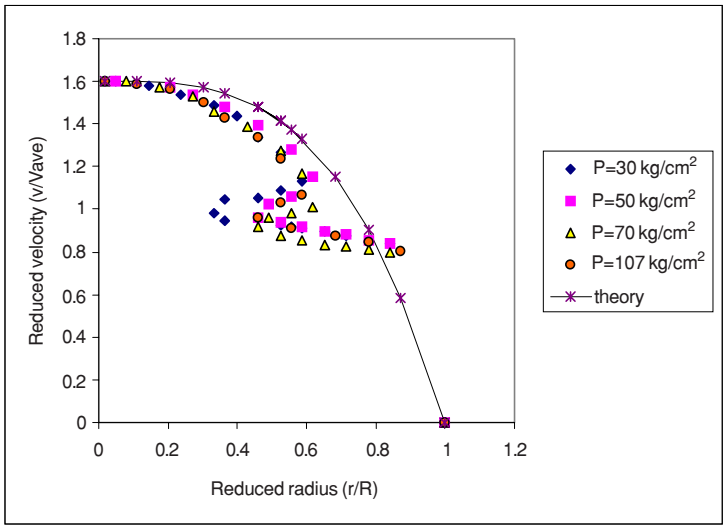

Figure 8 Comparative evaluation of velocity profiles of ABS polymer obtained from experiment with calculated theoretical velocity profiles at different extrusion pressures Notes: Extrusion temperature = 180°C and $L/D = 4$

Velocity profiles comparison (Figure 8) shows significant deviation of experiment velocity profile with that of calculated theoretically. This displays how complex actual polymer melt flow is where the experimental profiles seems to exhibit mushroom-like features. Factors such as plunger dimension, leakage and re-circulation flow may be pointed as the causes of such complexity in polymer flow.

3.4 Influence of plunger displacement

In the extrusion process, the plunger progresses towards the die with time extruding more polymer melts out of the die. The displacement of the plunger changes ABS polymer flow patterns inside the barrel and this is shown in Figure 9.

Figure 10 displayed better representation of Figure 9 where all profiles were plotted in the same figure for comparative purposes. It seems that as the plunger advances, the flow profile change from parabolic shape to a mushroom-like shape. When the extrusion time has elapsed 60 min, it can be seen that the layers adjacent to the surface of the plunger are gradually being swept away from the wall across the face of the piston and into the centre of the barrel. Sombatsompop and Wood [5] also observed this in capillary extrusion of natural rubber using a piston-type plunger. More complex flow patterns emerges as extrusion progressed where the mushroom-like tip becomes flattened. A reasonable assumption to explain this complex flow is the flow inside the barrel was not fully formed but changes continuously.

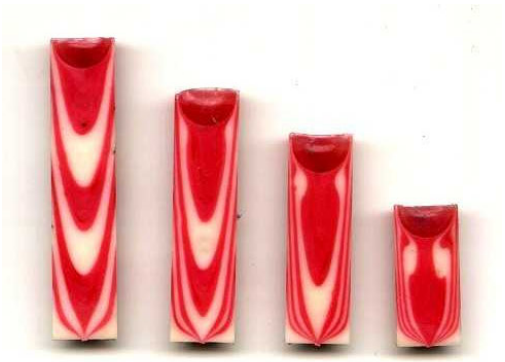

Figure 9 Effect of extrusion time or plunger displacement on flow patterns inside capillary rheometer barrel (a) 30 s, (b) 60 s, (c) 90 s and (d) 120 s Notes: Extrusion pressure = 50 kg/cm^2, L/D = 4 and temperature = 180°C

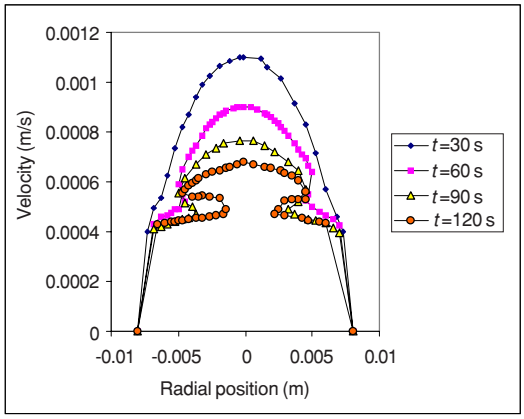

Figure 10 Effect of extrusion time or plunger displacement on flow patterns inside capillary rheometer barrel plotted in a graph of velocity versus barrel radial position

4.0 CONCLUSIONS

Flow patterns of ABS polymer melt evaluation in a constant stress capillary rheometer reveal that process parameters such as temperature, pressure and plunger displacement do have some influences towards the flow profiles. However, the extent of the influences varies with parameters investigated with temperature and plunger displacement displaying significant effects while pressure does not affect the profiles when the study was conducted at 180°C. Increasing the extrusion temperature, the flow patterns tip change from parabolic to a more rounded shape. ABS polymer melt seems to be pushed aside towards the barrel wall and die surfaces which were indicated by the thickness reduction of pigmented layer near these surfaces. For plunger displacement effect, complex flow patterns were obtained with large plunger displacement resulted from polymer adjacent to the surface of the plunger gradually being swept away from the wall across the face of the piston and into the centre of the barrel.

Measurements obtained from the experiment showed how important actual evidence (i.e. flow visualisation) on flow of polymer melts in support with theoretical estimation. Theoretically, a plug-like flow was expected for most polymer melts but experimental observations yielded various flows from parabolic to complex mushroom-like flow for ABS melt. Experimental findings may carry some errors since a lot of experimental procedures and manual measurements were involved in obtaining test specimens for flow pattern study. Nevertheless, it conveys valuable information in explaining and understanding complex flow of polymer melts.

REFERENCES

[1] Boger, D. V. and K. Walters. 1993. *Rheological Phenomena in Focus*. London: Elsevier.

[2] Agassant, J. F., P. Avenas, J. P. Sergent and P. J. Carreau. 1991. *Polymer Processing: Principles and Modelling*. New York: Hanser Publisher.

[3] Collyer, A. A.,. 1993. *Techniques in Rheological Measurements*. London: Chapman and Hall.

[4] Sombatsompop, N., M. C. Tan and A. K. Wood. 1997. Flow Analysis of Natural Rubber in Capillary Rheometer. 1: Rheological Behavior and Flow Visualization in the Barrel. *Polym. Eng. Sci.* **37**: 270-280.

[5] Sombatsompop, N. and A. K. Wood. 1997. Flow Analysis of Natural Rubber in Capillary Rheometer. 2: Flow Patterns and Entrance Velocity Profiles in the Die. *Polym. Eng. Sci.* **37**: 270-280.

[6] Bartos, O. and J. Holomek. 1971. Unstable Flow of Amorphous Polymers Through Capillaries 1. Velocity Profiles of Polymer Having Discontinuous Flow Curve. *Polym. Eng. Sci.* **11**: 324-334.

[7] Drexler, L. H. and C. D. Han. 1973. Studies of Converging Flows of Viscoelastic Polymeric Melts. II. Velocity Measurements in the Entrance Region of a Sharp-edge Slit Die. *J. Appl. Polym. Sci.* **17**: 2369.

[8] Sombatsompop, N. and A. K. Wood. 1999. A Novel Method for Velocity Profile Measurements in Flowing Polymer Melts. *Mat. Res. Innovat.*, 107-111.

[9] Munsted, H., M. Schwetz, M. Heindl and M. Schmidt. 2001. Influence of Molecular Structure on Secondary Flow of Polyolefin Melts as Investigated by Laser-Doppler Velocimetry. *Rheol. Acta*: 384-394.

[10] Harrison, P., L. J. P. Janssen, V. P. Navez, G. W. M. Peters and F. P. T. Baajiens. 2002. Birefringence Measurements on Polymer Melts in an Axisymmetric Flow Cell. *Rheol. Acta*: 113-133.

[11] Gotz, J., W. Kreibich and M. Peciar. 2002. Extrusion of Pastes with A Piston Extruder for the Determination of Local Solid and Fluid Concentration, The Local Porosity and Saturation and Displacement Profiles by Means of NMR Imaging. *Rheol. Acta,* 134-143.

[12] Toray Plastics (M) Sdn. Bhd., *private communication.*

[13] Ariff, Z. M. and M. N. Z. Arif. 2000. Melt Rheology of ABS Terpolymer and Its Influence on Die Swell of Extrudate. *Proceeding of National Symposium on Polymeric Materials 2000*, USM, Penang.

[14] Dealy, J. M. 1982. *Rheometers for Molten Plastics*. New York: Von Nostrand Reinhold.

[15] Ariff, Z. M., *Year Rheology and Processing of ABS*. Ph.D. Dissertation. USM. in progress.

[16] McKelvey, J. M. 1962. *Polymer Processing*. New York: John Wiley and Sons.

[17] Mitsoulis, E. 2000. Numerical Simulation of Entry Flow of The IUPAC-LDPE Melt. *J. Non-Newtonian Fluid Mech.,* 13-30.

[18] Gupta, R. K. 2000. *Polymer and Composite Rheology*. 2nd. Edn. New York: Marcel Dekker.

[19] Han, C. D. 1976. *Rheology in Polymer Processing*. New York: Academic Press.

FOREWORKD

Polymeric materials have become an essential and ubiquitous part of our lives. The materials are widely used in many applications, ranging from household items to engineering and advanced applications. In fact, they are now part and parcel of our daily life, thanks to their versatility and extremely large window of properties, ease of design and modification. Their widespread use confirms the success and the immense benefits of polymeric materials, thus the dire need to continually focus on research and development effort in order to meet the increasing stringent future requirements.

The Third National Symposium of Polymeric Materials was jointly organized by the postgraduate students of Polymer Engineering Department, Universiti Teknologi Malaysia, Plastics Rubber Institute of Malaysia (PRIM), and Research Management Centre (RMC) of Universiti Teknologi Malaysia on the December 30-31, 2002. The theme of the symposium entitled "Polymeric Materials for Future Living" was deemed most appropriate as Malaysian polymer industry is facing many new challenges. In the wake of trade liberalisation through AFTA and WTO, these challenges will not only affect our product competitiveness in the international market but also our future in terms of economy and the environment.

A total of 31 papers from five universities and research institutions were presented at the symposium – undoubtedly a step in the right direction to meet our common goal. The papers presented during the two-day symposium have generated stimulating discussion and enriched the knowledge of the partici pants on current and recent development of polymeric materials. It is hoped that all the research findings discussed will enhance our competitive edge in technology leading to product commercialization.

After careful evaluation, 14 papers were selected to be published in this special issue of *Jurnal Teknologi (A)*. I would like to take this opportunity to thank Assoc. Prof. Dr. Wan Aizan bt. Wan Abd. Rahman, Dr. Abd. Razak bin Rahmat, Dr. Shahrir bin Hashim, En. Aznizam bin Abu Bakar and En. Onn bin Hassan (members of the Editorial Committee of this special issue) for their full cooperation in making this publication a reality. The support and encouragement from the members of the existing Editorial Committee of *Jurnal Teknologi* and other staff are very much appreciated.

Associate Professor Dr. Azman bin Hassan
Guest Editor
Jurnal Teknologi (A) Special Issue on Polymeric Materials.