Annual Technical Conference - ANTEC, Conference Proceedings
Volume 2, 2012, Pages 984-987
70th Annual Technical Conference of the Society of Plastics Engineers 2012, ANTEC 2012; Orlando, FL; United States; 2 April 2012 through 4 April 2012; Code 92358

Computer simulation of rubber extrusion in the capillary die using viscoelastic models (Conference Paper)

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Abstract

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Indexed keywords

Capillary extrusions; CFD codes; Circulation flow; **Die extrusion**; **Die** swell; Extrudate swell; Polyflow; Pom-Pom **models**; **Rubber** compounds; **Rubber extrusions**; **Viscoelastic** behaviors; **Viscoelastic models**; **Viscoelastic** properties

Engineering controlled terms: Computational methods; **Computer simulation**; Experiments; **Extrusion**; **Models**; Plastic products; **Rubber**; Viscoelasticity

Engineering main heading: Dies

ISBN: 978-162276083-1 **CODEN:** ACPED **Source Type:** Conference Proceeding **Original language:** English
Document Type: Conference Paper

View in table layout

References (18)

COMPUTER SIMULATION OF RUBBER EXTRUSION IN THE CAPILLARY DIE USING VISCOELASTIC MODELS

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Abstract

Rubber compounds have high viscoelastic property. The viscoelastic behaviors shown in die extrusion are an extrudate swell and circulation flow at the entrance of die. Application of viscoelastic models to a capillary extrusion has been investigated in this study. Experiment and simulation have been performed using fluidity tester and commercial CFD code, Polyflow respectively. Die swells of rubber compounds through a capillary die have been predicted using various viscoelastic models, such as PTT, Giesekus, and POMPOM models. Simulation results of die swell were compared with the experiment. Pressure drops, velocity distributions and circulation flows at the corner of reservoir have been analyzed through computer simulations.

Introduction

Highly viscoelastic polymeric materials such as rubbers, rubber compounds, and elastomers shows a memory effect, and it causes die swell or extrudate swell when the material exit to the outside of the die [1, 2]. The shape of extrudate is strongly related to elastic property that the material contains. Viscoelastic characteristics of material are dependent of shear rate, history of flow path, die length, temperature, and so forth on [1, 2]. The die design for the extrusion of rubber compounds would be very complicated since many parameters mentioned above are involved.

Many of researches about die swell have been published in the extrusion of capillary die for several polymers [3-5]. Die swell is mainly a function of shear rate and temperature. Die swell increases as shear rate increases. And it decreases as temperature increases because elasticity diminishes as temperature increases [2, 4, 6]. Early researches for viscoelastic flow simulations were mostly concerning the computing methods such as elastic-viscous stress-splitting and finite element formulations [7-11]. Hulsen used elastic and elongational properties in viscoelastic simulation using Gelerkin finite element method [12]. Lee and his coworkers published papers that simulated nonisothermal viscoelastic flow and suggested time-Weissenberg number superposition [13, 14]. Those papers were limited to one or two relaxation modes, a few viscoelastic models (Phan-Thien-Tanner, upper convected Maxwell, or Oldroyed-B) and geometries [7-14]. Researches for computer simulations of profile extrusion have been published [15-17]. More recently viscoelastic simulations using PTT model showed die swell and circulation flow at the entrance of die [18].

This research is an extension of previous paper [18]. The die swell of rubber compound was measured using the Fluidity Tester that contains capillary die. Computer simulation of flow in the capillary die was performed using commercial CFD program, Polyflow. Various viscoelastic models such as PTT, Giesekus, and POMPOM models have been used for the simulation of flow behavior of rubber compound in a capillary die using full 3D model and three relaxation modes. Pressure profiles, pressure drops at the entrance of capillary die, streamlines, and velocity profiles can be obtained by computer simulations for various models. Simulation results of die swell have been compared with experimental results.

Experimental

Material and Capillary Extrusion

The rubber compound used in this experiment was consisted of 90% of styrene butadiene rubber and 10% of butadiene rubber. Viscosity, Storage and loss moduli were measured at 110^{o}C using RPA 2000 (Monsanto) and shown in Figure 1. Figure 2 shows the geometry of Fluidity Tester. Temperature of the reservoir and capillary die was set to 110^{o}C during extrusion experiment.

Computer Simulations

Modeling for FEA and Boundary Conditions

Figure 3 shows a mesh for finite element analysis of die extrusion. A quarter of total region was considered for full three dimensional viscoelastic isothermal analysis using commercial CFD program, Polyflow. Flow rate was imposed on the inlet sectional area denoted by 'Boundary

1' and outflow condition was imposed on the exit sectional area denoted by 'Boundary 2'. The surface of extrude, 'Boundary 3' was set to free surface condition. Symmetry surface, 'Boundary 4', was set to symmetry condition, and die wall, 'Boundary 5', was set to no slip condition. Remeshing has been adapted during the calculation to determine the free surface of extrude.

Viscoelastic Models

Three viscoelastic models, PTT, Giesekus, and POMPOM models have been used for numerical simulations.

PTT Model

Equation (1) shows a PTT model.

$$T = T_1 + T_2 \tag{1a}$$

$$T_2 = 2\eta_2 D \tag{1b}$$

$$T_1 = \exp\left[\frac{\varepsilon\lambda}{\eta_1} tr(T_1)\right] + \lambda\left[\left(1-\frac{\xi}{2}\right)\overset{\triangledown}{T_1} + \frac{\xi}{2}\overset{\triangledown}{T_1}\right] = 2\eta_1 D \tag{1c}$$

Total stress T is sum of T_1 and T_2. T_1 is a viscoelastic portion and T_2 is a viscous portion in a stress fields. η_1 is a shear viscosity in the viscoelastic portion and η_2 is a shear viscosity in the viscous portion. ε is a control parameter of extensional flow of material, λ is a relaxation time, ξ is a control parameter of shear viscosity, and D is a deformation rate. All parameters were determined by curve fitting using experiment data shown in Figure 1.

Giesekus Model

Giesekus model can be expressed as Equation (2) instead of Equation (1c) in PTT model.

$$\left(\mathrm{I} + \frac{\alpha\lambda}{\eta_1}\mathrm{T}_1\right)\cdot \mathrm{T}_1 + \lambda \overset{\triangledown}{\mathrm{T}}_1 = 2\eta_2 D \tag{2}$$

α is a material constant that controls the extrusion viscosity.

POMPOM Model

Pompom model can be expressed as Equation (3) instead of Equation (1c) in PTT model.

$$\mathrm{T}_1 = \frac{G}{1-\xi}\left(3\Lambda^2 S - \mathrm{I}\right) \tag{3a}$$

ξ is a non-liner material parameter, and S and Λ are defined as

$$\lambda\left[\left(1-\frac{\xi}{2}\right)\overset{\triangledown}{S} + \frac{\xi}{2}\overset{\triangledown}{S}\right] + \lambda(1-\xi)[2D:S]S + \frac{1}{\Lambda^2}\left[S - \frac{\mathrm{I}}{3}\right] = 0 \tag{3b}$$

$$\lambda_0 \frac{DA}{Dt} - \lambda_S(\nabla v : S)\Lambda + (\Lambda - 1)e^{\frac{2(\Lambda-1)}{q}} = 0 \tag{3c}$$

Relaxation time was calculated 0.0185 sec by taking reciprocal number of average shear rate in the capillary die, which was obtained by non Newtonian simulation (power law model) [18]. Three relaxation modes were used in all viscoelastic models based on calculated relaxation time.

Results and Discussions

Pressure Profile

Figure 4 shows pressure profiles along the reservoir and capillary die for various viscoelastic models and non-Newtonian model (Bird-Carreau model). Pressure drops at the entrance of die were different from models. PTT and Giesekus model showed higher pressure profiles than other models. The longer L/D showed the higher pressure profile. The pressure drops at the die entrance showed wide range of varieties according to models. Table 1 shows pressure drops for models and L/D. Non-Newtonian and POMPOM model showed low pressure drop compare with other models.

Velocity Distributions and Path Lines

Figure 5 shows velocity distributions and velocity profiles in the capillary die according to viscoelastic models. Velocity distributions were similar to all models however the velocity profiles were different. Non-Newtonian and PTT models showed high center velocity. Figure 6 shows path lines of flows. Circulation flows were observed at the corner of reservoir for all viscoelastic models. However it was not showed in the non-Newtonian result. Circulation flow is one of the well known viscoelastic effect during flow. All viscoelastic models studied in this paper well predicted circulation flows.

Die Swells

Figure 7 shows die swells at the exit of the capillary die for various viscoelastic models and measured data. Die swells increased as flow rate increased for all models and experiment. Measured die swells were distributed in 1.26 to 1.30 for tested flow rates. PTT model predicted the highest die swell whereas POMPOM model predicted the lowest die swell. Die swell predicted by PTT model showed good agreement with the experimental data among the simulated viscoelastic models in this paper.

Conclusions

Viscoelastic flow behaviors of rubber compound have been simulated using various viscoelastic models such as PTT model, Giesekus model and POMPOM model. Viscoelastic models predicted circulation flow at the corner of reservoir, which is the typical viscoelastic characteristic of flow. However non-Newtonian model could not predict circulation flows. Predicted die swell by viscoelastic models showed similar tendency as experimental data. Die swell predicted by PTT model showed good agree with experiment.

Acknowledgements

This work (research) is financially supported by the Ministry of Knowledge Economy (MKE) and Korea Institute for Advancement in Technology (KIAT) through the Workforce Development Program in Strategic Technology. This work (research) is financially supported by the Ministry of Knowledge Economy (MKE) through the World Class-300 Project in Knowledge Economy Technology Innovation Program.

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Table 1 Pressure drops at the entrance of capillary die for rheological models and L/D.

[Unit : Pa]

Model	L/D =1	L/D=5
Non-Newtonian	2.78E6	2.85E6
PTT	2.8E7	3E7
Giesekus	2.9E7	3E7
POMPOM	2.98E6	3.1E6

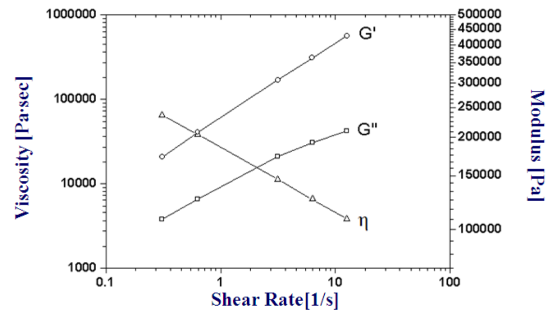


Figure 1 Shear viscosity, storage and loss moduli of rubber compound used in this study.

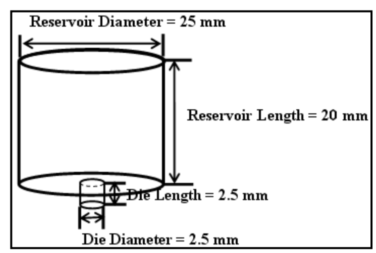


Figure 2 Geometry of fluidity tester containing reservoir and capillary die.

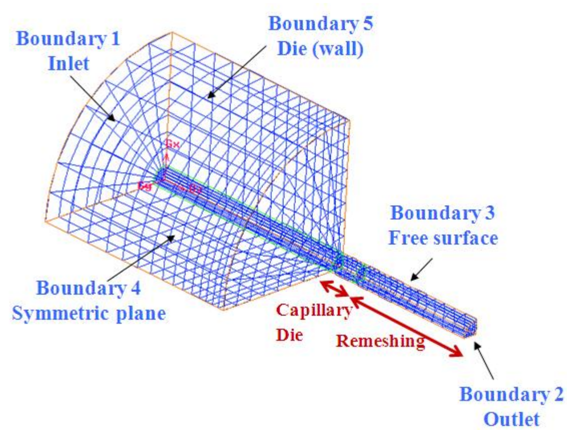
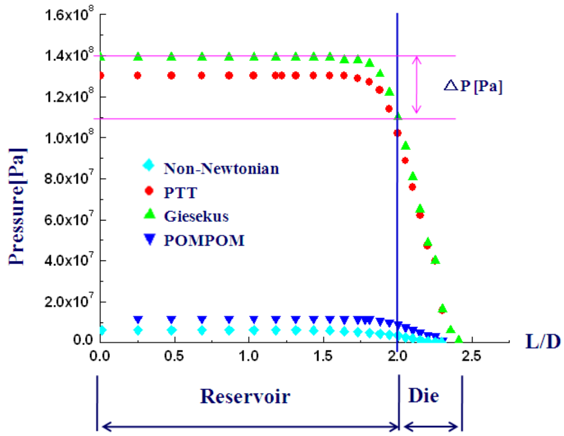
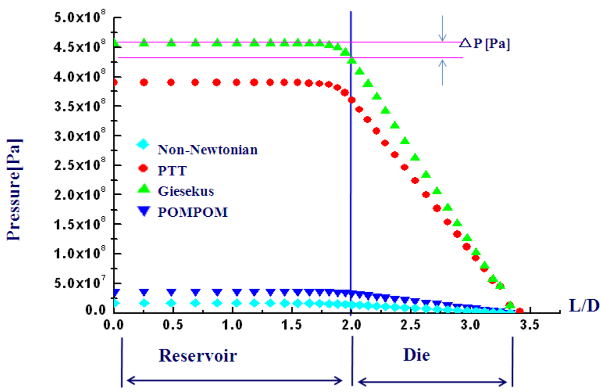


Figure 3 Mesh and boundary conditions for computation.

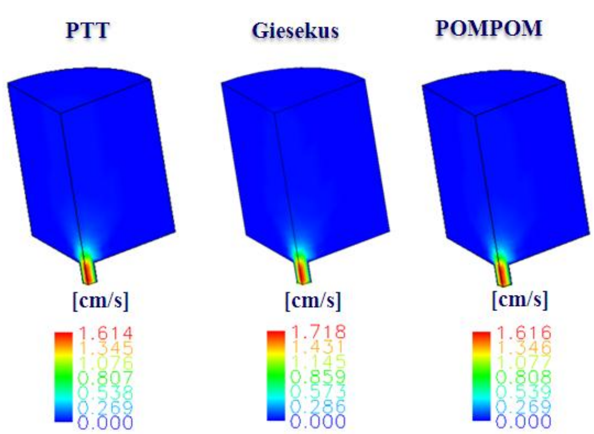


(a) L/D=1

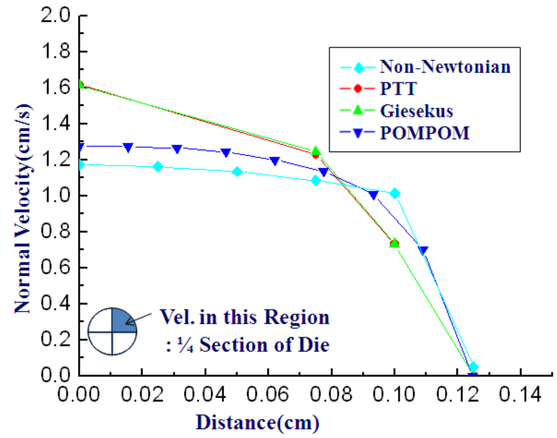


(b) L/D=5

Figure 4 Pressure profiles along the reservoir and capillary die predicted by viscoelastic models.



(a) Velocity distributions



(b)Velocity profiles in a capillary die

Figure 5 Velocity distributions and profiles in a capillary die for various viscoelastic models.

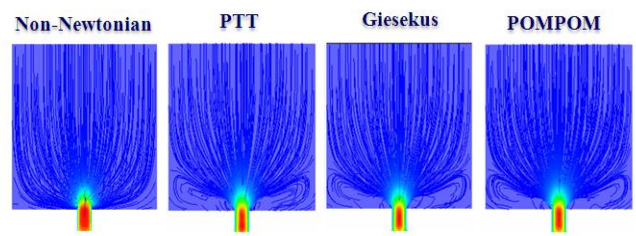


Figure 6 Circulation flows at the corner of reservoir (entrance of capillary die) for various viscoelastic models.

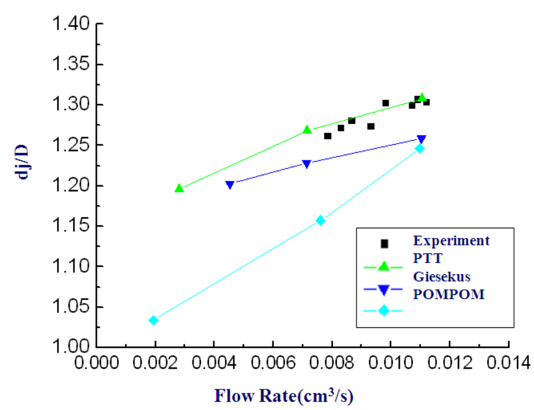


Figure 7 Measured and predicted die swells.