Viscoelastic Effects in Multilayer Polymer Extrusion

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Abstract:
The effect of viscoelasticity on multilayer polymer extrusion is discussed. In these coextrusion processes predetermined patterns are created with a remarkable breadth of complexity even in geometrically simple dies via elastic rearrangements caused by the second-normal stress differences. A computational method is offered, based on the mapping method, which quantitatively describes the flow-induced patterns. Besides that the results are esthetically beautiful, they are also relevant for practice, since process and die design optimization is now possible. Not only to minimize interface distortion, but potentially also to deliberately create new processes and products based on this flow-induced patterning of polymers.

Zusammenfassung:
Der Einfluss der Viskoelastizität auf die Mehrschichtextrusion bei Polymeren wird diskutiert. Bei diesen Koextrusionsprozessen werden vorher bestimmte Muster mit einer bemerkenswerten Komplexitätsvielfalt erzeugt, sogar in geometrisch einfachen Düsen mit Hilfe elastischer Umlagerungen, die durch die zweite Normalspannungsdifferenz erzeugt werden. Eine numerische Methode, die auf der Abbildungsmethode basiert, wird dargestellt, die die strömungsinduzierten Muster quantitativ beschreibt. Die Resultate sind nicht nur ästhetisch schön, sondern auch für die Praxis relevant, da die Optimierung des Prozess- und Düsendesigns nun möglich ist – nicht nur um die Verzerrung der Grenzfläche zu minimieren, sondern um möglicherweise auch gezielt neue Prozesse und Produkte zu schaffen, die auf der strömungsinduzierten Musterbildung bei Polymeren basieren.

Résumé:
L'effet de la viscoélasticité sur l'extrusion de polymères multicouches est discuté. Dans ces procédés de co-extrusion, des empreintes prédéterminées sont créées qui possèdent une gamme remarquablement étendue de complexité et ceci même pour des filières à géométrie simple. Ces empreintes sont associées à des réarrangements élastiques causés par la seconde différence de contraintes normales. Une méthode de calcul numérique est proposée, basée sur la méthode de cartographie qui décrit quantitativement les empreintes induites par l'écoulement. En plus de l'obtention de résultats esthétiquement magnifiques, ceux-ci sont pertinents pour ce qui concerne la pratique, puisque l'optimisation des procédés ainsi que des conceptions des filières est maintenant possible. Non seulement est-il possible de minimiser les distorsions d'interface, mais aussi de nouveaux procédés et produits peuvent être potentiellement créés de manière délibérée grâce à cette technique d'empreintes de polymères induites par l'écoulement.

Key words: extrusion, rheology, secondary flow, normal stresses, pattern formation

1 INTRODUCTION

Multilayer coextrusion is a process in which polymers are extruded and joined together in a feedblock or a die with the purpose of forming a single structure with multiple layers. The attraction of coextrusion is both economic and technical as it is a single-step process. Starting with two or more polymer materials, that are simultaneously extruded and shaped in a single die, a multilayer sheet or film can be formed. Coextrusion avoids the costs and complexities of conventional multistep lamination and coating processes, where individual plies must be made separately, and then primed, coated, and laminated. Moreover, coextrusion readily makes it possible to manufacture products with layers thinner than can be made and handled as an individual ply. Consequently, only the necessary thickness of a high performance polymer is used to meet a particular specification of the product. In fact, coextrusion has been used commercially to manufacture unique films consisting of hundreds of layers with individual layer thicknesses less than 100

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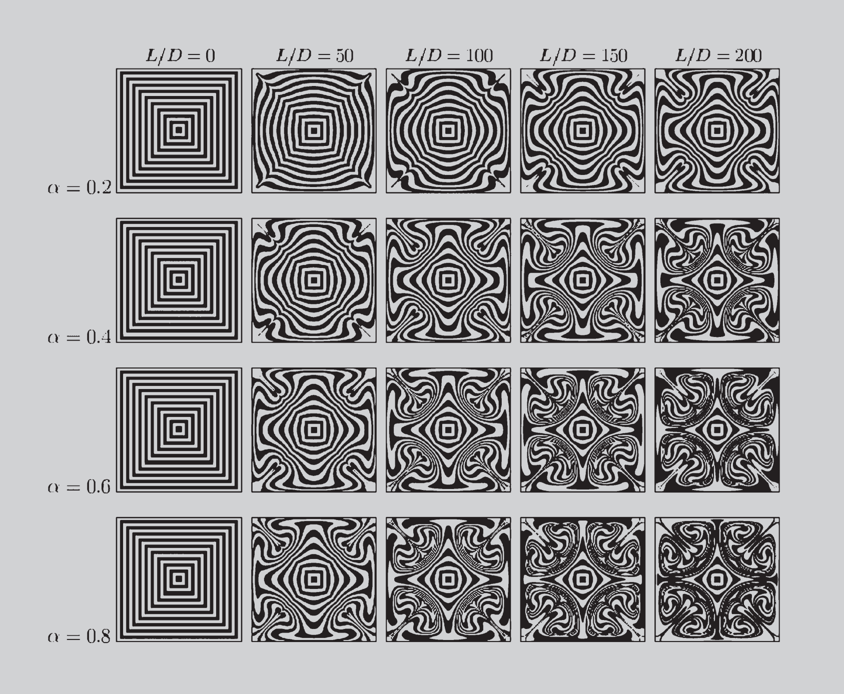

Figure 9: Numerical simulations comparing layer rearrangement as a function of distance traveled down a square channel. The viscoelasticity was changed by changing the non-linear α parameter in the one mode Giesekus model from 0 to 0.8 with steps of 0.2.

level of viscoelasticity can indeed be determined based on the amount of layer deformation caused by second-normal stress difference driven flows. These results indicate that the technique can be used to determine the second-normal stress difference under realistic flow rates by applying he technique in an inverse way. It is suggested by these results that (for this flow rate) a channel length of $50 < L/D < 100$ should be chosen to differentiate the level of viscoelasticity. Via an iterative numerical and experimental approach, these flows could even help to design improved constitutive equations that can quantitatively predict second normal stresses over a broad range of deformation rates. Note that the secondary flow-induced deformations are (sensitive) *integrals* of the velocity field over time, rather than (non-sensitive) *differentials*, which are stresses.

5 CONCLUSIONS

The mapping method was used to determine interface locations for coextruded polystyrene structures as they flow through square and rectangular channels. Excellent agreement between the experimental and numerical results was obtained. These results show the power of the mapping technique in determining interface deformation in monolithic coextruded structures. Moreover, the simulation results suggest that the technique can be used to determine the second-normal stress difference under realistic flow rates.

Clearly, the flow-induced patterning method which was demonstrated here would be more useful if part of the polymer is provided with additional functionality, such as electrical conductivity to be used for LED or capacitor applications. Other possibilities include a controlled difference in the refractive indices of the different structures to control optical properties.

REFERENCES

[1] Southern JH, Ballman RL: Stratified bicomponent flow of polymer melts in a tube. Appl. Polym. Sci. 20 (1973) 175.

[2] White JL, Ufford RC, Dharod KR, Price RL: Experimental and theoretical study of the extrusion of two-phase molten polymer systems. J. Appl. Polym. Sci. 16 (1972) 1313.

[3] Han CD: A study of bicomponent coextrusion of molten polymers. J. Appl. Polym. Sci. 17 (1973) 1289.

[4] Everage Jr AE: Theory of stratified bicomponent flow of polymer melts. 1. Equilibrium newtonian tube flow. Trans. Soc. Rheol. 17 (1973) 629.

[5] Karagiannis A, Hrymak A, Vlachopoulos J: Three-dimensional studies on bicomponent extrusion. Rheologica Acta 29 (1990) 71–87.

[6] Xue SC, Phan-Thien N, Tanner RI: Numerical study of secondary flows of viscoelastic fluid in straight pipes by an implicit finite volume method. J. Non-Newtonian Fluid Mechanics 59 (1995) 191–213.

[7] Takase M, Shinichi K, Funatsu K: Three-dimensional viscoelastic numerical analysis of the encapsulation phenomena in coextrusion. Rheologica Acta 37 (1998) 624–634.

[8] Sunwoo KB, Park SJ, Lee SJ, Ahn KH, Lee SJ: Numerical simulation of three-dimensional viscoelastic flow using the open boundary condition method in coextrusion process. J. Non-Newtonian Fluid Mechanics, 99 (2001) 125–144.

[9] Sunwoo KB, Park SJ, Lee SJ, Ahn KH, Lee SJ: Three-dimensional viscoelastic simulation of coextrusion process: Comparison with experimental data. Rheologica Acta 41 (2002) 144–153.

[10] Kim YJ, Han CD, Chin HN: Rheological investigation of interfacial instability in two-layer flat-film coextrusion. Polym. Eng. Rev. 4 (1984) 177.

[11] Arvedson MA: Rheological considerations in coextrusion. TAPPI/PLC Conference Proceedings 513 (1984) 84.

[12] Hickox CE: Instability due to viscosity stratification in axisymmetric pipe flow. Phys. Fluids 14(1971) 251.

[13] Yih CS: Instability due to viscosity stratification. J. Fluid Mech. 27 (1967) 337.

[14] Khan AA, Han CD: A study on the interfacial instability in the stratified flow of two viscoelastic fluids through a rectangular duct. Trans. Soc. Rheol. 21 (1977) 101.

[15] Hooper AP, Boyd WG: Shear-flow instability at the interface between two viscous fluids. J. Fluid Mech. 128(1983) 507.

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http://www.appliedrheology.org

[16] Schrenk WJ, Pinsky J: Coextruded iridescent film. TAPPI Paper Synthetics Proceedings (1976) 141–176.
[17] Han CD, Rao DA: Studies on wire coating extrusion. ii. the rheology of wire coating coextrusion. Polym. Eng. Sci. 20 (1980) 128.
[18] Alfrey T Jr., Schrenk WJ, Bradley NL, Maack H: Interfacial flow instability in multilayer coextrusion. Polym. Eng. Sci. 18 (1978) 620.
[19] Khomami B: Interfacial stability and deformation of two stratified Power law fluids in plane poiseuille flow. 1. stability analysis. J. Non-Newt. Fluid Mech. 36 (1990) 289.
[20] Khomami B: Interfacial stability and deformation of two stratified Power law fluids in plane poiseuille flow. 2. interface deformation. J. Non-Newt. Fluid Mech. 37 (1990) 19.
[21] Waters ND: The stability of two stratified Power-law liquids in couette flow. J. Non-Newt. Fluid Mech., 12 (1989) 85.
[22] Wilson GM, Khomami B: An experimental investigation of interfacial instabilities in multilayer flow of viscoelastic fluids. 1. Incompatible polymer systems. J. Non-Newt. Fluid Mech. 45 (1992) 355.
[23] Wilson GM, Khomami B: An experimental investigation of interfacial instabilities in multilayer flow of viscoelastic fluids. 2. Elastic and nonlinear effects in incompatible polymer systems. J. Rheol. 37 (1993) 315.
[24] Dooley J: Viscoelastic Flow Effects in Multilayer Polymer Coextrusion. Ph.D. thesis (2002) Eindhoven University of Technology.
[25] Hirt CV, Nichols BD: Volume of fluid (VOF) methods for the dynamics of free boundaries. J. Comput. Phys 39 (1981) 201–225.
[26] Unverdi SO, Tryggvason G: Computations of multi-fluid flows. Phys. Fluids D 60 (1992) 70–83.
[27] Kruijt PGM, Galaktionov OS, Anderson PD, Peters GWM, Meijer HEH: Analyzing fluid mixing in periodic flows by distribution matrices. AIChE J. 47 (2001) 1005–1015.
[28] Galaktionov OS, Anderson PD, Peters GWM, Tucker III CL: A global, multi-scale simulation of laminar fluid mixing: The extended mapping method. Int. J. Multiphase Flows 28 (2002) 497–523.
[29] Anderson PD, Meijer HEH: Chaotic mixing analyses by distribution matrices. Appl. Rheol. 10 (2000) 119–133.
[30] Dietsche L, Dooley J: Numerical simulation of viscoelastic polymer flow - effect of secondary flows on multilayer coextrusion. SPE-ANTEC Technical Papers 41 (1995) 188.
[31] Dooley J, Debbaut B, Avalosse T, Hughes K: On the development of secondary motions in straight channels induced by the second normal stress difference: Experiments and simulations. J. Non-Newtonian Fluid Mech. 69 (1997) 255.
[32] Hyun KS, Dooley J, Hughes KR: An experimental study on the effect of polymer viscoelasticity on layer rearrangement in coextruded structures. Polymer Engineering and Science 38 (1998) 1060.
[33] Martinez-Ruvalcaba A, Chornet E, Rodrigue D: Dynamic rheological properties of concentrated chitosan solutions. Appl. Rheol. 14 (2004) 140–147.
[34] Bogaerds ACB: Stability analysis of viscoelastic flows. Ph.D. thesis (2002) Eindhoven University of Technology.

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