Visualization of Injection Molding

THOMAS J. BRESS* AND DAVID R. DOWLING
Department of Mechanical Engineering and Applied Mechanics
University of Michigan
Ann Arbor, MI 48109-2121

ABSTRACT: Even though it is considered a mature technology, the commercial importance of injection molding continues to drive research on how processing parameters impact final part characteristics. In particular, the influence of flow phenomena, which largely control molecular orientation within the mold cavity, is not fully understood. Results are presented from a study of polymer flow during injection molding using a clear mold that allows optical access from three sides, in a standard commercial machine, under standard molding conditions for polystyrene. Comparisons are drawn between the experimental results and the predictions of a commercial code for global mold filling properties.

KEY WORDS: injection molding, flow visualization.

INTRODUCTION

POLYMERS NOW PLAY, and will continue to play, a vital role in consumer product manufacturing. For example, in 1990 the passenger car market in the United States was worth approximately $530 billion [1] and 7.7% (by weight) of each car was made of polymers or polymer matrix composites [2]. Injection molding (and related processes such as resin transfer injection molding) is currently the most common industrial manufacturing technique for producing high volume polymer and polymer matrix composite components. Because of the inherent flexibility in mold design, this process offers rapid forming of complicated production parts for commodity industries as well as engineering and manufacturing applications.

The highest priority technical issue in injection molding of polymers for the automotive industry is determining how process parameters influence the anisotropic strengths, extensibilities, and net shape of the finished part. Ideally, when the part is removed from the mold, its anisotropic properties would be pre-

This technical paper was originally presented at the *55th Annual Technical Conference of the Society of Plastics Engineers* in Toronto, April 27–May 2, 1997. The Society holds the copyright.
*Author to whom correspondence should be addressed.

0731-6844/98/15 1374–08 $10.00/0

dictable and the part would retain the mold's shape. Unfortunately, the ideal case is seldom realized so polymer engineers are frequently plagued by an expensive, time consuming design-test-revise process before injection-molded polymer parts meet specifications. Shortening or eliminating this iterative process is an important technical issue in manufacturing polymer parts and materials, particularly for automotive applications which must contend with annual model-year styling changes.

Injection molding of thermoplastics involves transient flow of a non-Newtonian fluid through a complicated geometry. The process also involves rapid cooling of the melt to the solid state, possible crystallization, heat transfer to the mold, and strain- and thermal-induced changes in shear and extensional viscosities as the polymer chains elongate, relax, or break. All these processes add to the complexity of the injection molding operation [3].

The current state of scientific research in polymer behavior has unfortunately not advanced to the point of allowing reliable predictions for either the warping characteristics during initial cooling or the anisotropic mechanical properties of the injection molded components [4,5]. While theoretical and numerical treatments of polymer melt flow abound (for example see [6]), experimental results applicable to the industrial issues in injection molding are limited, and front line polymer engineers consistently rely on experience, rules of thumb, and trial-and-error methods to achieve acceptable results [3,7].

The software packages available for mold filling analysis often fall short of the critical goal—predicting the final part shape and strength for a given set of process conditions. Typically these packages predict warpage and shrinkage within only 25% of the actual. Flow analysis programs make extensive use of computational fluid dynamics to predict the location and shape of the flow front, and heat transfer analysis to predict the effects of cooling. These programs use information about the pressure and temperature dependent specific volume of thermoplastics together with non-uniform cooling to predict warpage and volumetric shrinkage. The critical role of polymer microstructure is not seriously taken into account in any of the software packages available for molding analysis [8], even though it is the critical element leading to anisotropic material behavior.

This paper presents the results from a visualization study of injection molding that seeks to determine how processing parameters influence polymer melt flow during injection molding, with the long term goal of determining the role of polymer fluid flow in setting final part properties. The studies presented here are based on pictures taken of a flowing polystyrene melt in a new specially designed optical-access mold in a modern commercial injection molding machine. The special mold, which makes a thick rectangular plate, is transparent on three sides and has been designed to handle the extreme pressures seen during mold packing. The current visualization approach is similar to that of previous studies [9–12], except here the observation window exposes the largest side of the part.

The visual results from this experimental mold filling study are compared to computed results from a commercial software package, the intent of this research project being to bridge the gap between scientific investigation and industrial-practice, and lay the groundwork for further studies involving more complex polymer part fabrication. In the near future, quantitative multi-dimensional flow measurements will be made during the entire molding process. Possible extensions of this research include a wider range of processing parameters, other thermoplastics, fiber loading, weld line formation, etc.

EXPERIMENTAL DESIGN AND SETUP

The flow visualization experiments were conducted with a specially designed optical access mold in a modern computer-controlled commercial injection molding machine with a 30 metric ton clamp. The special mold produces rectangular plates with dimension 117.5 mm × 73.0 mm × 6.3 mm. The mold has three windows: two along the smallest side of the mold cavity (73.0 mm × 6.3 mm), and one along the largest side (117.5 mm × 73 mm). The rectangular shape was chosen to facilitate planar windows for undistorted viewing and to ease the gridding requirements for the companion computational mold-filling studies. The parts were made with one of the 117.5 mm × 6.3 mm faces on the parting plane. Typically parts such as these would be made with the largest face on the parting plane. This unusual choice of orientation allows full visualization of the mold cavity from the side of the mold facing the operator of the machine, and extensions of the machine's clamping capability to parts with a larger planform area. Presentation of a smaller face to the mold platens admits the use of higher packing pressures without flashing than would be possible with the typical plate-platen orientation.

A schematic of the melt-flow visualization technique is shown in Figure 1. The optical access mold has been designed to allow full visualization of the mold cavity from the side of the mold. Illumination can be provided through either the top or bottom of the mold cavity. The gates may be placed anywhere along the edge of the part that is in the parting plane. In the flow experiments described here, the gate was placed near the lower right hand corner of the part and the cavity was illuminated from below with a high intensity white light.

An exploded view of the mold structure is shown in Figure 2. The mold has a window that forms the outside wall of the mold cavity. The main challenge was to design a window that could withstand the extremely high melt pressures found in the packing phase of a typical injection molding cycle. Finite element analysis was used to create a design capable of withstanding a 69 MPa melt pressure. The portion of the window in contact with the melt is a quartz block 19 mm thick. Quartz was chosen for its capability of withstanding significant temperature gradients. A 3 mm thickness of polycarbonate acts as a buffer between the quartz and three 25 mm thick pieces of plate glass. These are followed by another 3 mm thickness of

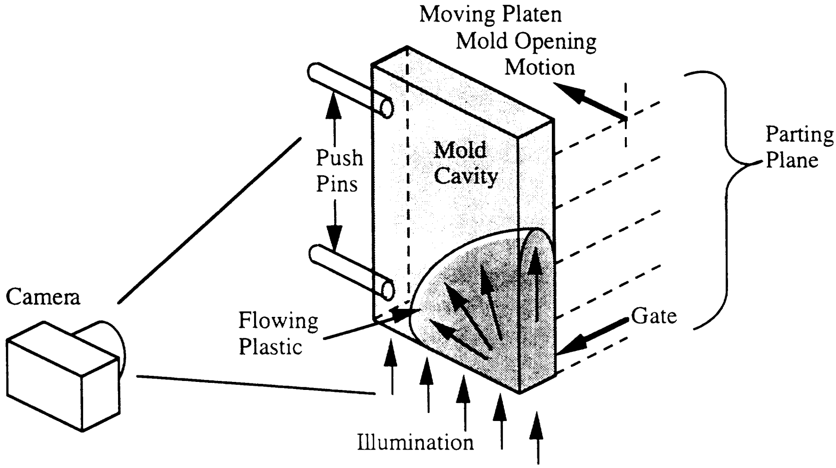

Figure 1. *Melt flow visualization schematic. The liquid plastic enters the rectangular mold at the lower right corner. The mold cavity is contained within the portion of the mold base attached to the moving platen. The flowing plastic is viewed through a window over the planform area of the part. Light may enter or leave the mold through the windows on its top and bottom.*

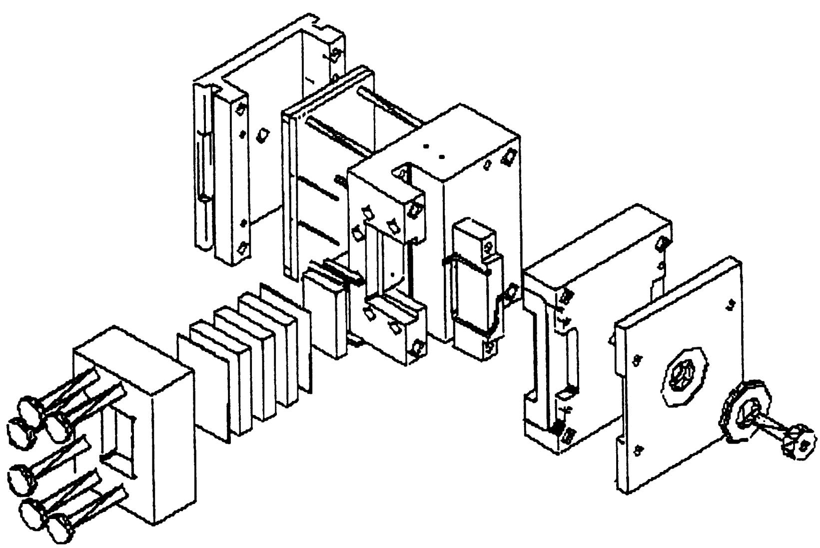

Figure 2. *Exploded view of the mold hardware. The high-pressure window extends to the front left. The moving platen hardware extends to the rear left. The stationary platen hardware extends to the front right.*

polycarbonate and the whole assembly is held in place by a steel brace and six hardened grade-eight 25 mm diameter bolts. The top and bottom walls of the cavity are also transparent. They are formed by rectangular blocks of quartz that are held in place by slots machined into a steel block inserted in the mold base.

This steel insert is another notable feature of the mold design. The insert holds the quartz pieces that form the top and bottom of the mold, and forms the rear face and left side wall of the mold cavity (as viewed through the main window assembly). The insert also contains the runner and the gate which allows great flexibility in the design of the mold cavity. The thickness, length and width of the final part are all controlled by the steel insert. The number, type, size and location of the gates are also determined by the insert. Transducers of various types can be placed on the rear wall of the cavity by modifying the insert. The draft angles on all faces except for the large quartz face are also fixed by the insert. The insert makes the optical access mold a modular design that can easily be adapted for different melt-flow experiments.

The present flow visualization experiment used a high impact polystyrene resin and the following process parameters. The melt temperature was 230°C, the melt injection pressure was 36 MPa and the screw ramming speed was 25 mm/s. The gate was placed along the right hand edge of the cavity 5.5 mm from the lower right corner. The cavity has no draft on any of the faces. This made part ejection difficult but it greatly simplified the computational model of the mold cavity. The mold was neither heated nor cooled for these experiments.

EXPERIMENTAL AND COMPUTATIONAL RESULTS

Photographs of the mold filling process are shown in Figure 3. The advancing plastic front appears as a bright arc in the pictures progressing from the lower left corner to the upper region of the mold. These pictures were taken with a standard 35 mm camera having an internal motor drive capable of taking 3.3 pictures per second. The shutter speed of the camera was insufficient to completely freeze the motion in the first frame [Figure 3(a)], and the detailed shape of the flow front near the left side wall is lost in the later frames because of lighting limitations. Progress of the plastic front beyond Figure 3(e) was not included in this sequence because stray reflections from the illumination source obscured the flow front. While all of the challenges associated with photographing the flow of clear plastic through a 100 mm thick window have not yet been completely surmounted, these pictures do define the melt flow well enough for a few interesting observations and a comparison with mold filling computations. The haze ahead of the plastic front is a vapor precursor that precedes the flowing plastic into the mold. The bright white object inside the flowing plastic near the lower end of the mold is an air bubble. It appears to be almost motionless because it is trapped near the wall of the mold where the flow velocity is small.

A simulation of the polymer flow depicted in Figure 3 was performed using the commercial molding analysis code C-Mold. The results of the simulation are shown in Figure 4. A comparison of the experiment and the simulation shows that the simulation gives the correct overall flow behavior. There are some differences, however. The photos show that the no-slip boundary condition is in effect along the bottom and right side walls. This causes the flow to slow down near the wall and gives the flow front a convex shape near the wall. The simulation predicts a different side wall behavior, particularly along the left boundary. The simulated flow slips along the wall, giving the flow front a concave or straight-line shape at the wall. In effect, the simulation predicts that the flow near the left wall actually

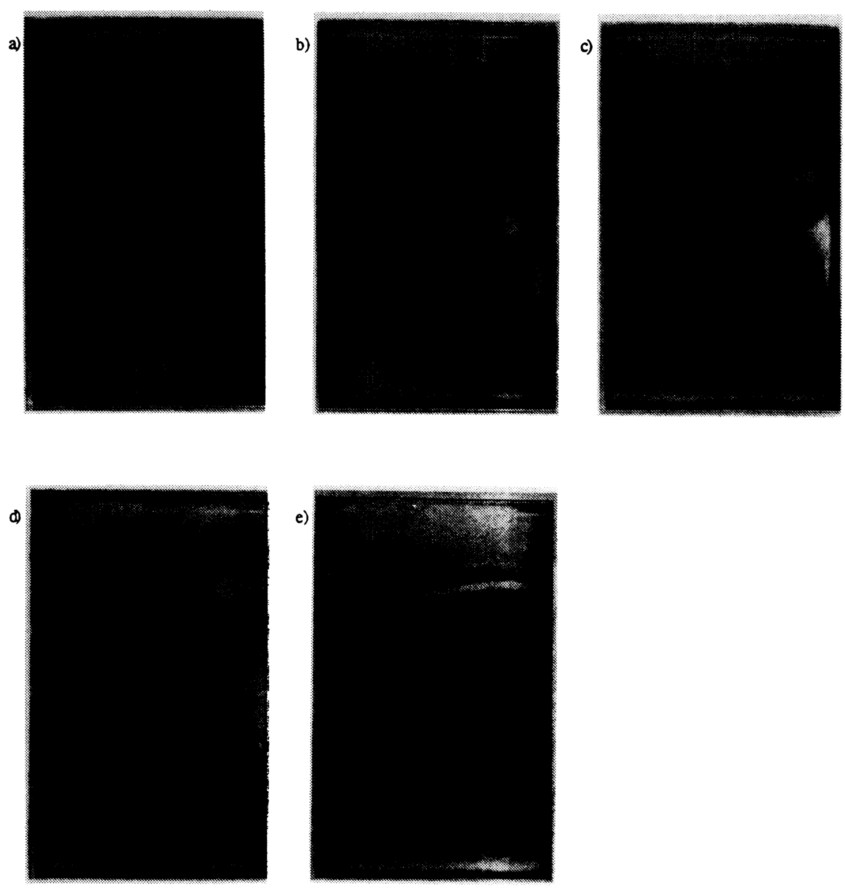

Figure 3. *Photographs of melt flow during injection molding of polystyrene. The sequence progresses from frame (a) to (e). There is approximately 0.3 seconds between pictures. The field of view in each picture is approximately 120 mm × 75 mm.*

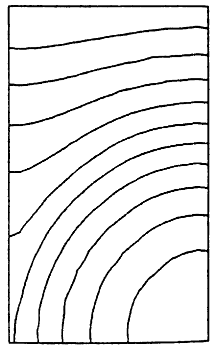

***Figure 4.** Simulation results from a commercial mold filling program for comparison with the visualization experiments.*

leads the flow front, while the flow visualization, and operator observations, support the opposite view.

CONCLUSIONS AND DISCUSSION

This short study has shown that it is possible to visually monitor the progress of the melt front during injection molding under commercially relevant conditions. The findings to date suggest that some three-dimensional effects during mold filling are not captured by currently available computational packages. Additional quantitative work will determine how processing parameters, mold geometry, and melt characteristics influence melt flow. The current mold flexibility afforded by the replaceable cavity insert will allow investigation of weld lines by double gating the existing cavity. Through visualization research of the type presented here (and that forecast for the near future), a more thorough characterization of melt flow during injection molding will be possible so that some of the trial-and-error engineering refinements, which are typically part of industrial molding, may be eliminated. It is hoped that eventually quantitative monitoring of mold filling will be used to confirm, contradict, or identify the accuracy of rheological constitutive models of liquid polymers.

ACKNOWLEDGEMENTS

The project was sponsored in part by Colonial Engineering Inc. through a gift to the Department of Mechanical Engineering and Applied Mechanics at the University of Michigan. The authors wish to thank Cincinnati Milacron and their Michigan distributor, Plastic Provisions, for assistance with the purchase of the injection molding machine. In addition, the authors acknowledge Prof. Ellen M. Arruda for contributions to the text of the introduction.

REFERENCES

1. Bureau of the Census. 1992. *Statistical Abstracts of the United States: The National Data Book,* (U.S. Department of Commerce, Washington, DC).
2. Stoddard, H. 1992. *Wards Automotive Reports,* D. C. Smith (ed.), Detroit, MI: Intertec Publishing, Vol. 67.
3. Dealy, J. M. and K. F. Wissbrun. 1990. *Melt Rheology and Its Role in Plastics Processing,* New York: Van Nostrand Reinhold.
4. Dealy, J. M. 1990. "Nonlinear Viscoelasticity of Polymeric Liquids," in D. D. Kee and P. N. Kaloni (eds.), *Recent Developments in Structured Continua,* New York: John Wiley and Sons, pp. 132–139.
5. Isayev, A. I. 1991. *Modeling of Polymer Processing, Recent Developments,* New York: Oxford University Press.
6. Bird, R. B. and R. C. Armstrong and O. Hassager. 1987. *Dynamics of Polymeric Liquids, 2nd Ed.,* New York: John Wiley and Sons, Vol. 1.
7. McCrum, N. G., C. P. Buckley and C. B. Bucknall. 1988. *Principles of Polymer Engineering,* Oxford: Oxford University Press.
8. Puttre, M. 1993. "Computer-Aided Injection Molding," *Mechanical Engineering,* 115(6):58–62.
9. Yokoi, H., T. Hayashi, K. Tado and N. Morikita. 1988. "Direct Observation of Jetting Phenomena under a High Injection Pressure Using a Prismatic Glass Inserted Mold," *SPE Technical Papers (ANTEC),* 34:329–333.
10. Yokoi, H. and Y. Maurata. 1991. "Visual Analysis of Weld Line Vanishing Process by Glass Inserted Mold," *SPE Technical Papers (ANTEC),* 37:367–371.
11. Yokoi, H., S. Kamata and T. Kanematsu. 1991. "Visual Observation of Three-Dimensional Melt Flow by Gate Magnetization Method," *SPE Technical Papers (ANTEC),* 37:358–362.
12. Yokoi, H. and Y. Inagaki. 1992. "Dynamic Visualization of Cavity Filling Process Along Thickness Direction Using a Laser-Light-Sheet Technique," *SPE Technical Papers (ANTEC),* 38:457–461.