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POLYMER PROCESSING: MODELING AND VALIDATION

edited by
H. P. WANG

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FOREWORD

This volume contains papers presented at the Polymer Processing: Modeling and Validation session, under the sponsorship of the Materials Division, held at the ASME Winter Annual Meeting, San Francisco, December 10-15, 1989. In recent years, polymer processing has been recognized by ASME members as one of the emerging research areas in manufacturing automation. The laminar flow nature of polymer processing renders modeling an attractive approach for tooling design and process automation. Through the fundamental understanding of process mechanics, process modeling can help both the tooling engineer reduce or eliminate costly cut-and-try mold making and the process engineer optimize process control parameters. However, the validity of the assumptions and simplifications used in the model and the accuracy of the materials database have caused some concerns, especially under extreme process conditions. Validation of model predictions has become one of the most critical tasks in any new development of process models, and differentiating the complex interactions between process conditions, design/geometry, and materials has become one of the major issues in the validation task. A quantitative assessment of modeling accuracy can sometimes be very difficult and expensive. Research work in this validation area definitely needs to be strengthened in the process modeling community.

H. P. Wang
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CONTENTS

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MIXING IN SINGLE SCREW EXTRUDERS

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ABSTRACT

The development of polymeric materials has grown at a rapid pace over the last few decades. Many new polymer blends in the form of mixtures of various polymer components have been available in the marketplace and have replaced traditional materials like metal or glass in many applications. The quality of polymeric resins or blends is very often determined by the uniformity of additives in the base resin or dispersed polymeric components in the polymer matrix. In the process of making finished resins or blends mixing becomes very critical.

In this paper mixing visualization is carried out by inspection of carbon black dispersion in the base resin in the extrudate. Two types of the mixing-pin screws in a 2.5-inch single screw extruder are used in this study: one with pins installed around the circumference of the screw channel without interrupting flights and another with pins across interrupted flights allowing the pins to make a "continuous" ring. Experimental observations show that screws with pins implemented in non-interrupted flights give poor mixing. With pins installed through interrupted flights the screws can produce good mixing results but with reduced throughputs. Results of visualization experiments provide guidance in the design of mixing devices in screw-extrusion processes.

Introduction

The development of polymeric materials, particularly in the area of polymer blends, composites or alloys, has grown extensively over the last few decades. Many traditional materials such as metal, ceramic, glass and wood are replaced by polymers because of their low manufacturing cost, light weight and superior properties.

There are very few commercial plastic resins in the form of "pure" polymers. In order to make final products associated with certain properties, commercial resins are usually mixtures of base resins with various additives such as colorants, thermal and UV stabilizers, fillers, plasticizers, processing aids or others. The process of incorporating additives into base resins is called compounding. In addition to many single-component polymers there are many blends and composites which are mixtures of multi-component polymeric resins. The process of mixing two or more different polymers to make new materials is called blending.

Qualities of polymer resins or blends are usually related to the uniformity of additives being mixed in the base resins or uniformity of dispersed polymer components in the polymer matrix. Therefore mixing becomes very important in determining the uniformity of resin or blend properties in compounding or blending processes.

Rubber compounding was practiced about a century ago although fundamental principles of mixing for this process were not attempted until two or three decades ago. Similarly, during the development of thermoplastic materials, the understanding of mixing theory in compounding and blending lagged far behind its practice.

Because of the nature of high viscosities of polymer melts in processing operations, mixing is primarily dominated by convection[1]. Convection is basically the movement of fluid particles, blobs or solid clumps from one location to another. Under the laminar convective condition mixing is induced by complicated shear, elongation or squeezing flow which occurs in commercial processing equipment. The development of mathematical modeling for mixing during polyer processing is extremely complicated. It is primarily due to the large number of unknown parameters and boundary conditions. For instance, properties of interfacial area in polymer blending processes are usually unknown or difficult to measure. Furthermore, lack of connection between molecular and macroscopic theory makes the evaluation or modelling of mixing more difficult. As a result, existing models or reported theories are often too unrealistic to explain the complexity of real mixing processes especially in the area of multi-component polymer systems. Therefore experimentation is still an indispensable way to characterize mixing processes.

The mechanisms of mixing are a combination of the mechanical movement of the mixing device and flow-induced deformation of the polymeric material in the processing equipment. Since extruders are almost exclusively used for compounding and blending operations, designing mixing devices associated with screw configurations has become a common practice for improvement of both plasticating and mixing polymeric materials.

One of the most popular types of processing extruders for compounding and blending is the single screw extruder. The development of various types of mixing devices combined with screw element designs has reached a certain level of success in making complicated polymer blends in single screw extrusion processes. Some of the most widely adopted units, like Maddock mixing unit[2], mixing pins or mixing rings, have been in practice for several decades. Each design has its own merit in certain applications. For instance, mixing pins implemented along the circumference of the screw root can provide dividing mechanism for the flow of polymer melt and hence improve the degree of mixing. Mixing pins can be easily installed in the screw root and can also be removed without much difficulty.

In this paper screws with various mixing pin arrangements are used for mixing visualization studies. Results of the mixing effects under different arrangements of the pins in the screw are compared and discussed. It is also expected that fundamental studies of mixing phenomenon will provide useful guidance in the design of mixing devices in the screw extrusion process.

Experimental

Although there are many ways to measure the quality of mixtures and to evaluate the performance of mixers, most practical methods are still empirical. One of the most widely adopted methods of determining the degree of mixing in extrusion is to evaluate striation distribution or thickness of colorants or tracers in the extrudate. Visual observation may enable one to discriminate good mixing from poor mixing by inspecting the degree of agglomeration of the dispersed phase in the continuous phase.

Mixing of low molecular weight additives or colorants in polymer melts is generally satisfactory in single screw extruders. Most problems occur when incompatible polymers are to be mixed together. Fine dispersion of the minor component in the matrix requires the generation of interface as well as the break-up of the minor component. To study the mixing of two polymers, we chose the high impact polystyrene (HIPS) as the major continuous phase and polycarbonate resin as the minor dispersed phase. Polycarbonate was preblended with 0.6% by weight carbon black which serves as the tracer in the extrusion process.

The extruder used in the experiments is a 2.5-inch, 24:1 L/D single screw extruder (where L is the length and D is the internal diameter of the barrel). Figure 1 shows a schematic diagram of a plasticating extruder.

Three single stage, 24:1 L/D screws with the same design but different arrangement of mixing pins are used in the test. Screw No. 1 has two single rows of pins installed in the metering section. The flight intersected with the ring of mixing pins is continuous, not interrupted. The even-spaced pins in the circumference of the screw root stop near both sides of the continuous flight. Screw No. 2 has four single rows of pins in the metering section. Near the intersections with the mixing pins the screw flights are interrupted so that "continuous" rows of pins along the circumference of the screw root are established. Screw No. 3 is arranged in the same way as screw No. 2 with interrupted flights but two double rows of pins in the metering section.

The diameter of each pin is 1/8-inch. The gap between two pins is about the same as the pin diameter. In screw No. 3 where a double-row of pins are arranged, the pin and gap are aligned alternately between the two adjacent rows. The height of the pin is the same as the flight height. Figure 2 shows a section of a schematic pin screw.

The feedstock was prepared by dry-blending HIPS pellets with a small amount of polycarbonate pellets in which about 0.6% carbon black was added as the tracer. The mixed pellets were flood-fed into the extruder by gravity from the hopper. Experiments with two screw speeds, 50 RPM and 100 RPM, were conducted for each screw.

During the plasticating operation barrel temperature zones were set at 250^{o}C. An adaptor with 1.25-inch internal diameter was connected to the end of the barrel. The extrudate as a 1.25-inch diameter rod was collected in each run. The cross section of each sample was prepared and polished for visual inspection. The degree of mixing associated with each screw was determined by visual inspection of color uniformity in the cross sectional area of each sample.

Results and Discussions

The degree of mixing in screw extrusion processes can be visually determined by the uniformity of color tracer in the cross section of the extrudates. If a uniform grey color is seen in the entire area, the mixing of the black polycarbonates in the opaque HIPS is considered good. Partial mixing can also be distinguished as striations in dark black color appearing in the light grey area. Poor mixing is represented by separated area of grey, opaque and dark striations on the surface.

Figure 3 shows the mixing pattern in the extrudate produced from screw No. 1. Figures 3a and 3b represent patterns of the rods produced at 50 RPM and 100 RPM respectively. The mixing is apparently very poor. As seen in Figure 3a, many distinguishable striations in the grey area indicate that only partial mixing is achieved with non-interrupted flight, pin-mixing screws at lower screw speed. At higher screw speed, thicker striations as well as separated grey and opaque areas are observed showing that mixing becomes worse under this condition.

The degree of mixing is much improved when the pin-mixing screws with interrupted flights are used in the extrusion. Figures 4a and 4b show cross sections of the extrudate produced in screw No. 2 at 50 RPM and 100 RPM respectively. Figures 5a and 5b are pictures of those produced in screw No. 3 at 50 and 100 RPM respectively.

The pin-mixing screws with non-interrupted flights produce poor mixing as shown in Figures 3a and 3b. The degree of mixing is dramatically improved with interrupted-flight screws, as one compares Figure 3 with Figure 4. In Figure 4 one can still see some dark colored rings in the cross-sectional area, which indicates that the laminar flow pattern carried over in the screw-rotating barrel still inhibits dispersive mixing. This defect, however, can be reduced by installing a double row of pins in the screw metering section. As shown in Figure 5, the mixing is better than that shown in Figure 4 because the dividing function in the double-row pin design can further enhance the mixing. It must be noted that mixing pins arranged in double rows can only become effective in the interrupted screw designs.

As mentioned earlier, mixing is induced by deformation of particles resulting from the flow field of the matrix. The interfacial area between the particle and matrix is generated by the total strain applied on the particle. If the dispersed phase and the continuous phase are compatible, the interfacial force is reduced which minimizes the resistance to the particle deformation in the flow field. As a result, mixing is relatively easy and homogenized blends can be made. Most commercial blends or alloys, however, are produced from incompatible components. In many commercial processing operations not only the generation of interface but also the break-up of particle striations are important. Therefore in addition to the extensive shear deformation, the introduction of the interruption mechanism of the mixer design is necessary to provide better mixing. Screws with mixing pins and interrupted flights are just some examples in this category.

In the mixing practice, material properties of both phases are also important and can influence the deformation and particle break-up. For example, Taylor [3,4] explained that the shearing force which tends to stretch the particle for interface generation is balanced by the interfacial forces that minimize the total interfacial area. Parameters including viscosity ratio of dispersed-to-continuous phase, interfacial tension, shear rate and others are important in the mixing correlation [5]. Such fundamental knowledge of idealized mixing, however, is inadequate to distinguish the degree of mixing as shown in the color-distribution studies in this paper. On the other hand, the flow fields in advanced compounding or blending equipment are so complicated that detailed particle/matrix mixing behavior, especially in the multi-component systems, is difficult to simulate mathematically.

The flow of high viscosity melts in an extruder follows a laminar pattern unless disturbances or interruptions are introduced. In screw No. 2 the drag flow in the metering section is confined by the screw flight which is basically a "non-disturbed" down channel flow. The mixing pins provide some dividing mechanism but only divide the down channel flow in this case. The division of the strong laminar flow down the channel is not sufficient to disturb flow patterns and hence mixing is not good enough for the system of polycarbonate dispersed in HIPS.

If the flight is interrupted, significant back flow through the flight cut occurs. Mixing pins in this area provide ways to divide not only the down channel flow but also the cross channel flow. The forward and backward flow across the pins generates a very good mixing mechanism for the multi-component system. Such a vigorous mixing can be further refined if a double row of mixing pins is implemented. Comparing Figures 4 and 5, one can see that the grey color is more uniform if a double-row pin screw is used.

A significant amount of back flow occurs through the interrupted flight of the mixing screw, therefore the delivery rate, or the net downstream pumping capability, of these screws is reduced accordingly. This is the main drawback of using the interrupted-flight screws in commercial compounding operations. Table 1 shows the throughput under different screw-operating conditions.

Another important observation of laminar flow mixing is that mixing is generally a weak function of screw speeds. Higher screw speed does not often provide better mixing in multi-component-polymer-blending operations. As shown by comparing Figures 3a and 3b, better mixing was not achieved simply by increasing the bulk shear rate.

Summary

A mixing visualization study was carried out to demonstrate important factors governing mixing behavior in a single screw extruder. Based on experimental observation, it was concluded that effective ways of improving mixing in a laminar flow system are mixing devices or screw designs which can generate interruptions or disturbances of the flow pattern in an extruder.

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Table 1. Throughput (lb/hr)

	Screw No. 1	Screw No. 2	Screw No. 3
50 RPM	171	72	88
100 RPM	309	141	142

Figure 1. A schematic diagram of a plasticating extruder

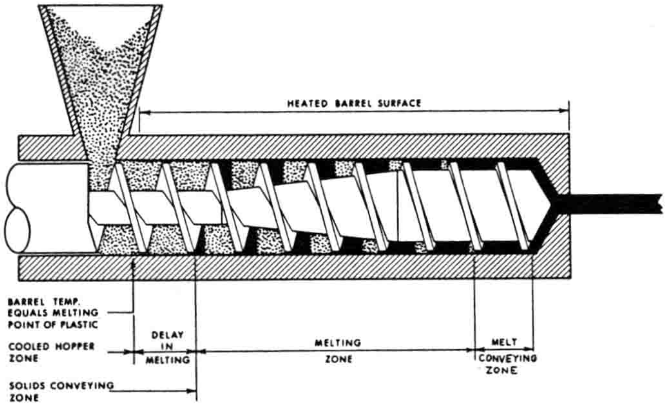
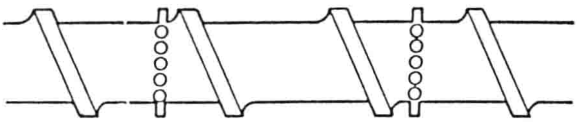
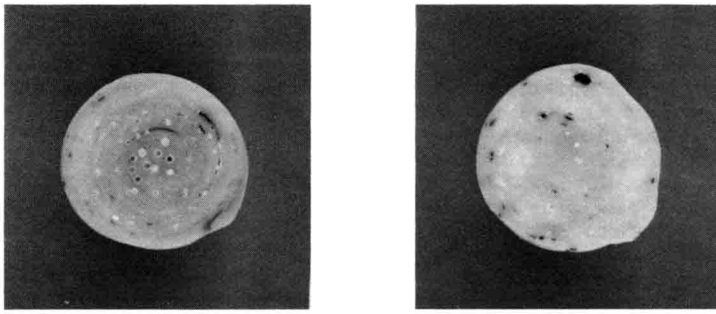


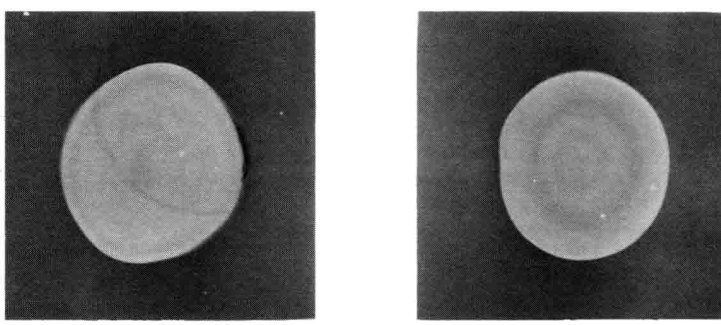
Figure 2. A schematic picture of a mixing-pin-screw section



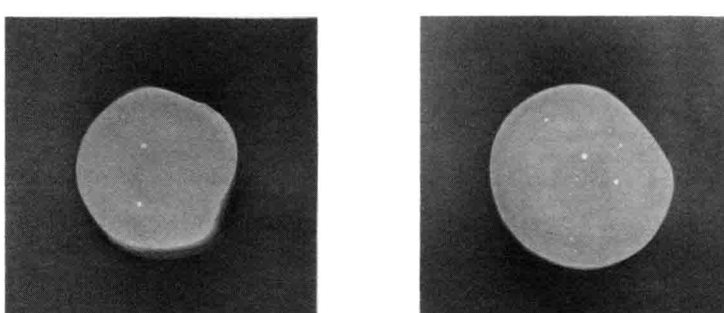
Figures 3a. & 3b. Cross sectional areas of extrudates in screw No. 1



Figures 4a. & 4b. Cross sectional areas of extrudates in screw No. 2



Figures 5a. & 5b. Cross sectional areas of extrudates in screw No. 3



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EXPERIMENTAL AND MATERIAL FACTORS TO CONSIDER IN THE VERIFICATION OF CAE INJECTION MOLD FILLING SOFTWARES

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ABSTRACT

The paper focuses on the quantitative assessment of the CAE mold filling softwares. Injection molding experiments with a high impact polystyrene and a well instrumented, complex test mold were performed on a 3200 kN (350 ton) injection molding machine using different injection speeds. The precautions necessary to ensure accurate measurements of the input data for the mold filling softwares such as the fill time, injection speed profile, melt temperature, and mold temperature are discussed. The influence of the material properties, particularly the rheological data, on the simulation results is examined. C-FLOW, a commercially available injection mold filling software, is used as an example. The pressure results of the CAE simulations are compared with the experimental data.

INTRODUCTION

A number of CAE mold filling softwares (1) are now commercially available and used as aids by plastics engineers to design injection molds. Most of these softwares are based on the mathematical modeling of polymer melt flow during injection. In order to reduce the degree of complexities in solving the governing partial differential equations of the conservation of mass, momentum and energy, a number of simplifying assumptions including the melt being inelastic and incompressible are made in the mathematical modeling. The results obtained from the CAE mold design softwares need to be assessed both qualitatively and quantitatively for the materials, molds, and molding conditions of interest. The qualitative assessment normally involves a comparison of the experimental short shots with the advancement of flow fronts predicted by the mold design software under given injection molding conditions for a part geometry. Available information in the literature (2,3) centers mostly on the qualitative assessment of various mold design softwares. To determine the limitations and accuracy of any mold design software particularly for production applications, each CAE software should be evaluated quantitatively through injection molding experiments on molds of industrial significance. This paper describes how experimental and material factors can affect a quantitative assessment of injection mold filling softwares.

CAE MOLD DESIGN SOFTWARE, MOLD AND MATERIAL

A number of commercial and proprietary mold filling softwares were evaluated and used at the David Sarnoff Research Center, formerly RCA Laboratories, to design injection molds of varying sizes and complexities (4,5). For this paper, C-FLOW (6) of Advanced CAE Technology, Ithaca, New York, a commercially available injection mold filling analysis software based on the two-dimensional non-isothermal and non-Newtonian melt flow using finite element and finite difference numerical methods was chosen as an example.

The test mold used in the injection molding experiments contained 28 bosses and 8 ribs of varying shapes and sizes typically found on the production molds. The mold was designed to run on a production size injection press. The melt delivery system starting from the injection nozzle consisted of the sprue, runners and gates of typical shapes and sizes found in the production molds. With the help of shut-offs in the runner system, the mold cavity could be filled with a single gate or multiple gates. The mold was also designed to take inserts to accommodate various possible complexities in the molded part geometries. It could be used with either a cold or hot runner system. The mold was instrumented with 7 piezoelectric Kistler pressure transducers, type 6155 with a 2.5 mm diameter quartz measuring element. As shown in Figure 1, the sprue transducer was placed as close to the sprue tip as physically possible, and the other six transducers were so located in the mold cavity as to detect the beginning and the end of mold filling for different gate combinations. The sprue transducer was 5 cm from the nozzle of the injection unit. The cooling channels of the test mold were designed for a uniform mold temperature distribution according to a mold design software. The mold surface temperature variation was determined by an infrared imaging method to be less than 5° C.

Huntsman 351, a flame retardant high impact polystyrene, was the plastic used in the injection molding experiments. The material properties relevant to the CAE injection mold filling softwares are described in a latter section of this paper.

CAE INPUT AND RESULTS

The CAE mold filling software input information consists of the mold geometry, the experimental processing conditions and the material properties. The processing conditions include mainly the mold fill time, injection speed profile, melt temperature, and mold temperature. The material properties needed for the CAE mold filling analysis are the rheological and thermal data. The special care needed to determine the processing parameters, and the influence of the material properties on the CAE simulation results are the focal topics of this paper.

Mold Geometry

The test mold was a 20 cm by 40 cm rectangular mold with two 2.5 cm wide tracks of 2.3 and 3.3 mm thick bases. Figure 1 shows the details of the test mold, including the sprue, the runner system, the bosses and the ribs. The finite element mesh points used in the CAE analysis are also shown. The model consisted of 536 nodes and 830 triangular elements. Thin shell elements were used to represent the base and the ribs, and beam elements to represent the bosses, the sprue, and the runner system.

Experiments

The injection molding experiments were performed on a microprocessor controlled 3200 kN (350 ton) Battenfeld injection molding machine, using a wide range of barrel temperatures and injection speeds. The overall CAE mold filling software assessment comprised of studying the filling behavior of the test mold through a cold manifold system and the use of a single gate, multiple gates, and combinations of gates. The present discussion, however, focuses on the injection through a single 6 mm diameter gate, using a moderate injection speed of 60 mm/s.

Figure 2 shows the experimental curves of injection speed, ram position, sprue pressure, and cavity pressures measured at four transducer locations during the mold filling phase of an injection molding cycle. It is essential to select and calibrate the instrumentation carefully to ensure the accuracy of these data. The scope of this paper, however, will be limited to a discussion on the procedures for obtaining accurate process input data for a mold filling analysis.

A. Fill Time

Fill time is the elapsed time between the start and the end of the fill of a particular portion of the mold. It is perhaps the most critical process input data in a mold filling analysis. The accuracy of the fill time affects the calculated results directly. Fill time can be accurately determined if the mold is instrumented with well-placed pressure transducers. Some factors which might affect the determination of the fill time are discussed below.

1. Start and end of fill. The start of the fill time is often chosen as the moment when the polymer melt enters the gate, and the end of the fill time as the instant when the mold is completely filled. The starting point of the mold filling process was selected in this study as the moment when the melt front reached the sprue tip. Whether the sprue tip or the gate is selected as the starting point, it is not easy to determine this accurately in practice because a device for melt front detection, such as a pressure transducer, often cannot be placed at the exact location of interest. The ram position, however, can become a useful tool in estimating fairly accurately the time when the melt front reaches a certain point in the mold. The ram stroke is directly proportional to the volume of the melt being injected into the mold, assuming the melt in the barrel is incompressible. For instance, knowing that the volume of the 5 cm long conical section from the sprue tip to the sprue transducer location shown in Figure 1 was 7% of the total volume of the sprue and runner system, the ram position could then be used to determine the time when the molten plastic entered the sprue tip by extracting from the times when the melt front reached the sprue and the gate transducer locations.

The end of fill of a mold is prominently recognizable by a sharp rise in the cavity pressures, as seen in Figure 2. The end of fill was taken as the time when the pressure detected by the transducer located at the farthest point from the gate showed the steepest increase. Particular attention was paid to making sure the end of fill was reached before the injection was stopped, as indicated by a sharp decrease in the "injection speed" in Figure 2. In addition, to ensure that the pressure rise at the end was due solely to mold filling, the experiments were conducted using no holding pressure.

2. Data collection rate. Accurate determination of the fill time depends also on the data collection rate. The fill time of the 250 gram part ranged from over 10 seconds at slow injection speeds to a fraction of a second at high speeds. A 200 samples per second data collection rate was used to ensure that the fill time was determined to an accuracy of 0.01 second.

3. Runner and gate size consideration. Selecting the gate as the starting point of a mold filling analysis may not be ideal, particularly for a mold with small runner and gate. The effect of viscous heating may make the actual melt temperature significantly higher than the air shot melt temperature. Considerable error can be introduced if the air shot temperature is used as the melt temperature in a mold filling analysis starting from the gate. The possibility of such an error is eliminated if the sprue tip is chosen as the starting point of the mold filling analysis.

B. Injection Speed

A ram position signal differentiator was built and used to convert the ram position data to injection speed. The injection speed data made possible the option of using either a constant or variable injection speed profile in the mold filling analysis. It can be seen in Figure 2 that the injection speed profile showed an accelerating flow during the filling of the sprue and runner system, and a constant volumetric flow was attained only after the melt had entered the gate of the mold.

C. Melt Temperature

Several attempts were made to measure the in-mold melt temperature by thermocouples. Using a thermocouple placed just below the surface of the mold or an ejector pin was not satisfactory because of the long temperature response time. Exposing the thermocouple to the in-coming melt in the mold cavity for accurate melt temperature measurements would require fitting the mold with a cumbersome mechanism to retract the thermocouple before the plastic solidified. The air shot temperature was used as the melt temperature in this work. The air shot temperature depended on such variables as the material, barrel temperature, injection speed, screw rotational velocity, back pressure, and nozzle diameter. Since the mold filling analysis discussed here used the sprue tip as the starting point of the simulation, the air shot temperature reflected the accurate melt temperature. The temperature was measured with a thermocouple made of 0.09 mm iron-constantan wires protected inside a hypodermic needle sleeve.

D. Mold Temperature

The mold temperature was monitored by two methods: infrared imaging and thermocouple. Using an AGA Thermovision model 782, the mold surface temperature was photographed and videotaped when the mold opened to eject the molded parts. In addition, an iron-constantan thermocouple was placed below the mold surface at the gate to monitor the mold temperature during the whole injection molding cycle. Depending on the cooling channel design and the plastic part thickness variations, the mold surface temperature could be quite uneven. A variable mold surface temperature profile consisting of up to ten zones can be used in a mold filling analysis. The mold temperature also varied cyclically with time as an injection molding cycle progressed through its different stages. Thus, the question of whether to use a constant or variable mold temperature, or the temperature measured at which point of a molding cycle to use, as the mold temperature input in a mold filling simulation can be an interesting topic in itself. The coolant temperature was used as the mold temperature in the present work.

Material Properties

Commercially available mold filling softwares have databases which contain the material properties of many generic plastics. These material properties, however, are not accurate enough for a quantitative assessment of the mold filling softwares. Huntsman 351 high impact polystyrene used in the injection molding experiments was therefore fully characterized in-house for its thermal and rheological properties.

A. Thermal Properties

The input data for the material thermal properties are the density, specific heat, and thermal conductivity. Figure 3 shows the melt density variations with increasing pressure for Huntsman 351 polystyrene at 240° C. The melt density measured in the temperature range between 200 and 260° C was largely dependent on the pressure and not the temperature. Figure 4 shows the specific heat of polystyrene as a function of temperature, with the glass transition around 100° C clearly noticeable. Unlike the melt density, the specific heat was largely dependent on the temperature. The line source method developed by the Cornell University (7) was used to measure the thermal conductivity of the molten polystyrene at 240° C. Figure 5 shows the temperature variations in the melt during transient heat conduction. The temperature vs. time data were used to determine the thermal conductivity of the melt.

The thermal properties are input in the mold filling software programs as single point values. The data shown in Figures 3 to 5 help one determine the appropriate single point values of the melt density, specific heat, and thermal conductivity at the relevant pressure or temperature to use in the simulation.

B. Melt Rheology

The most fundamental assumption made in the currently available CAE mold filling softwares is that the plastic melt is inelastic. This means the only rheological data needed for simulation is the viscosity of the mold filling plastics. The influence of melt rheology on the mold filling simulation results was studied by examining the specific effects of the use of apparent or true viscosity, the rheological models used to represent the viscosity data, and the temperatures at which the viscosity was measured.

1. The influence of the use of the apparent or true viscosity. Either a capillary or a slit rheometer can be used to measure the viscosity of polymer melts in the range of high shear rates relevant to the injection molding operation. The capillary rheometer is the more common of the two. For the present work, the viscosity was measured by the capillary flow method on a Goettfert Rheograph 2001, which could be used as either a capillary or a slit rheometer. The capillaries had a diameter of 1 mm with L/D of 10, 20 and 30. The raw data are known as the apparent viscosity. After the data are corrected for the end effect by the Bagley correction and for the non-Newtonian effect by the Rabinowitsch correction, they become the true viscosity. The corrections result in lower viscosities. Figure 6 shows the apparent viscosity of Huntsman 351 polystyrene measured in the shear rate range between 10 and 10,000 1/s and for the temperatures ranging from 180

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