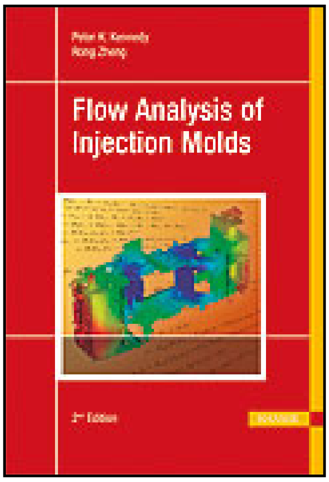

Sample Pages

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Flow Analysis of Injection Molds

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1 Introduction

Automotive and consumer electronics are two disparate industries that rely heavily on injection molding. Moreover, they both involve updating of products on a regular basis. Both these industries have been leaders in the development of *concurrent engineering*, meaning the parallelization of tasks from inception to manufacture. Regardless of the degree to which concurrent engineering is practiced, there is no doubt that simulation is a valuable aid in linking design to manufacture. For injection molding, the benefit of simulation is based on the fact that it is cheaper and faster to avoid problems in the design phase than to fix them in production.

Simulation of injection molding, particularly flow analysis, has had a major impact on industry. Indeed, the editors of *Plastics Technology* magazine, a leading industrial journal, proposed a list of the fifty most important innovations in the plastic industry [264]. Number one was the reciprocating screw injection molding machine, while simulation of injection molding was listed nineteenth. Whether one agrees with the editor's ranking or not, simulation of injection molding has been an outstanding aid to industry.

In this chapter, we review the molding process, terminology, and simulation so as to provide a background for the remainder of the book.

1.1 The Injection Molding Process

Injection molding is a cyclic process. Initially, the mold is closed to form the cavity into which the material is injected. The screw then moves forward as a piston, forcing molten material ahead of it into the cavity. This is the injection or filling phase. When filling is complete, pressure is maintained on the melt and the packing phase begins. The purpose of the packing phase is to add further material to compensate for shrinkage of material as it cools in the cavity. At some time during packing, the gate freezes and the cavity is effectively isolated from the pressure applied by the melt in the barrel. This marks the beginning of the cooling phase in which the material continues to cool until the component has sufficient mechanical stiffness to be ejected from the mold. During cooling, the screw starts to rotate and moves back. The rotation assists plastication of the material and a new charge of melt is created at the head of the screw. When the molded part is sufficiently solid, the mold opens and the part is ejected. The mold then closes and the cycle begins again.

In summary, the injection molding process is characterized by the following phases:

1. Mold closing
2. Injection
3. Packing
4. Cooling

5. Plastication and screw back
6. Ejection

Most effort in computer simulation has been devoted to phases 2–4. There have been significant advances in modeling plastication [162, 163, 173, 245, 261, 352, 387, 408] but generally, for molding simulation, it is assumed that the melt enters the cavity with a prescribed flow rate or pressure and a uniform temperature. While this may be reasonable, the ultimate goal of simulation is to predict the properties of the molded material, both during and after the molding process. This requires a deep understanding of crystallization for semi-crystalline materials. Vleeshouwers and Meijer [389] reported that the effect of shear on crystallization of isotactic polypropylene at 200°C, was still evident after a period of 30 min with the sample maintained at 200°C . Hence the plastication stage may be ultimately very important. Simulation of the ejection phase requires accurate shrinkage analysis and complex boundary conditions for the frictional resistance of the part on the core. Again, advances have been made in these areas [118], but today no simulation combines all these effects.

Readers of this book should know the basic terminology of the molding and simulation industry as explained in [31, 333]. For completeness we provide a very brief overview of some key concepts below.

1.2 Molding Terminology

In order to understand the molding process, it is important to define some basic terms. When we speak of a "mold" we are referring to a complex electric/mechanical assembly. There may be electrical heating elements within the mold, for some materials. There will certainly be some temperature regulation system consisting of a network of fluid channels. Fluids may be water, glycol/water, or oil. These may be used for both cooling the melt after injection or increasing the temperature of the mold. There may also be inserts of varying conductivity or even mechanically actuated parts of the mold that create holes or special features.

In the simplest case, the mold comprises two halves. One of these is called the *fixed side* or *cavity side* and is held fast to the injection molding machine. The other is the *moving side* and moves in one direction to form the mold cavity and in the opposite direction to allow ejection of the part.

These ideas are presented in Figure 1.1 where we depict a simple two-cavity mold. By "two cavity" we mean that two moldings will be produced each cycle—in this case two hemispheres. In this case the moldings are of the same shape. However that is not necessarily the case in reality. It may be that each molding is of different shape. Moreover, while we have shown just two cavities, it is possible that there may be many more cavities.

Despite its simplicity, Figure 1.1 illustrates some important terminology. In particular, the concept of mold core and cavity. The mold cavity is fixed to the molding machine whereas the mold core is able to move back as the mold opens. Usually, the molding will shrink onto the mold core, and so will be attached to the core, as the mold opens. Ejection of the part is done by mechanical or pneumatic means.

Note also the sprue. This is the channel by which melt from the injection machine flows into the mold. Figure 1.2 illustrates some further terms, namely runners and gates. Runners transfer the melt from the sprue to the cavities. At the entry to each cavity is an area called the *gate*. The gate is generally much smaller in diameter that the runner. It allows the molded part to be removed easily from the runner system. It is important to realize that the properties of the melt fed into the cavities will depend on the flow rate through the sprue, runners, and gates. This in turn will affect the properties of the material in the cavities during and after molding. Hence a comprehensive simulation should incorporate the entire system; within and from the molding machine, into the sprue and runners, through the gates, and finally into the cavity. While some commercial codes claim to do this, their analysis is subject to conditions that overlook some of these aspects.

Our depictions in Figures 1.1 and 1.2 show what are known as cold sprues/runners. In practice, since the molding is the item of value, the sprue and runner system become scrap material. This material may be recycled however. An alternative method used in large molds, or molds with many cavities, it to use *hot runners*.

Hot runners use heating elements to maintain the melt at an optimum temperature prior to injection into the mold. They are frequently used in large molds, such as large automotive components like bumpers or large panels, or multi-cavity molds, such as bottle tops. Cold or hot runners obey the same physical laws from a simulation viewpoint. The difference is in the boundary conditions of the governing equations.

1.3 What is Simulation?

Simulation of injection molding involves using a computer to solve a set of equations, and their associated boundary conditions, that constitute a mathematical model of the molding

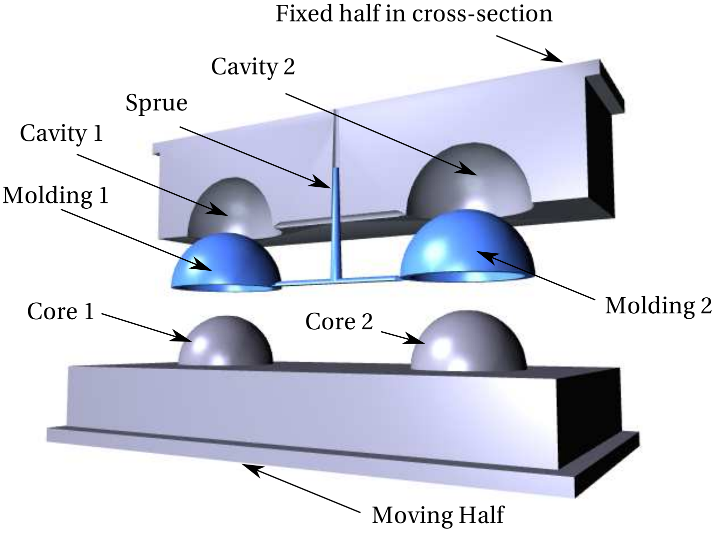

Figure 1.1 A simple two-cavity mold

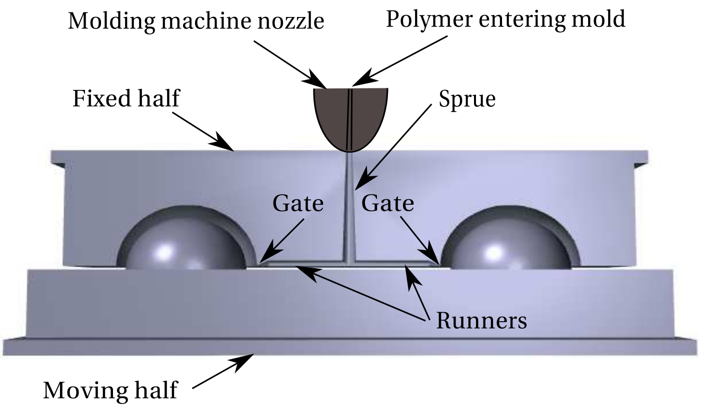

Figure 1.2 A simple two-cavity mold showing runners and gates

process. Generally speaking, today's simulations lead to a huge amount of calculated data that are frequently displayed as colored contour plots of some particular variable of interest, such as:

- fill patterns
- pressure distributions
- shrinkages
- warpage of the component under consideration

In this book we do not attempt to interpret or discuss these results. Shoemaker [333] and Beaumont et al. [31] provide background for the interested reader. Moreover, they provide information on the molding process and industry practice.

1.4 The Challenges for Simulation

While the description of the process in the previous section appears straightforward there are complications, namely:

- the nature of injection molding, in particular the basic physics of the process
- the properties of the material
- the geometric complexity of the mold

We now briefly introduce each of these as background to the problems associated with simulation and discussed in this book.

1.4.1 Basic Physics of the Process

The filling phase is characterized by high flow rates and hence high shear rate. During mold filling, the molten material enters the mold and convection of the melt is the dominant heat transfer mechanism. Due to the rapid speed of injection, heat may also be generated by viscous dissipation. Viscous dissipation depends on both the viscosity and deformation rate of the material.

Viscous heating may be most apparent in the runner system and gates where flow rates are highest, however, it can also occur in the cavity if flow rates are sufficiently high or the material is very viscous.

In addition to forming the shape of the part to be made, the mold causes solidification of the material. Heat is removed from the melt by conduction through the mold wall and out to the cooling system. As a result of this heat loss, a thin layer of solidified material is formed as the melt contacts the mold wall. Depending on the local flow rate of the melt, this "frozen layer" may rapidly reach equilibrium thickness or continue to grow thereby restricting the flow of the incoming melt. This has a significant bearing on the pressure required to fill the mold and an important role in shrinkage and warpage prediction. When the cavity is volumetrically filled, the filling phase is complete but pressure is maintained by the molding machine. This is the start of the packing or holding phase.

Since the cavity is now full, mass flow rate into the cavity is much smaller than during injection. Indeed, further flow is due to shrinkage of the material and consequently both convection and viscous dissipation are minor effects—though they can be important locally such as at the gate or in a thin region that feeds a thicker region. During packing, conduction becomes the major heat transfer mechanism and the frozen layer continues to increase in thickness. At some time, the gate will freeze, thereby isolating the cavity from the applied pressure. Conduction is still the dominant heat transfer mechanism as the material solidifies and shrinks in the mold. It is possible that the material will pull away from the mold wall during this time [43, 76]; a condition that greatly complicates the calculation of the temperature of the material whilst in the mold. Finally, when the part is sufficiently solidified, it is ejected from the mold.

To summarize then, we see the injection molding process involves several heat transfer mechanisms, is transient in nature, and involves a phase change and time-varying boundary conditions at the frozen layer in filling, packing, and during cooling. While these considerations are substantive, simulation of the process is further complicated by material properties and the geometry of the part.

1.5 Why Simulate Injection Molding?

The previous section provides some feeling for the complexity of the molding process. It is no surprise that part quality is related to processing conditions. Indeed, the notion that processing has a dramatic effect on the properties of the manufactured article has been known since plastic processing began. In practice, the relationship between process variables and article quality is extremely complex. It is very difficult to gain an understanding of the relationship between processing and part quality by experience alone. It is for this reason that simulation of molding was developed, and it is interesting to note that CAE has been much more successful in injection molding than in other areas of polymer processing.

The last point requires some explanation. Many polymer forming processes are continuous and, although the process physics may be complex, the die is generally quite simple and inexpensive to make. Moreover, there is considerable flexibility in changing process conditions. For blow-molding and thermoforming, the cost of tooling is relatively inexpensive. In fact the cost of a blow-molding mold can be as low as one-tenth that of an injection mold for a similar article [127]. Moreover, blow-molding machines provide the operator with enormous control so problems can often be solved on the factory floor.

By contrast, in injection molding, problems experienced in production may not be fixed by varying process conditions as with other processes. While there is scope to adjust process conditions to solve one problem, often the change introduces another. For example, increasing the melt temperature, and so decreasing the viscosity of the melt, may cure a mold that is difficult to fill and that is flashing slightly. The increase in temperature may, however, cause gassing or degradation of the material that leads to visual imperfections on the product. The fix may be to increase the number of gates or mold the part on a larger machine. Both of these are economically unfavorable. The first, involving significant retooling, is also costly in terms of time, and the second will erode profit margins as quotes for molding were based on the original machine, which would be cheaper to operate. On the other hand, simulation can be performed relatively cheaply in the early stages of part and mold design and offers the ability to evaluate different options in terms of part design, material, and mold design.

1.6 How Good is Simulation?

Frequently people ask the question, "How good is molding simulation?" A simple question, but it belies the complexity, both scientific and in human terms, of simulation. Two common criteria used to assess the success or otherwise of a simulation are:

1. Did the simulation lead to an improved design of the mold or part?
2. Did the simulation agree with what we saw in the molding plant?

Both these criteria require some explanation. The first depends on the fidelity of the results and the competence of the user. This book is devoted to the former. However, the competence of the user also requires an understanding of the assumptions made in simulation as well as industrial experience in injection molding. Users of injection molding software will find details of assumptions, and shortfalls in mathematical modeling, in the first part of this book.

The second criterion is often used by companies as a test prior to buying simulation software. While it appears reasonable, it is an extremely complex area. One major problem is that injection molding machines are not laboratory instruments. Settings by an operator on the control panel of a molding machine, and what happens in reality, may not correlate. Consequently, inputs to the software from machine settings may give rise to errors in simulation.

Generally, we can say that the results of simulation will only be as good as the data given to the simulation and the assumptions made by the software. This book attempts to provide information on the issues of material data and assumptions made in software. The issue of comparing simulation results to those seen in a molding plant, or even a well-equipped laboratory, are not discussed here. Comparison of computer simulation results with experiments is a huge topic and a relatively new scientific discipline. It is often referred to as validation and verification of software. Interested readers are referred to the works of Roache [310] and Oberkampf and Roy [272].