COMPUTER MODELING FOR INJECTION MOLDING

Simulation, Optimization, and Control

Edited by

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When Wiley approached me to write a book on injection molding, I indicated that I would be interested in writing a book on the basics and applications of computer models, tools, and simulations in injection molding. This idea was embraced by Wiley, and the result is *Computer Modeling for Injection Molding: Simulation, Optimization, and Control*.

No one doubts that injection molding is the most important process used in the manufacture of plastic products, which has consumed about 32 wt% of all plastics. Typical injection-molded products can be found everywhere, including automotive parts, household articles, and consumer electronics goods. Owing to growing plastics applications, increasing customer demand, and rapid growth of the global marketplace, quality requirements of injection-molded components have become more stringent, forcing companies in the constant struggle for just-in-time production with a zero-fault quota. Effective quality assurance is therefore very necessary in enhancing the efficiency and competitiveness of the industry.

Computer application has played a crucial role in the quality control of injection molding. In practice, a high quality component can be obtained only when various factors regarding the part and mold designs as well as the material selection and process setup have been considered. The quality of the injection-molded product is thus inherently difficult to predict and/or control without employing sophisticated computer simulation/optimization software during the design stage and/or frequent monitoring and intervention during the production stage. Instead of the past costly trial-and-error manufacture process, prediction and optimization of the product quality at the lowest cost has now become possible. Now it is unquestionable that a proper use of computer application can sharpen a company’s competitive edge in various aspects such as product design, process simulation, monitoring, control, and optimization.

Computer modeling for injection molding has been an active research area for many years. In my opinion, computer models in injection molding can be generally organized into three categories, namely, simulation, optimization, and process control. Numerical simulation describes the physical process of injection molding directly, which is developed based on the first principle, involving the use of computer-aided engineering (CAE) software or mathematical models, whereas optimization employs various artificial intelligence-based models that should use expert knowledge, cases, empirical models, as well as simulation results, as their reasoning basis. These two approaches aim at establishing a reasonably accurate mapping between the influencing factors and part quality. On the other hand, process control of the injection molding machine attempts to repeat the molding process consistently with high accuracy, in order to ensure the repeatability and reliability of the product quality.

Although there have been some introductory books on computer modeling of injection molding, none of them has involved all the above three essential ingredients in improving the product quality. As a result, the major problem for students and researchers who are desirous of an extensive knowledge in injection molding is that applications of the latest computer technology in quality improvement are scattered about, and rarely introduced comprehensively or systematically in postgraduate-level texts, forcing the students and researchers to wade through stacks of published papers looking for useful information.

This book is intended to serve as a systematic and comprehensive introductory textbook on the computer
modeling for injection molding, with important expansions into the successful application of the latest computer technology. It is based on the constant efforts of authors and colleagues in this area over the last few years, and provides what we have determined after years of working in this field to improve the product quality through computer modeling in simulation, optimization, and control. Students and researchers new to the field can get started with the basic information provided, and also, scientists and people involved in the polymer industry, institutes, and institutions seeking new ways to gain a competitive edge can work closely with the latest information provided in the book. Actually, the reader will obtain a comprehensive understanding and a lot of practical knowledge about how the latest computer technology can benefit the injection molding industry.

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PART I

BACKGROUND
INTRODUCTION

This book is primarily concerned with the computer modeling technology in the quality enhancement of polymer injection molding. This chapter outlines the injection molding process, factors that influence the quality of injection-molded products, and computer applications in injection molding.

1.1 INTRODUCTION OF INJECTION MOLDING

The past century has witnessed the rapid expansion of polymers and plastics (the term plastics describes the compound of a polymer with one or more additives) and their incursion into all markets. Although just over a century old, relatively new when compared to other materials, plastics are now among the most widely used materials, surpassing world’s consumption of steel, aluminum, rubber, copper, and zinc by weight (and volume, of course), as shown in Figure 1.1.1 Plastic materials and products cover the entire spectrum of the world economy in a position to benefit by a turnaround in any one of a number of areas: packaging, appliance, transportation, housing, automotive, and many other industries.

Injection molding is regarded as the most important process used to manufacture plastic products. Today, more than one third of all thermoplastic materials are injection molded and more than half of all polymer processing equipment is for injection molding.2

1.1.1 The Injection Molding Process

Injection molding is a repetitive process in which melted (plasticized) polymer is injected (forced) into a mold cavity or cavities, packed under pressure, and cooled until it has solidified enough. As a result, it duplicates the cavity of the mold (Fig. 1.2). Generally speaking, the mold consists of a single cavity or a series of similar or dissimilar cavities, connected with each other to flow channels or runners that direct the flow of the melt to the individual cavities.

During this process, there are three basic operations: (i) heating the polymer in the injection or plasticizing unit so that it will flow under pressure; (ii) making the polymer melt to fulfill and solidify in the mold; and (iii) opening the mold to eject the molded product.

The injection molding process is of great significance as it can produce finished, multifunctional, or complex molded parts accurately and repeatedly in a single, highly automated operation. It permits mass manufacture of a great variety of shapes, from simple to intricate three-dimensional ones, and from extremely small to large ones. When required, these products can be molded to extremely tight tolerances, very thin, and in weights down to milligrams. Typical injection moldings (molded products) can be found everywhere in daily life. Examples include automotive parts, household articles, consumer electronics components, and toys.

1.1.2 Importance of Molding Quality

In plastic industry, for years the so-called product innovation was the only rich source of new developments, such as reducing the number of molded components by making them able to perform a variety of functions. In recent years, however, the process innovation has also been moving into the forefront. The latter includes all the means that
help tighten up the manufacturing process, understanding, and optimizing it. The core of all activities has to be the most efficient application of production materials, a principle that must run right through the entire process from polymer materials to the finished product. That is, the aim is no longer merely to manufacture particular components, but to manufacture a finished product with the best quality and in the most rational way if possible. Other new factors also enjoy recognition, such as shorter development time, lower cost, and higher productivity.¹
On the other hand, the quality of molded products will continue to be the major criteria determining the competitiveness and performance of an injection molding company. Owing to growing applications of plastics, increasing customer demand, and rapid growth of the global marketplace, the quality requirements of injection-molded components have become more stringent for various market sectors such as the automotive, computer, consumer appliances, medical, microelectromechanical systems (MEMS), optical, and telecommunication industries. At present, part quality is crucial to the survival and success of enterprises. Quality features include mechanical properties, dimensional accuracy, absence of distortion, surface quality, etc.

Only with the beginning of a deeper understanding of process mechanisms and their underlying physical laws, could injection molding technology make any real progress and improve the final quality to the greatest extent. Unfortunately, it is clear that very little was known about what happens inside the molding process. In spite of what has been achieved so far, the industry has surmounted only the first hurdle of systematic development. The present should not be regarded as the last word in progress. On the contrary, there are great possibilities in development that must be recognized and examined with the close cooperation of theoretists and technologists.

1.2 FACTORS INFLUENCING QUALITY

The mechanical properties and performance of a finished product is always the sequence of events. Manufacturing of a plastic part begins with part design and material choice in the early stages, followed by mold design and manufacturing, and then processing, at which time the material is not only shaped and formed but the properties that control the performance of the product are also set or frozen into place.

In the development of any plastic product, it is important to understand that the entire manufacturing process and all involved factors in the links have an influence on the quality of molded products. These factors mainly include polymer properties and its performance during molding, product design and its characteristics, mold design and its configuration, process conditions (parameters), and injection molding machine and its process control. For example, various elements regarding the part and mold designs as well as the material selection and process setup have to be considered to ensure that the mold can be fulfilled; the inherent, nonuniform material shrinkage throughout the cavity due to cooling and crystallization (in the case of semicrystalline materials) is further affected by packing, mold cooling, constraints of mold geometry, and the possible presence of reinforcing fibers.

The following subsections will introduce these factors briefly.

1.2.1 Molding Polymer

Polymers (plastics) are a family of materials, including many thousands of different materials. Extensive compounding of different amounts and combinations of additives (colorants, flame retardants, heat and light stabilizers, etc.), fillers (e.g., calcium carbonate), and reinforcements (glass fibers, glass flakes, graphite fibers, whiskers, etc.) are used to produce new plastic materials, each having its respective melt behavior, product performance, and cost.

Plastics can be classified according to several criteria. Our initial differentiation is between cross-linked and non-cross-linked materials. Whatever are/is their properties or form, most plastics fall into one of two groups: thermoplastics (TPs, non-cross-linked) and thermosets (TSs, cross-linked).

TPs, which are predominantly used, can go through repeated cycles of heating/melting and cooling/solidification. Different TPs have different practical limitations on the number of heating—cooling cycles before appearance and/or properties are affected. The TP resins consist of long molecules, either linear or branched, having side chains or groups that are not attached to other polymer molecules. Usually, TP resins are purchased as pellets or granules that are softened by heat under pressure allowing them to be formed. When cooled, they harden into the final desired shape. No chemical changes generally take place during forming.

TSs, on their final heating (usually at least to 120°C), become permanently insoluble and infusible. During heating they undergo a chemical (cross-linking) change. The linear polymer chains are thus bonded together to form a three-dimensional network. Therefore, once polymerized or hardened, the material cannot be softened by heating without degrading some linkages. TSs are usually purchased as liquid monomer–polymer mixtures or a partially polymerized molding compound. In this uncured condition, they can be formed to the finished shape with or without pressure and polymerized with chemicals or heat.

Most of the literature on injection molding refers entirely or primarily to TPs; very little, if any at all, refers to TSs. Considering that at least 90 wt% of all injection-molded plastics are TPs, this book mainly deals with injection molding of TPs, and the terms plastic and polymer used later in this book refer primarily to TPs. Injection-molded parts can, however, include combinations of TPs and TSs, as well as rigid and flexible TPs, reinforced plastics, TP and TS elastomers, etc.

Polymers are said to be viscoelastic. The mechanical behavior of polymers is dominated by the viscoelastic parameters such as tensile strength, elongation at break,
INTRODUCTION

and rupture energy. The viscous attributes of polymer melt are important considerations during injection molding. The rheology of polymers deals with the deformation and flow of polymer melt under various conditions.

Owing to the thermomechanical history experienced by the polymer during processing, macromolecules in injection-molded objects present microstructure and morphology influencing greatly the final performance of molded parts. In the case of TPs, some of the molecules can come closer together than others. These are identified as crystalline; the others are amorphous. The performance of these two microstructures varies to a great extent. There are no purely crystalline plastics; the so-called crystalline materials also contain different amounts of amorphous material.

1.2.2 Plastic Product

A plastic product must be designed to satisfy certain functional, structural, aesthetic, cost, and manufacturing requirements. One of the significant advantages of plastic parts is that a part that incorporates a multitude of features that might otherwise require machining and assembly of multiple parts can be molded. Therefore, the expectations in the plastic part and the pressure on the designer to satisfy the multiple functions present further challenges. Compounding this challenge is the need to combine these features while not overly complicating the tooling requirements that might reflect on the manufacturability of the product and its cost.

So, in the product design stage, one has to comprehend factors such as the range of the material properties, structural responses, product performance characteristics, and available fabricating processes, as well as their influence on product performances. For structural applications a designer can use either standard design formulas (rough) or finite-element structural analysis (more accurate) to calculate deflections and stress. Moreover, to simplify molding, whenever possible one should design the product with features that simplify the mold-cavity filling operation. Many such features can facilitate the molding process, improve the product’s performance, and/or reduce cost. An example is setting the mold-cavity draft angle according to the plastic being processed, tolerance requirements, etc. A too small draft of molded part will lead to poor mold release, distortion of molded part, and dimensional variations. And also, sharp transitions in part wall thickness and sharp corners will result in parts unevenly stressed, dimensional variations, air entrapment, notch sensitivity, and mold wear. Figure 1.3 shows a situation where it is possible to eliminate or significantly reduce shrinkage, sink marks, and other defects.

Thus, in the design of any injection molded part, there are certain desirable goals that the designer should achieve. If neglected, problems can unfortunately develop. For example, the most common design errors usually occur in the following areas:

- thick or thin sections and transitions resulting in warpage and stress;
- parts too thin to mold properly (such as diaphragms);
- parts too thick to mold properly;
- flow path too long and tortuous;
- orientation of polymer melt in flow direction;
- hiding gate stubs;
- stress relief for interference fits;
- living hinges;
- slender handles and bails;
- thread inserts;
- creep or fatigue over long-time stress.

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**FIGURE 1.3** Example of coring in products to eliminate or reduce shrinkage and sink marks.
1.2.3 Injection Mold

The mold is the central element of the injection molding process. Under pressure, hot melt moves rapidly into the mold. With TPs, temperature-controlled water circulates in the mold to remove heat; with TSs, electrical heaters are used within the mold to provide the additional heat required to solidify the plastic melt in the cavity. The mold basically consists of a sprue, a runner, a cavity gate, and a cavity. The sprue transports the melt from the plasticator nozzle to the runner. Next, melt flows through the runner and gate into the cavity.

The mold for producing a plastic part must be custom designed and built. The challenges in designing a mold include the following, among many others: the mold must accommodate delivery of the melt and accomplish automatic separation of runner and part; the cavity dimensions must be sized to account for the part’s shrinkage; the mold must provide adequate and uniform cooling and venting of gases; the mold must be strong enough to withstand cyclic internal loads from injection pressures and external clamp pressures; the mold components must be machinable.

Many parts of an injection mold will influence the final product’s performance, dimensions, and other characteristics. These mold parts include the cavity shape, gating, parting line, vents, undercuts, ribs, hinges, etc., which are listed in Table 1.1. The mold designer must take all these factors into account. At times, to provide the best design, the product designer, processor, and mold designer may want to jointly review where compromises can be made to simplify the process of meeting product requirements. With all these interactions, it should be clear why it takes a significant amount of time to prepare a mold for production.

1.2.4 Process Conditions

Different product requirements and material conditions are considered in choosing the most efficient injection molding process. It is well known that the process conditions have a direct influence on the performance of injection moldings. Mold filling involves both high deformation and high cooling rate. The process conditions are correlated with the internal structure of the plastic material, which represents the key for the behavior of the molded product, as shown in Figure 1.4.

In order to have a stable and high-quality production, the following issues and relevant process parameters are worth investigating. The plasticization phase can be optimized by varying the screw rotation speed and back pressure so as to provide sufficient and uniform polymer melt. The injection velocity (speed) is critical to influencing the pressure drop, temperature difference after filling, shear rate (and thus orientation), etc. The switchover from filling to packing can be made based on smooth changes of pressure and filling

<table>
<thead>
<tr>
<th>TABLE 1.1 Examples of Errors in Mold Design</th>
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<tbody>
<tr>
<td>Faults</td>
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<tr>
<td>Wrong location of gates</td>
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<tr>
<td>Gates and/or runners too narrow</td>
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<tr>
<td>Runners too large</td>
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<tr>
<td>Unbalanced cavity layout in multiple-cavity molds</td>
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<tr>
<td>Nonuniform mold cooling</td>
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<tr>
<td>Inadequate provision for cavity air venting</td>
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<tr>
<td>Poor or no air injection</td>
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<tr>
<td>Poor ejector system or bad location of ejectors</td>
</tr>
<tr>
<td>Sprue insufficiently tapered</td>
</tr>
<tr>
<td>Sprue too long</td>
</tr>
<tr>
<td>No round edge at the end of sprue</td>
</tr>
<tr>
<td>Bad alignment and locking of cores and other mold components</td>
</tr>
<tr>
<td>Mold movement due to insufficient mold support</td>
</tr>
<tr>
<td>Radius of sprue bushing too small</td>
</tr>
<tr>
<td>Mold and injection cylinder out of alignment</td>
</tr>
</tbody>
</table>
rate. Optimizing the magnitude and duration of applied packing pressure can prevent sink marks, dimension out-of-tolerance, and underweight. Cooling time depends on the melt temperature and part thickness. Attention must be paid to the mold and injection (barrel) temperature that influence both the quality and productivity.

Process windows are the ranges of process conditions, such as injection speed, injection temperature, mold temperature, and holding pressure, within which a specific plastic can be molded with acceptable or optimum properties. A window is a defined “area” in the space of process variables. For example, by plotting injection temperature versus holding pressure, a molding area diagram that shows the best combinations of injection temperature and holding pressure to produce quality parts is developed, as shown in Figure 1.5. The size of the diagram denotes the molder’s latitude in producing good parts.

To mold parts at the shortest cycle time, the molding machine would be set at the lowest temperature and highest pressure location on this diagram. If inferior quality appears, one has to move the parameters to higher temperature and/or lower pressure. This is a simplified approach to producing quality parts because only two variables are controlled here. Using this approach for making process windows, one can analyze all other process parameters. The process window for a specific plastic part can significantly vary if changes are made in its design, material choice, and/or the fabricating equipment used. Developing the actual data involves plenty of molding trials.

### 1.2.5 Injection Molding Machine

The injection molding machine is one of the most significant and rational forming methods that exist for processing plastic materials. There are different types of injection molding machines. The reciprocating screw injection molding machine is the most widely used one in plastics industry owing to its better reliability and overall performance, such as improved melting rates, closer tolerances on shot size, better control of temperatures, and simpler structure. A simplified general layout for an injection molding machine is shown in Figure 1.6. The injection molding machine has four basic components: the injection unit, the clamping unit, the control system, and the drive system.

The injection unit, also called the plasticator, prepares the proper plastic melt and transfers the melt into the mold. The most important elements of an injection unit are (in the sequence of polymer flow) as follows: hopper, screw, homogenizing elements on the screw (in some cases), nonreturn valve (check valve) at the screw tip (in some cases), nozzle, and heater bands. The clamping unit opens the mold for demolding and closes it for the next shot. Because the polymer is pressed under high pressure into the mold, the clamping unit must also be
The injection molding machine has extensive process-controlling devices to maintain correct operating procedures. The physical values to be controlled (temperature, position, velocity, and pressure) are recorded with special sensors (thermocouples, displacement, and pressure transducers). These signals are then transformed and read in by the supervising computer. On the basis of these input data, the control program induces certain actions: for example, if the temperature of the plasticating unit is too low, the heater bands are switched on, or, if the screw has reached a set position during plastication, the control system shuts a valve, to switch off the screw rotation. Process control closes the loop between process parameters and appropriate machine control devices to eliminate the effect of process disturbances. Tighter operational controls permit production of high-quality products with less effort.

In addition, the design of the control system has to incorporate the logical sequence of all basic functions, including injection speed, clamping and opening the mold, opening and closing of actuating devices, barrel temperature profile, melt temperature, mold temperature, cavity pressure, and holding pressure.

1.2.6 Interrelationship

As mentioned above, all factors involved in the entire manufacturing process affect the final quality of the molded products, including plastic properties, product characteristics, mold configuration, process conditions, and process control. This relationship can be illustrated as a fishbone diagram (Fig. 1.7). As an example, the dimensional accuracy of injection molding, which can be met, depends on such factors as properties of materials; accuracy of mold and machine performance; operation of the complete molding cycle; wear or damage of machine and/or mold, shape, size, and thicknesses of the product; postshrinkage (which can reach 3% for certain materials); and the degree of repeatability in performance of the machine, mold, material, etc.

Moreover, there are strong and complicated interrelationships among these factors. For instance, it is well known that different plastics have different melt flow characteristics. What is used in a mold design for a specific material may thus require a completely different type of mold for another material. These two materials might, for instance, have the same polymer but use different proportions of additives and reinforcements. It is necessary to consider these interrelationships so as to fabricate a cost-performance effective molded product.

Unfortunately, at present, the development stages of injection-molded parts are often handled sequentially and independently. A part designer will design a part with limited knowledge of mold, processing, and/or materials.
A mold designer will inherit this part and design and build a mold with limited understanding of processing and material behaviors during processing. The injection molder then inherits this mold and must try to find a process condition that can produce the required part. At this stage his options are very limited. In addition, we find that the processor often has had limited opportunity to take formal training that would allow him to understand the fundamental cause-and-effect relationship of his actions on the molded part. Is the warpage problem which he is encountering dominated by part design, material, mold cooling, gating, process, or other factors? The attempts at solving problems are often based on trial and error, seat of the pants, gut feel, and intuition.3

On the basis of the above facts, it is of great importance to recognize that the best quality can only be achieved by overall optimization from the very beginning of a design concept through to production of injection-molded parts, and thus it is necessary to establish effective cooperation among part designers, mold designers, molders, and material engineers. The best approach may be to integrate computer modeling within an overview of the interrelated building blocks of an injection-molded part: product design, plastic material, mold design, process conditions, and the injection molding machine.

1.3 COMPUTER MODELING

One of the most revolutionary technologies to affect injection molding in the past decades certainly would be computer applications in the industrial production process. In the injection molding industry, computers permeate all aspects from the concept of a product design, mold manufacturing, raw material processing, marketing and sales, recycling, to administration and business, and so on. They provide word processing, databases, software, spreadsheets, design and manufacturing support, etc., while this book focuses on the computer’s service in improving the product quality.

Most accept the fact that computers can, if properly used, improve efficiency, reduce costs, improve the quality of products, and reduce time for bringing new products to the marketplace. Mold costs can be reduced 10–40%, lead time cut by 20–50%, molding cycle time cut by 10–50%, material usage reduced by 5–30%, and product cycle time reduced by 50–80%.1

The advantages of computer modeling are, in particular, accentuated because in order to produce a single part to evaluate its performance first a custom-designed mold must be built, which may cost tens to hundreds of thousands of dollars. This is typically several million times the selling price of the product it is to produce. The process of designing and building a mold, and molding the first plastic