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INTRODUCTION

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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

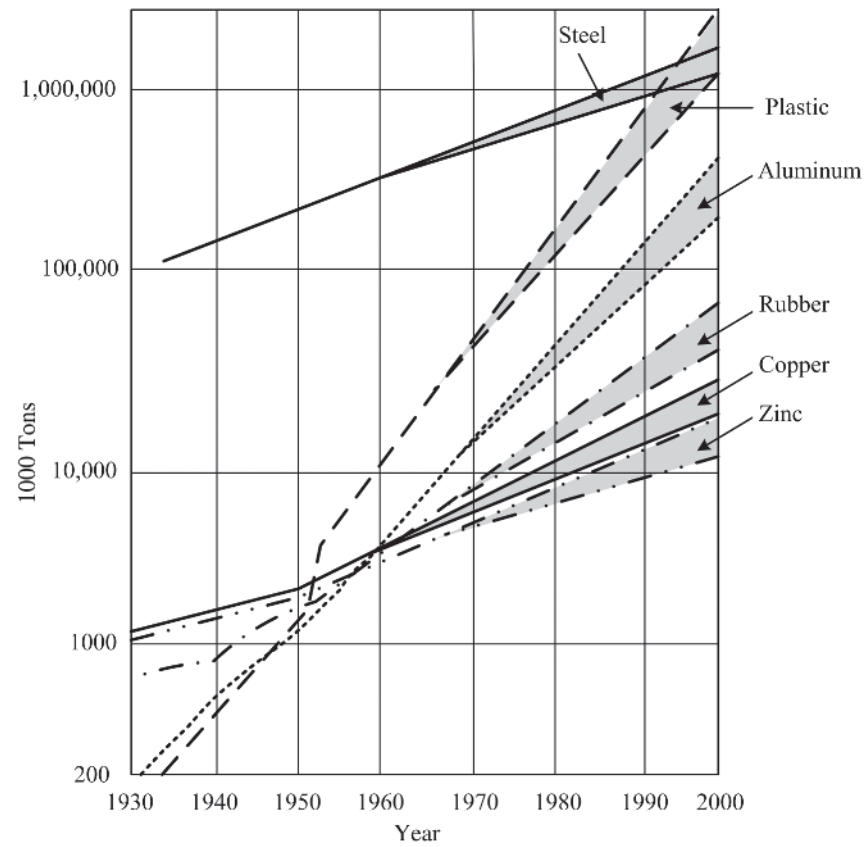


FIGURE 1.1 World consumption of raw materials by weight.

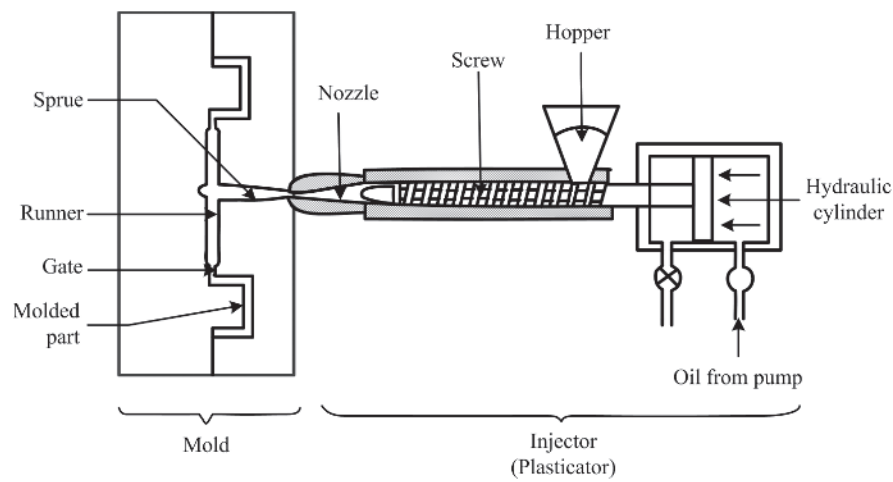


FIGURE 1.2 Diagram of the injection molding process.

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 theorists 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,

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.³

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.

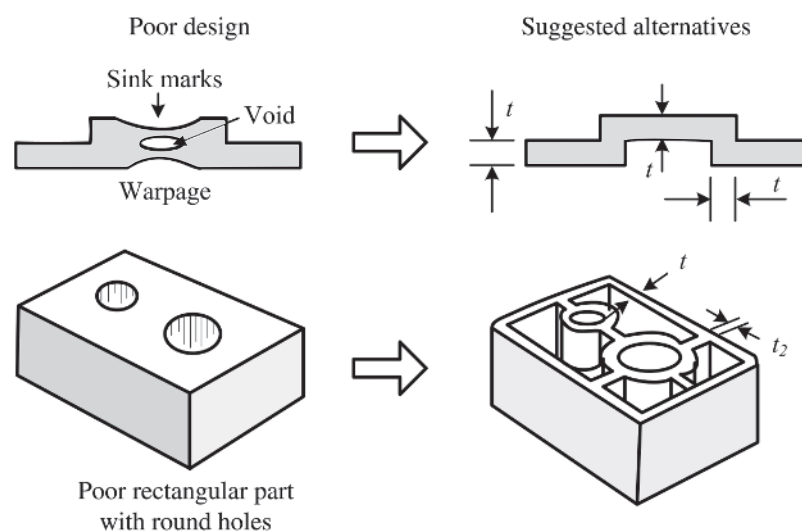


FIGURE 1.3 Example of coring in products to eliminate or reduce shrinkage and sink marks.

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 usually 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 and 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 1.1 Examples of Errors in Mold Design

Faults	Possible Problems
Wrong location of gates	Cold weld lines, flow lines, jetting, air entrapment, venting problems, warpage, stress concentrations, voids, and/or sink marks
Gates and/or runners too narrow	Short shots, plastics overheated, premature freezing of runners, sink marks, and/or voids
Runners too large	Longer molding cycle and waste of plastics
Unbalanced cavity layout in multiple-cavity molds	Unbalanced pressure buildup in mold, mold distortion, dimensional variation between products (poor shrinkage control), poor mold release, flash, and stresses
Nonuniform mold cooling	Longer molding cycle, high after-shrinkage, stresses (warpage), poor mold release, irregular surface finish, and distortion of part during ejection
Inadequate provision for cavity air venting	Need for higher injection pressure, burned plastic (brown streaks), poor mold release, short shots, and flow lines
Poor or no air injection	Poor mold release for large parts, part distortion, and higher ejection force
Poor ejector system or bad location of ejectors	Poor mold release, distortion or damage in molding, and upsets in molding cycles
Sprue insufficiently tapered	Poor mold release, higher injection pressure, and mold wear
Sprue too long	Poor mold release, pressure losses, longer molding cycle, and premature freezing of sprue
No round edge at the end of sprue	Notch sensitivity (cracks, bubbles, etc.) and stress concentrations
Bad alignment and locking of cores and other mold components	Distortion of components, air entrapment, dimensional variation, uneven stresses, and poor mold release
Mold movement due to insufficient mold support	Part flashes, dimensional variations, poor mold release, and pressure losses
Radius of sprue bushing too small	Plastic leakage, poor mold release, and pressure losses
Mold and injection cylinder out of alignment	Poor mold release, plastic leakage, cylinder pushed back, and pressure losses

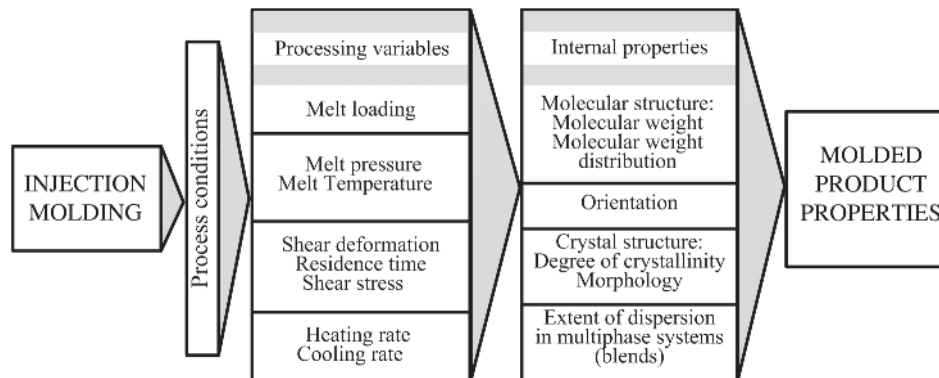


FIGURE 1.4 Relationship between process conditions and properties of products.

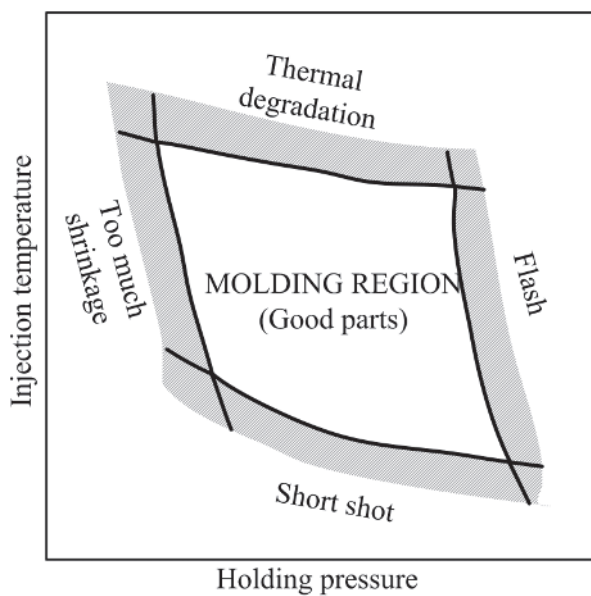


FIGURE 1.5 Illustration of process window.

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

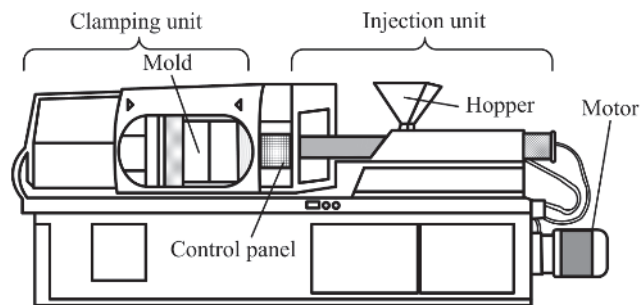


FIGURE 1.6 Schematic of an injection molding machine.

able to keep the mold tightly sealed during the filling and holding stages. At present, clamping units are available in three different forms in the market: mechanical, hydraulic, and hydraulic mechanical systems. The control system coordinates the machine sequences, keeps certain machine parameters constant, and optimizes individual steps in the process. All motion sequences of the machine, the correct order of these sequences, their initiation, the signaling of positions reached (such as by limit switches), and the reaction at predetermined times within a cycle have to be achieved, initiated, and coordinated. The temperature requirements during molding (including barrel, melt, and mold temperatures) are set up by the control system, and implemented by the tempering devices. The drive system provides power for the above components by the conventional way of hydraulic or by the recent developed ways of all-electric or hybrid-electric-hydraulic. At present, the hydraulic system is the most popular, while the electric one has the development tendency. The essential advantage of oil hydraulic systems is that the fluid can be distributed easily by hoses and pipes, and that no complicated mechanical transfer elements such as rods, cables, and toothed racks are necessary. Compared with electric systems, the main drawback is their higher energy loss.

The injection molding machine performs certain essential functions: (i) *plasticizing*—heating and melting the plastic in the plasticator; (ii) *injection*—injecting from the plasticator under pressure a controlled-volume shot of melt into a closed mold; (iii) *after-filling*—maintaining the injected material under pressure for a specified time to prevent back flow of melt and to compensate for the decrease in volume of melt during solidification; (iv) *cooling/heating*—cooling the TP molded part or heating the TS molded part in the mold until it is sufficiently rigid to be ejected; and (5) *molded-part release*—opening the mold, ejecting the part, and closing the mold so it is ready to start the next cycle. The type and size of an injection molding machine to be used are dependent on the dimensions and volume of the molded product.

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.⁴ 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.

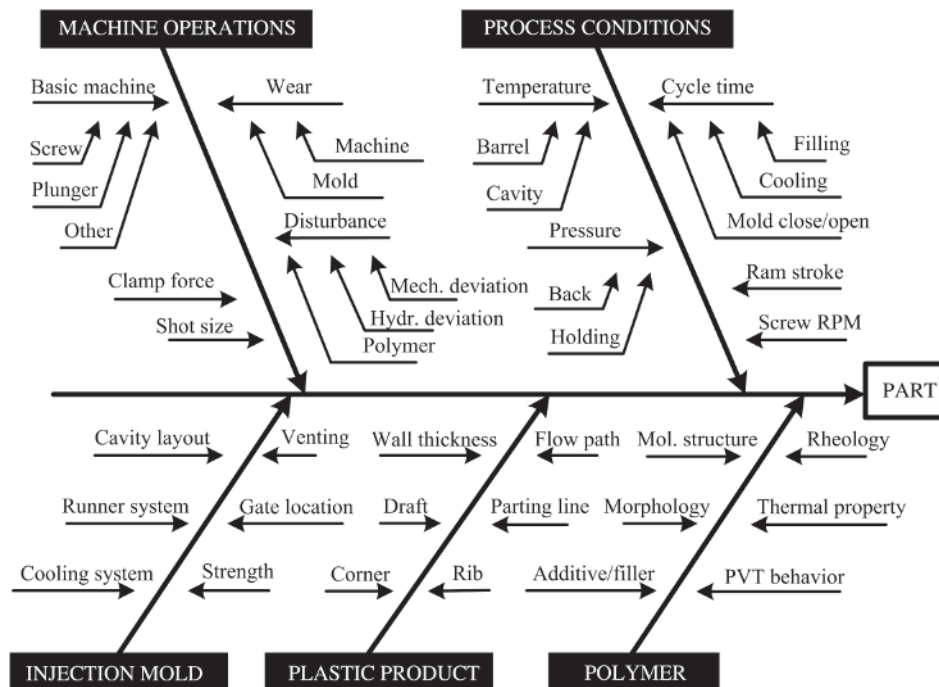


FIGURE 1.7 The factors influencing the final quality of molded parts.

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

parts can easily take 20 weeks. Not until this time can the actual size, shape, and mechanical properties of a molded part be known. It is rare that these first parts possess the required specifications. The next stage is typically a long, costly process of trying to produce parts that obey the specification, maybe involving changes to the mold, process, or the plastic material. This is in contrast to the development of machined products. Here, if the part does not satisfy expectations, it can be easily modified or a second part will be machined reflecting an altered design. So, if the first parts do not work, the investment in engineering and machine time is minimum compared to building a mold.³

1.3.1 Review of Computer Applications

The use of computers in manufacturing operations dates back to early work in the 1950s in which the dream was to control metal-cutting machine tools by computer. It was hoped that this would eliminate the requirement for many tooling aids, such as tracer templates, that favored the accuracy and repeatability of machining operations on the shop floor. During this period, the only types of computers available were extremely expensive “mainframe” computers. Programming was accomplished via a punched card medium and was tedious and time consuming to develop and debug. The only means to check cutter paths developed by the computer was to do a “prove out” run on the shop floor.

The concept of using a graphic display device to visualize cutter paths was proposed and developed during the 1960s. During this same period, an important hardware progress was the development of microcomputers. This newcomer to the computer field brought in a totally new price and performance spectrum, which created a dramatic increase in the acceptance of computers (and also the concept of CAD/CAE/CAM) in general, particularly in the scientific, engineering, and manufacturing areas.

The 1970s not only engendered a continued development of hardware and software products but also brought about a change in the business climate. The computer industry spawned the “turn-key” CAD/CAE/CAM suppliers that could supply both the computer hardware and user-friendly software, ready to run. The first predominant applications were in the area of two-dimensional printed circuit board (PCB) and integrated circuit (IC) design. Both of these applications were relatively easy to capitalize on, as they can be described by geometries on planar surfaces.

During the following two decades, the rapid developments of CAD/CAE/CAM resulted in three-dimensional representations of objects. This implied a complete expansion in the capabilities of CAD/CAE/CAM systems, moving them from two-dimensional drafting tools into

true spatial mathematical modeling tools. The three-dimensional modeling and the fast, smooth shading of surfaces help one to understand the shape geometry. Besides CAD/CAE/CAM, the computer applications for design and manufacture support in injection molding extended into computerized databases of plastics, trouble shooting, optimization, process control of molding machines, etc.

In this new century, new software packages of CAD/CAE/CAM continued to enhance their usefulness to part designers, moldmakers, and molders. The related technologies include two-dimensional drafting; three-dimensional modeling, design and assembly; finite-element analysis and simulation; visualization and virtual reality; (on-line and real time) optimization; numerical control programming; integrated, intelligent, Internet-based, and cooperative design; product data management (PDM); enterprise resource planning (ERP); manufacturing execution system (MES); product lifecycle management (PLM); etc. In the present time, the technologies of computer applications imply a completely different methodology of engineering design.

The benefits that result from computer applications in injection molding are productivity improvement, quality enhancement, turnaround time improvements, more effective utilization of scarce resources, etc. Examples include (i) fewer errors in drawings, which improves mold quality and speeds up delivery time; (ii) better communication among part designers, mold designers and moldmakers; (iii) improved machining accuracy; (iv) standardization of parts and components, which reduces the amount of supervision required in a manufacturing facility; (v) improved speed and accuracy in the preparation of the quotation; and (vi) a faster response to market demand.

1.3.2 Computer Modeling in Quality Enhancement

Among all the benefits of computer applications, the quality benefits are perhaps the most underrated. Computer modeling has played a crucial role in the quality control of injection molding. Many of the analysis packages promote a better understanding of molding process and the interrelationships among correlated parameters. This contributes to a better ability to control previously mysterious phenomena (such as warpage). 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. The increased computer-aided process control has resulted in quick setup, automatic production, and an overall increase in part quality. It is unquestionable that a proper use of computer applications can sharpen a company’s competitive edge in various aspects such as analysis, design, simulation, optimization, control, and monitoring.

Here, we review the development process of injection-molded products. During the early design stage, the

material's choice and product geometry are both decided mainly based on the functional requirements. After that, the mold is custom designed and manufactured. Once an injection mold is built and mounted on a machine, a molding engineer (or setup person) has to determine the process conditions (such as shot size, injection speed, pack/hold time and pressure, cooling time, back pressure, coolant temperature, and barrel temperature), depending on the material, product, and mold. Typically, these parameters can be set at the machine's operating console. The machine control executes the commands set for moldings, and its performance has a direct impact on the final part quality. This development process is illustrated in Figure 1.8, and the relevant parameters are called *design variables* in this book.

Instead of the design variables, numerous research efforts has showed that the thermomechanical histories during the injection molding process (referred to as *processing variables* here) finally determine the quality of the molded part (labeled as *quality variables*). The processing variables mainly denote the flow, temperature, and pressure within the polymer melt throughout all phases of injection molding such as melt temperature, melt pressure, melt shear rate, melt shear stress, and heating/cooling rate. The quality variables include quantitative and qualitative indices such as part weight and thickness, volume shrinkage, warpage, sink marks, weld lines, part strength, and part appearance. Because the processing variables are the true indicators of the conditions of the material inside the mold, they are more closely related to quality variables than are the design variables. Of course, these processing variables cannot be set up directly, depending on the collective effect of the specific resin and mold used, the machine setting, and the nonlinear, distributed, and time-varying process dynamics.⁵ Figure 1.8 describes the three-level hierarchy and dependency of the injection molding quality.

The processing variables serve as the connection between the design variables and the quality variables. However, no generic quantitative models have been established for the connections from the design variables to the

processing variables and from the processing variables to the quality variables. The relationship between the design variables and the quality variables of molded parts can be expressed as a mapping in the following form:

$$Q = f(m, p, d(m, p), c(m, p, d)) + v(c) \quad (1.1)$$

where Q is the collection of quality variables; m , p , and d are the collections of material properties, product characteristics, and mold configuration, respectively; c denotes the process conditions; v is the disturbances from the machine, affecting the execution of process conditions; and f is a mapping function without considering the disturbances.

Unfortunately, f is typically complicated or unknown *a priori*. In practice, the expression of f has to be simplified to a certain extent in order to establish a reasonably accurate mapping between the influencing factors and part quality. The methods of mapping can be categorized into two approaches, namely, the numerical simulation approach and the optimization approach. The first approach 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. While the latter approach employs various artificial intelligence (AI)-based models such as case-based reasoning (CBR), artificial neural networks (ANNs), expert systems (ESs), fuzzy logic, genetic algorithm (GA), and design of experiments (DOE, using less AI technique). These AI methods should use expert knowledge, cases, and empirical models, as well as simulation results, as their reasoning basis.

On the other hand, to achieve consistent quality, the machine controller should be able to repeat the process conditions consistently with high accuracy. However, there are plenty of unpredictable disturbances, including the mechanical and hydraulic deviations of machines and those coming from polymer pellets and melt, which are difficult to model and predict. Therefore, an accurate and robust process control of the injection molding machine also

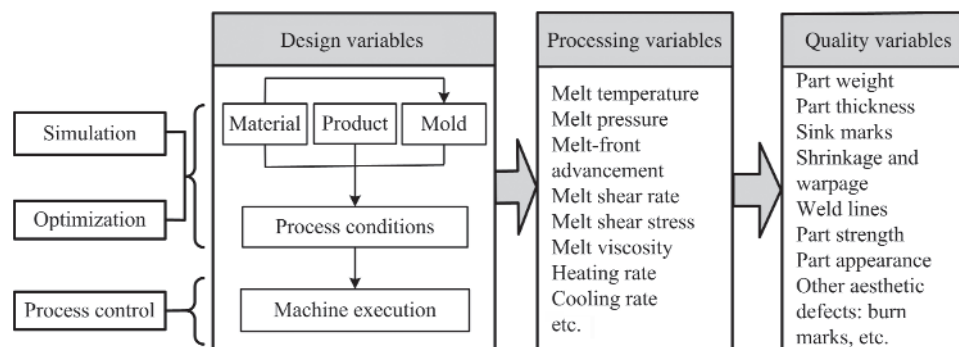


FIGURE 1.8 Architecture of computer modeling in quality enhancement.

plays an important role in ensuring the repeatability and reliability of the product quality. Besides the individual variable control of process conditions, newer works have attempted a direct (on-line) control of the final molded part quality (termed *direct quality control*), but it is difficult to implement owing to the lack of an accurate quantitative description of the complex relation between quality characteristics and process conditions.

In short, computer modeling for quality enhancement of injection molding could be organized into three categories, namely, numerical simulation, optimization, and process control, as shown in Figure 1.8. These are the focus of this book. In the following paragraphs, these three categories are reviewed briefly.

1.3.3 Numerical Simulation

Numerical simulation for injection molding is generally based on the rigorous, first-principle model that provides reasonably accurate descriptions and trends of the injection molding process.

In the early stage, quite a few mathematical models (i.e., simplified numerical simulation) have been developed for describing the injection molding process.⁶ For example, Kamal and Kenig,^{7,8} Wu et al.,⁹ and Stevenson¹⁰ developed the mathematical models to describe the filling in a center-gated disc; Toor et al.,¹¹ Harry and Parrott,¹² and Lord and Williams¹³ studied the one-dimensional filling behavior in rectangular cavity geometry; while Williams and Lord¹⁴ and Nunn and Fenner¹⁵ developed the mathematical models to describe the filling in a circular tube. These filling models are all limited to one-dimensional geometry. To apply these one-dimensional flow representations to simulate polymer flow in typically complex mold cavities, branching flow approach^{16,17} and network flow approach^{18,19} were proposed and implemented. These approaches involve laying flat and decomposing the cavity geometry into several conjectured flowpaths comprising a series of one-dimensional segments such as strips, discs, fans, and/or tubes.

With respect to mold cooling, Busch et al.²⁰ and White²¹ derived mathematical models for the estimation of the cooling time. Tan and Yuen²² developed computer systems for calculating the process parameters and deriving an initial parameter setting for injection molding. Tan and Yuen²³ proposed an analytical model for injection molding based on which the filling pressure, clamp force, shear stress, shear rate, and temperature at different time instants and locations can be calculated and used to determine suitable process conditions.

In addition to the mathematical models, many numerical simulation models were developed to simulate the process behavior of injection molding. Hiber and Shen²⁴ and Wang et al.²⁵ employed a finite-element/finite difference

scheme for simulating filling of thin cavities of general planar geometry. These models were implemented based on the generalized Hele-Shaw flow for an inelastic, non-Newtonian fluid under the nonisothermal conditions. Chiang et al.²⁶ developed a unified simulation model for the filling and postfilling stages on the basis of the hybrid finite-element/finite difference numerical solution of the generalized Hele-Shaw flow for the compressive viscous fluid under the nonisothermal conditions. This 2.5-dimensional Hele-Shaw approach was extended or incorporated by other researchers to simulate mold cooling,²⁷ fiber orientation,²⁸ residual stresses,²⁹ and shrinkage and warpage,^{30,31} as well as various special molding processes such as co-injection molding,³² gas-assisted injection molding,³³ microchip encapsulation,³⁴ injection/compression molding,³⁵ reaction injection molding, and resin transfer molding.³⁶ Zhou et al.^{37,38} presented a surface-model-based simulation which still used the Hele-Shaw assumption, but represented a three-dimensional part with a boundary mesh instead of the mid-plane.

Some fluid behaviors at the free surface (flow front), near and at the solid walls, and at the merging of two or more fluid streams cannot be accurately predicted using the Hele-Shaw approximation.³⁹ To date, several full three-dimensional simulation approaches for injection molding have been developed. Rajupalem et al.,^{40,41} Kim and Turng,⁴² Zhou et al.⁴³ and Cheng et al.⁴⁴ used equal-order velocity–pressure formulations to solve the Stokes equations in their three-dimensional mold filling simulation. Haagh and Van De Vosse⁴⁵ implemented a finite-element program for injection molding filling, which employed a pseudoconcentration method. Hetu et al.⁴⁶ employed the Petrov–Galerkin method to prevent these potential numerical instabilities. Chang and Yang⁴⁷ developed a numerical simulation program for mold filling on the basis of an implicit finite-volume approach. Estacio and Mangiavacchi⁴⁸ and Jiang et al.⁴⁹ used the control-volume-based finite-element-method (CVFEM) to solve flow and heat transfer in injection molding.

Considering the fact that product properties are, to a great extent, affected by internal structures (morphology),⁵⁰ numerical simulation of the effect of operative conditions of injection molding process on the morphology distribution inside the obtained moldings has been performed, with particular reference to semicrystalline polymers.⁵¹ As for crystallization, the crystallization kinetics models include Avrami model,⁵² Nakamura model,^{53,54} Ozawa model,^{55,56} Mo model,^{57,58} Urbanovici–Segal model,^{59–61} and the flow-induced crystallization models.^{62–64} Evolution of crystallization morphology in injection molding is based on the nucleation and growth process.^{51,65–67} In the case of polymer blends, the molding process often gives rise to a heterogeneous microstructure that can be characterized by the size, shape, and distribution of the

constitutive domains.⁶⁸ Direct numerical simulations have been developed for single and multiple droplets behaviors in emulsions.^{69–73} Under the shear (or elongation) stress field in the cavity during processing, a skin–core structure is common in injection-molded parts.^{73,74} The study of orientation is closely related to the fact that orientation will inevitably lead to anisotropy in polymer properties, mainly including molecular orientation^{75–79} and fiber orientation.^{80–84}

Some of the achievements in simulating the injection molding process were commercialized in the simulation packages such as Moldflow, Moldex 3D, HSCAE. Reliable CAE simulation tools could replace the traditional trial-and-error approach and assist to select material, design the product and mold, and set up the molding conditions in a more effective manner. Moreover, some special CAE software could suggest optimal process conditions to achieve acceptable parts by using certain built-in criteria and rules. For example, it is capable to carry out an automated DOE to determine a robust process window for producing “good parts.” And also, several process parameters can be first set step-by-step in the process setup stage, and further refined in the process optimization stage to achieve 100% yield by improving the process robustness and reducing the probability of producing defective parts.^{85,86} Nirkhe and Barry⁸⁶ compared the software-based setup method with the manual approach and the results show that the former approach could obtain process conditions that lead to more consistent part weights and dimensions than the latter approach. Turng and Peic⁸⁷ have integrated a CAE tool with various optimization algorithms to help identify the optimal process conditions to achieve a variety of optimization objectives while satisfying certain constraints. Lam et al.⁸⁸ presented a simulation-based system to assist the determination of process parameters, allowing the designers to specify their intended quality measuring criteria such as minimum cavity pressure and shear stress, a uniform distribution of cooling time, end-of-fill temperature, and volumetric shrinkage.

Although CAE software and mathematical models provide the developer with effective tools, their ability should not be overestimated. They also have many limitations. The underlying assumptions and simplifications in these first-principle models can sometimes lead to discrepancies between the real optimal scheme and those obtained from the models. And also, adequate training is important for proper use of these tools. The analyst should be trained not only in modeling and running the programs but also in traditional molding and design.

1.3.4 Optimization

Optimizations in injection molding have already been very popular with modern industries showing their substantial

power in competitiveness enhancement. Computer optimizations can be classified into two categories: noniteration methods (such as gray relational analysis, ES, fuzzy logic, and CBR) and intelligent optimization algorithms (including GA, simulated annealing algorithm, and particle swarm algorithm). And recently, surrogate modeling is often employed in optimization, including response surface method, ANN, and support vector regression. Only some of these methods are reviewed in this section. It should be noted that numerical simulation trials are sometimes used as data sources of optimization algorithms.

DOE techniques, especially the Taguchi method, were widely used to generate meaningful experimental data and determine optimal process parameters for injection molding.^{89–92} These studies show that Taguchi parameter design can uncover subtle interactions among process variables with a minimum number of test runs. For instance, Liao et al.⁹³ started with the process conditions suggested by a CAE tool and then optimized them with DOE to minimize the shrinkage and warpage of a cellular housing part. To improve the effectiveness of DOE, other techniques were incorporated with the Taguchi method. Yeung and Lau⁹⁴ attempted to link quality function deployment (QFD) with DOE to establish a prioritization mechanism for setting the selected parameters with respect to all of the quality characteristics. Kuhmann and Ehrenstein⁹⁵ combined the Taguchi method and the Shainin method to improve the robustness of the injection molding process.

Amidst the diverse ways of building the AI models, ANN is one of the widely used methods.^{96–99} Generally, ANN approaches were applied far and wide in building a process model for quality control in injection molding.^{100–106} In these approaches, some indices of part quality, such as weight, thickness, warpage, shrinkage, flash, and/or strength, are established as the output of neural networks while the inputs are either the process conditions (such as injection speed, holding pressure, holding time, cooling temperature, and barrel temperature) or the processing variables (such as nozzle pressure, cavity pressure, and melt temperature), or a combination of them. For example, the ANN method was successfully used in predicting the shrinkage and warpage of injection-molded thin-wall parts.¹⁰⁷ It is not surprising that networks based on processing variables could predict the part quality more accurately than those based on process conditions. Note that the ANN model has to be trained with a set of well-prepared data capable of describing the process sufficiently accurately. Otherwise, the model would only have little use.

The ES simulates the human reasoning process by applying specific knowledge and inference. A typical ES consists of two major elements: the knowledge base and the inference engine. Quite a few ESs were developed to recommend the qualitative correction instructions¹⁰⁸ and/or the quantitative change of molding parameters in response

to the input molding defects. Jan and O'Brien^{109,110} developed an algorithm to calculate the decision indices that show the likelihood of the influencing variables responsible for defects. They were used to specify the assurance of possible remedies for the given injection molding problems.^{111,112} Kameoka et al.¹¹³ applied the multidimensional matrix technique to develop an ES called *ESIM* so as to realize the skilled operators' inference procedures into the system. Kimura et al.,¹¹⁴ Dwivedi et al.,¹¹⁵ and Mok et al.^{116,117} developed integrated knowledge-based systems for mold design support in which flexible representation frameworks were studied for various types of expert knowledge. Bozdana and Eyercioglu¹¹⁸ developed a frame-based, modular and interactive ES (called *EX-PIMM*) for the determination of the injection molding parameters of TP materials.

Fuzzy logic was applied in the development of an ES, which can recommend the quantitative change of molding parameters.¹¹⁹ Tan and Yuen¹²⁰ proposed a fuzzy multiple-objective approach to set up the process for minimizing injection molding defects. In their study, the defects were expressed by a scale number through fuzzy functions. The relationship between the severities of the defects and the machine variables was approximated by a set of quadratic polynomials via regression analysis. Chiang and Chang¹²¹ applied a gray-fuzzy logic approach for the optimization of machining parameters to an injection-molded part with a thin shell feature. Through the gray-fuzzy logic analysis, the optimization of complicated multiple performance characteristics can be converted into the optimization of a single gray-fuzzy reasoning grade.

The basic idea of CBR is that a case-based reasoner solves a new problem by adapting the solutions that were used to solve the old problems. Kwong and colleagues developed a CBR system,^{122,123} a CBR system combined with fuzzy logic and neural networks,¹²⁴ and an intelligent hybrid system,^{125,126} to determine the initial process conditions. In their study, the model of the process was in the form of a case library. The match of the current problem with the library was solved through fuzzy inference, and the case adaptation was implemented in neural networks. Shelesh-Nezhad and Siores¹²⁷ also applied the CBR approach in deriving the first trial parameter setting of injection molding. Kwong¹²⁸ developed a case-based system for process design of injection molding, which aims to derive a process solution for injection molding quickly and easily without relying on the experienced molding personnel. Huang and Li¹²⁹ proposed a hybrid approach of CBR and Group Technology (GT) for injection mold design.

GA approach has been applied to develop optimization systems for the process parameters of injection molding.^{130,131} Because optimization of process parameters for injection molding is not a static process, an optimization

system called *Ibos-Pro* has been developed on the basis of evolutionary strategies approach for on-line optimization of the process parameters.¹³² On the other hand, once a minimal region is identified during the search process of GA in process conditions optimization, it is inefficient, even sometimes impossible, in reaching its minimum. Here, the gradient method can help to guarantee a local minimum.¹³³ Recently, a microgenetic algorithm (mGA)-based approach was presented to solve biobjective optimization of an injection mold design problem, such as gate positioning^{134,135}; a distributed multipopulation GA was used to optimize injection molding with weld line design constraint¹³⁶; and a multiobjective GA, denoted as *Reduced Pareto Set Genetic Algorithm with Elitism*, was applied to the optimization of the injection molding process.¹³⁷

Deng et al.¹³⁸ proposed a PSO (particle swarm optimization) algorithm for the optimization of multiclass design variables, including product characteristics (part thickness), process conditions (injection temperature, mold temperature, and injection speed), and mold configuration (gate location). The optimization is targeted at different aspects of molding quality, including part warpage, weld lines, and air traps. A computer program was developed that automates the steps such as adjusting the part thickness, the injection molding process parameters, and the gate location, activating the CAE software to simulate the injection molding process, retrieving the simulation results, and evaluating the objective functions.

From the above applications, it can be seen that different AI methods were often combined together in injection molding optimization so as to exploit their respective advantages. As a more representative example, Chen et al.¹³⁹ presented a hybrid approach for the process parameters optimization, which integrated Taguchi's parameter design method, back-propagation neural networks, GAs, and engineering optimization concepts.

The optimal design scheme and process conditions set by the above-mentioned methods are assumed to exist and remain constant for a specific combination of machine, mold, and material. However, this assumption may not be true in a real process, given various unexpected disturbances. Therefore, it requires some methodology to adjust the conditions in order to compensate for the disturbances and to improve the process control of the machine to minimize the disturbances.

1.3.5 Process Control

Process control and monitoring provide continual support toward achieving a higher level of technology implementation to meet performance demands at the lowest cost. Control systems available at present include feedback control, feed forward control, advanced control, learning control, etc. And monitoring may refer to the most lately

statistical process control (SPC), multivariate statistics, and multiphase statistical process control.

At present, there are many commercial control systems available in the market for the injection molding machine (e.g., Pro-Set,¹⁴⁰ Xtream XP,¹⁴¹ and MMI¹⁴²). These systems usually include function modules for controlling position/velocity, pressure, temperature, and motion sequences. Well suited for injection molding machine control, programmable logic controllers (PLCs) were widely used in these systems.¹⁴³ Typically, a PLC sequence program or logic program is created for controlling a motion sequence such as clamping close/open, ejection, injection unit forward/backward, and safety guard. The injection velocity, ram position, screw rotation speed, hydraulic system pressure at injection, barrel temperature, and coolant temperature can be controlled via a conventional PID (proportional–integral–derivative) controller embedded in the intelligent modules. Recently, some up-to-date machine controllers were built on industrial PCs (personal computers) directly,^{144–147} which brings about numerous benefits, including more powerful processing capabilities as well as more public and open resources available to machine control developers.

Because of unpredictable disturbances, traditional PID control sometimes cannot guarantee high standard machine performance. Therefore, there have been continuous efforts in pursuing advanced control technologies to improve machine control.^{148–158} As the barrel temperature, injection speed, ram position, and hydraulic pressure are closely related to the injection stage, some advanced strategies have been developed to control these parameters.¹⁵² Having obtained the general state equation, numerous modern control algorithms such as linear quadratic optimal control¹⁵⁹ and model predictive control¹⁶⁰ can be applied to achieve better performance than PID.

In particular, Bulgrin and Richards¹⁴⁸ proposed a barrel temperature state control on the basis of a state equation obtained from a lumped heat capacity analysis. Considering the slow responses of injection molding barrel temperature, Yao et al.¹⁶¹ presented a combined strategy using a feedback controller and in iterative learning feedforward (ILFF) controller for barrel temperature control.

Regarding injection velocity, there are many adaptive control schemes reported in the publications, such as the self-tuning regulator (STR) and generalized predictive control (GPC),^{154,162} sliding mode control (SMC),¹⁵⁵ fuzzy logic control (FLC),¹⁵⁶ iterative learning control (ILC),^{157,158} and on-line controller updating.^{163,164} Technically speaking, all of the above control schemes have a common key component—the process model—whose accuracy significantly affects the final performance, even though the proper controller design can partially compensate for a model mismatch.

When using the linear model structure proposed by Wang et al.,¹⁶⁵ Huang et al.¹⁶⁶ presented a predictive control scheme and analyzed the closed-loop properties. Furthermore, on the basis of a linear *auto regressive with exogenous* (ARX) input model, Yang and Gao¹⁵⁴ applied adaptive GPC to ram velocity control and compared it with a self-tuning pole-placement controller enhanced by several measures: antiwindup estimation to eliminate the estimation windup, cycle-to-cycle adaptation to improve the model convergence, and adaptive feedforward and profile shift to improve the tracking speed. They concluded that the adaptive GPC controller performed well over a wide range of process conditions. Furthermore, the GPC design has inherently good tracking performance and excellent tolerance to model mismatch.

As far as the nonlinear model based on physical principles is concerned,¹⁶⁷ it is difficult to design a controller directly from the model owing to its complexity. However, the nonlinear model can be approximated by a simpler model structure, which is suitable for the control while the error resulting from the approximation can be taken into account in design. For example, Tan et al.¹⁵⁵ developed an adaptive sliding mode controller, which was verified through simulation to be capable of achieving tight setpoint regulation. An on-line numerical simulation was developed recently that is capable of predicting state variables such as flow rate, melt temperature, shear rate, and melt viscosity by using real-time data from a nozzle pressure sensor.¹⁶⁸

There are also some unconventional ways to represent the process models. For example, Tsoi and Gao¹⁵⁶ used a fuzzy-logic-based model to control the injection velocity. Their experimental results revealed that the fuzzy logic controller worked well with different molds, materials, barrel temperatures, and injection velocity profiles, suggesting that the fuzzy logic controller has superior performance over the conventional PID controller in response speed, setpoint tracking, noise rejection, and robustness. Because of the cyclical nature of injection molding, it is well suited for an ILC strategy, which uses successive repetitions of the same action to refine the control input. ILC has been employed to control injection velocity by Gao et al.,¹⁵⁷ and to control hydraulic pressure/ram position by Havlicsek and Alleyne,¹⁵² where the traditional open-loop feedforward compensator was combined with feedback optimization control to achieve stable convergence and performance improvement akin to closed-loop control. Considering the difficulty of establishing a process model, a model-free self-organizing fuzzy controller (SOFC) was developed to control the molding machine.¹⁴⁶ Experimental results demonstrated that the SOFC exhibits better control performance than the fuzzy logic controller or the PID controller in controlling the screw velocity and the holding pressure.

Advanced control algorithms such as adaptive control and model predictive control have been adopted to deal with the inherent process nonlinearity and time-varying characteristics. These control algorithms are all focused on single-cycle control performance. Recently, a multicycle, two-dimensional model predictive learning control has been developed for batch process control.^{169,170} This method has been applied to injection molding.^{171–173}

Most of the work for process control of injection molding has tackled this challenging subject mainly through consistent machine operations or process condition control, that is, controlling the design variables. Recently, direct quality control has been proposed and developed, in which the quality variables, or the processing variables, are used as the setpoint parameters. The quality variables include part weight,^{174,175} flash,^{176,177} etc., whereas the processing variables include mold separation,¹⁷⁸ cavity pressure,^{179,180} melt-front velocity,¹⁸¹ etc. One essential difficulty in direct quality control is the lack of a quantitative description of the complex relation between the final quality and the process conditions. Another difficulty is how to measure the part quality and processing variables on-line. Fung et al.¹⁸² applied an in-mold capacitive transducer for on-line part weight prediction. Chen et al.¹⁷⁸ used a precision linear displacement transducer mounted on the outside of mold plates to monitor the momentary separation of the core and cavity plates. Chen et al.¹⁸³ developed a soft-sensor scheme for melt-flow-length measurement during injection mold filling. Panchal and Kazmer¹⁸⁴ developed a button cell type in-mold shrinkage sensor to measure in-mold shrinkage.

In addition to the control of machine variables, there is a unique sequence control in injection molding, which is the switchover point from the injection phase to the pack/hold phase. Typical signals used for determining the switchover point include machine variables such as time, ram position, and/or hydraulic pressure, as well as process variables such as nozzle pressure and cavity pressure. Chang¹⁸⁵ compared the process capability of five switchover modes where the part quality of weight and dimension were concerned. The research concluded that the desirable modes for switchover should be based on, in descending order, cavity pressure, hydraulic pressure, stroke, time, and speed. A similar sequence was also suggested in other independent works (e.g., Sheth et al.¹⁸⁶). Owing to the abrupt changes that occur at the moment of switchover, large disturbances could be introduced into the system. Zheng and Alleyne¹⁸⁷ developed a comprehensive model representing an injection molding machine with fill-to-pack dynamics and proposed a bumpless transfer in order to achieve a smooth transition from filling to packing. As the nonlinear and time-varying characteristics are inherent in the injection molding machine, advanced adaptive process control technologies are capable of reaching higher

standard performance than conventional PID if the machine dynamics are well modeled.

1.4 OBJECTIVE OF THIS BOOK

In conclusion, applications of plastic products have grown phenomenally during the last several decades, and injection molding is the predominant production process. Guaranteeing high quality of the final molded product is important but difficult to implement because so many interrelated factors are involved. It requires the integration of skills that include an understanding of the complex characteristics of plastic materials, product design, mold design, process conditions, and process control. In other words, the ideal developer should be a part designer, a mold designer, a process engineer, a materials specialist, and even a machine specialist. This problem will not be solved as long as one deals with injection molding. The best we can do is to acknowledge the problem and seek skills and tools to overcome it. Computer modeling technology is one tool that provides the engineer with a link through all the elements in the development of a plastic product.

Computer modeling for quality enhancement of injection molding can be organized into three categories: numerical simulation, optimization, and process control. These three terms are taken from the latest computer technologies and have become synonymous with future competitiveness for injection molding firms.

Although there have been some introductory books on computer modeling of injection molding, none of them has involved all the above three essential ingredients on the purpose of improving the product quality, only discussing either the fundamentals or a specific aspect. As a result, the major problem for students and researchers who are desirous of acquiring 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 turn to wade through stacks of published papers looking for useful information. This book will serve as a systematic and comprehensive introductory textbook on the computer modeling for quality enhancement of 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.

The objective of this book is to provide 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. In general, the reader will obtain a comprehensive understanding and much practical knowledge about how the latest computer technology can benefit the injection molding industry.

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