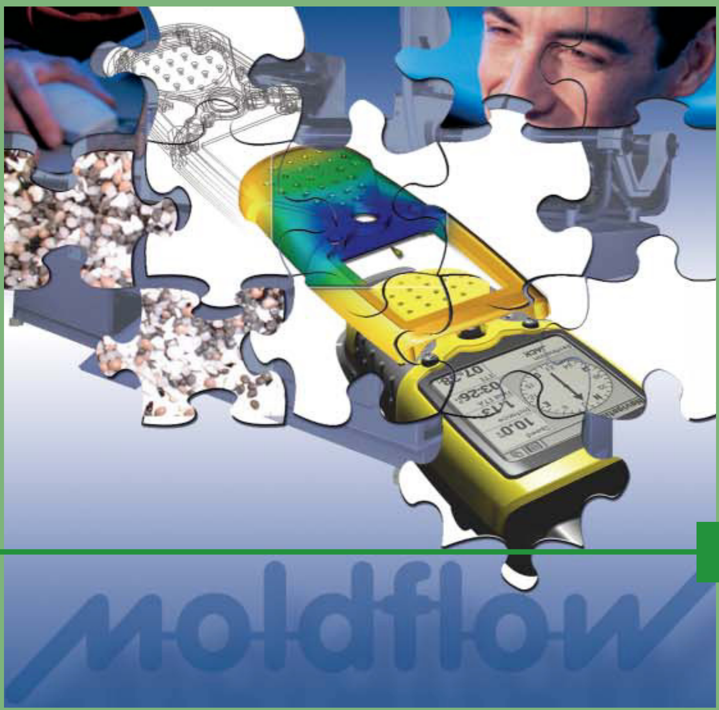
Jay Shoemaker (Ed.)

Moldflow Design Guide

A Resource for Plastics Engineers



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Foreword

The drive toward fast, cost-effective, and reliable plastics manufacturing has been Moldflow's sole guiding goal since the company was founded over 25 years ago.

This focused determination led us to introduce many new and exciting tools into the market, each contributing to achieving our goal in some way, whether by driving cost out of production with reduced material usage or shortened cycle times, reducing mold delivery time by minimizing re-work, or increasing the reliability of supply by enabling higher quality products to be manufactured with greater surety in scheduling.

The artificially balanced, multi-cavity and family molds that are now commonplace were made practical through the advent of our early simulation and runner balancing capabilities, which were introduced in the late 1970s and early 1980s. As these tools evolved, we were able to visualize, and therefore control, flow patterns and weld lines. This evolution continued until we arrived in the 2000s with an array of sophisticated technology to control warpage, account for heat transfer, predict core shift, adapt to new molding processes, and much more. From traditional midplane technology to fully three-dimensional simulations, all our solutions are well integrated into a solid-modeling design environment.

As the technology has evolved, so has its usage. When Moldflow simulation technology was introduced, its primary purpose was to search for remedies to pre-existing molding problems. It soon became evident that the insight the software provided to solve molding problems would be better applied ahead of actual molding, during the design process. This methodology, which we call "problem avoidance," was the primary use for Moldflow technology for the first 20 years of its existence.

For Moldflow, this created a unique challenge: to open the world of manufacturing to the designers of parts and molds. What constitutes an ineffective design for molding may be apparent to a seasoned processing engineer looking retrospectively at a poorly performing tool, but how can design engineers use the CAE tools to visualize, diagnose and solve these same issues ahead of time—without 20 years of molding experience? How can manufacturers go further and use information that cannot be seen in the real molding process but is revealed via simulation?

The key that unlocked this puzzle began its life as the *Moldflow Design Philosophy.* This is widely viewed as the most important publication Moldflow has ever produced and has spawned follow-on works on related subjects. Rather than provide insight into the operation of the simulation tools, *Moldflow Design Philosophy* set forth simple principles that transcend any specific software application and, as a result, are as valid with today's advanced simulation products as they were over two decades ago.

In more recent years, another transition has occurred. The global imperative to drive down the cost of manufacturing has led to the use of molding simulation as a cost optimization tool rather than for problem avoidance. This change has increased the number of Moldflow users by an order of magnitude across a far broader cross-section of the plastics industry. Greater design-centricity leads to even more dependence on the plastics design principles, which can be used to drive optimization.

Despite a quarter of a century of technological advances, the golden years of CAE are ahead of us as our industry takes a broader and more integrated view of what it takes to manage a product's life cycle. Moldflow is proud of its contributions to date and will continue to focus on developing innovative technology coupled with practical design principles to deliver more profitable manufacturing.

Roland Thomas
President & CEO, Moldflow Corporation

Preface

About this Book

The origins of this book include not only *Moldflow Design Principles*, but also *Warpage Design Principles* published by Moldflow, and the *C-MOLD Design Guide*. Collectively, these documents are based on years of experience in the research, theory, and practice of injection molding. These documents are now combined into this book: the *Moldflow Design Guide*. The *Moldflow Design Guide* is intended to help practicing engineers solve problems they frequently encounter in the design of parts and molds, as well as during production. This book can also be used as a reference for training purposes at industrial and educational institutions.

How to Use this Book

This book has several chapters and appendices that deal with different stages of the design process and provides background on the injection-molding process and plastic materials.

- The first three chapters introduce injection molding how polymers flow inside injection molds and how molding conditions and injection pressure influence the process.
- Chapter 4 discusses Moldflow design principles and how they relate to making quality parts.
- Chapter 5 introduces the finite element mesh technology used by Moldflow and how these meshes influence the quality of the analysis.
- Chapters 6 to 9 introduce design concepts for the product, gates, runners, and cooling systems.
- Chapter 10 introduces concepts relating to shrinkage and warpage and how Moldflow is used to determine the amount of shrinkage and warpage a molded part will have and what causes the warpage.
- Chapter 11 discusses the design procedure for analyzing injection-molded parts.
- Chapter 12 discusses major part defects found on injection-molded parts.
- Finally the four appendices discuss basic injection-molding machine operation, process control, variants of the standard injection-molding process, and plastic materials.

Benefits of Using CAE

The injection-molding industry has recognized that computer-aided engineering (CAE) enhances an engineer's ability to handle all aspects of the polymer injection-molding process, benefiting productivity, product quality, timeliness, and cost. This is illustrated by a wealth of literature and the ever-growing number of CAE software users in the injection-molding industry.

CAE Predicts Process Behavior

Ideally, CAE analysis provides insight that is useful in designing parts, molds, and molding processes. Without it, we rely on previous experience, intuition, prototyping, or molding trials to obtain information such as polymer melt filling patterns, weld-line and air-trap locations, required injection pressure and clamp tonnage, fiber orientation, cycle time, final part shape and deformation, and mechanical properties of molded parts, just to name a few. Without CAE analysis, other equally important design data, such as spatial distributions of pressure, temperature, shear rate, shear stress, and velocity, are more difficult to obtain, even with a well-instrumented mold. The process behavior predicted by CAE can help novice engineers overcome the lack of previous experience and assist experienced engineers in pinpointing factors that may otherwise be overlooked. By using CAE analysis to iterate and evaluate alternative designs and competing materials, engineering know-how in the form of design guidelines can be established relatively faster and more cost-effectively.

User Proficiency Determines the Benefits of CAE

While CAE technology helps save time, money, and raw material, as well as cuts scrap, reduces the rejection rate, improves product quality, and gets new products to market faster, it is by no means a panacea for solving all molding problems. Rather, it should be recognized that CAE analysis is essentially a tool, designed to assist engineers instead of taking over their responsibilities or replacing them. Like many other tools, the usefulness of CAE technology depends on the proficiency of the user. The benefits mentioned above will not be realized unless the CAE tool is used properly. To be more specific, the accuracy of CAE analysis depends greatly on the input data provided by the user. In addition, the results generated by CAE analysis need to be correctly and intelligently interpreted by the user before sound judgments and rational decisions are made. Otherwise, users will simply be swamped by the vast amount of data without getting any useful information.

Acknowledgements

The *Moldflow Design Guide* would not have been accomplished were it not for the vision of Ken Welch. Ken and I have discussed the value of assembling the best of the *Moldflow Design Principles*, *Warpage Design Principles*, and the *C-MOLD Design Guide* into a single book for several years. With Ken's leadership, he gave the project to Steve Thompson's training group, of which I am a part. Steve helped me coordinate the resources necessary to get this project done. I could not have done this project without Steve's help and guidance.

A review of the content was part of the development of the *Moldflow Design Guide*. Moldflow developers including Peter Kennedy, Rong Zheng, Zhongshuang Yuan, and Xiaoshi Jin have reviewed sections of the book. Moldflow's application engineers and other technical staff with Moldflow have also reviewed sections. These reviewers include Chad Fuhrman, Matt Jaworski, Christine Roedlich, Eric Henry, Olivier Anninos, Paul Larter, and Ana Maria Marin. A special thanks goes to Mike Rogers, who reviewed the entire book for me and provided critical feedback on the content and organization of the book. I would also like to thank Kurt Hayden of Western Michigan University for reviewing the appendix on process control. His many years of experience of process setup and optimization was invaluable.

Finally, I would like to thank members of Moldflow's Technology Transfer group for supporting me in the writing of this book. These members include Marcia Swan, Caroline Dorin, Robert Ashley, Melissa Haslam, Darren Seamons, and Gregory Brown.

On a personal note, I would like to acknowledge and thank Paul Engelmann, Professor and Department Chair, Western Michigan University, Department of Industrial and Manufacturing Engineering, for being my friend and mentor during my career. With Paul, I have been able to teach and participate in research he has done on injection molding tooling and processing at Western Michigan University. I have found working with Paul has made me a better Moldflow user and engineer by providing another perspective on how Moldflow can be used to solve injection molding problems.Jay Shoemaker, Editor

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1 Polymer Flow Behavior in Injection Molds

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1.1 Phases of Injection Molding

Any molder can prove that all the conditions and effects discussed in this chapter do indeed occur during the injection molding process. While this knowledge alone can somewhat improve quality, it is only with the use of Moldflow analysis during the initial design stage, with the mold designed for the optimum filling pattern, that these effects can be controlled and the full benefits obtained.

Flow technology is concerned with the behavior of plastics during the mold filling process. A plastic part's properties depend on how the part is molded. Two parts having identical dimensions and made from the same material but molded under different conditions will have different stress and shrinkage levels and will behave differently in the field, meaning that they are in practice two different parts.

The way the plastic flows into the mold is of paramount importance in determining the quality of the part. The process of filling the mold can be distinctly analyzed with the ability to predict pressure, temperature, and stress.

1.1.1 How Plastic Fills a Mold

This was investigated using a centrally gated mold shaped like a dinner plate with a thick rim around the outside as shown in Figure 1.1. It was found that the injection molding process, although complex, could be divided into three phases (we use the word *phase* to avoid confusion with injection stage, as used with programmed injection).

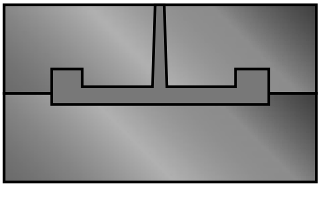

Figure 1.1 Cross-section of disk mold used to investigate flow

1.1.1.1 Filling Phase

As the ram moves forward, it first moves at a steady speed as the plastic flows into the cavity. This is the filling phase. This phase lasts until the mold is just filled. See Figure 1.2 and Figure 1.3.

1.1.1.2 Pressurization Phase

The pressurization phase begins when the ram moves forward after the filling phase to bring the mold up to pressure. When the mold is filled, the ram will slow down, but it still moves quite some distance because plastics are very compressible materials. At injection molding pressure, an extra 15% volume of material can be forced into the cavity. See Figure 1.2 and Figure 1.3.

Although fluids are usually assumed to be incompressible, molten plastics have to be considered to be more like a gas. The compressibility of plastics can be observed by blocking off the nozzle and attempting to purge the barrel. The ram will jump forward when the pressure is applied, but will spring back when the pressure is released.

1.1.1.3 Compensation Phase

After the pressurization phase, the ram still does not stop completely, continuing to creep forward for some time. Plastics have a very large volumetric change of about 25% from the melt to the solid. This can be seen in a short shot; the difference in volume between the molding and the cavity is due to this volumetric change. See Figure 1.2 and Figure 1.3.

The ram moving forward to compensate for the volumetric change in the part is called the compensation phase. As the volumetric change is 25% and, at the most, only an extra 15% can be injected in the pressurization phase, there must always be some compensation phase.

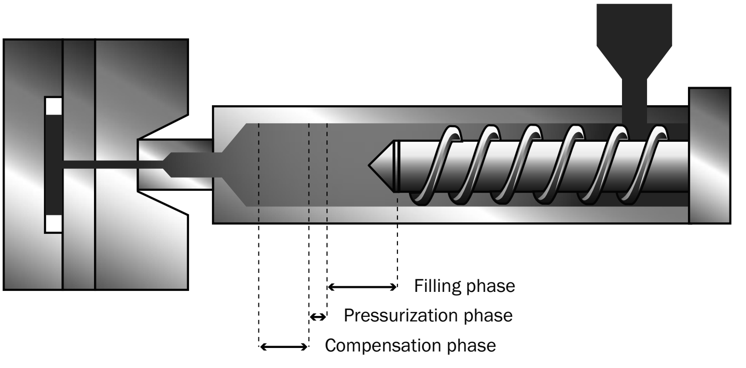

Figure 1.2 Phases of injection molding

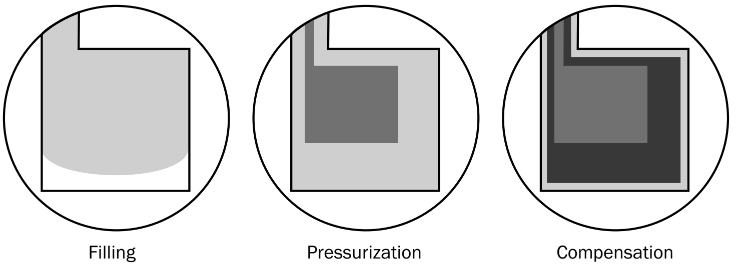

Figure 1.3 Phases of injection molding detail

1.1.2 The Filling Phase

A two-color technique best demonstrates this phase. After emptying the barrel of an injection-molding machine, a small amount of red plastic was charged, followed by green plastic.

Consider the closed mold with the plastic front just starting to flow from the nozzle. The plastic first fills the sprue and runner system, then enters the mold cavity itself, forming a small bubble of molten plastic.

The skin of the plastic in contact with the cool mold freezes rapidly, while the central core remains molten. When additional material is injected, it flows into this central core, displacing the material already there, which then forms a new *flow front*. The flow of this displaced material is a combination of forward flow and outward flow. The outward flow contacts the wall, freezes, and forms the next section of skin while the forward flow forms the new molten core. When more material enters the mold, it flows along a channel lined with these frozen walls of plastic, illustrated in Figure 1.4.

This flow pattern is often called *fountain flow* or *bubble flow* because the flow front is like a bubble being inflated with hot plastic from the center. The frozen layer is formed by the flow front inflating, and so is subject to only a low shear stress and, therefore, has a very low level of molecular orientation. Once it is frozen it cannot be orientated any further, so the frozen layer in the finished part has a low level of orientation.

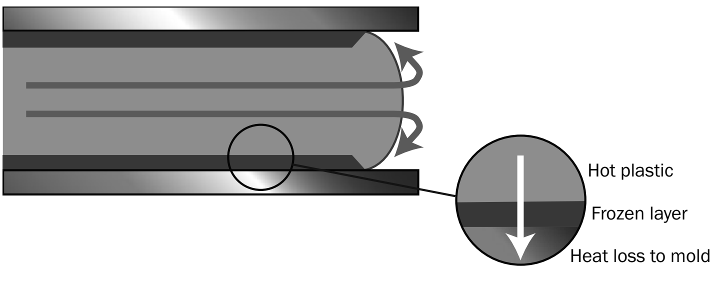

Figure 1.4 Fountain flow and heat transfer

Now, consider what happens upstream. Hot plastic is continuously flowing, bringing new hot material along and generating significant frictional heat. At the same time, heat is being lost through the frozen layer to the cold mold surface.

Initially, the frozen layer is very thin, so heat is lost very rapidly. This results in more plastic freezing and the frozen layer getting thicker, cutting down the heat flow. After a time, the frozen layer will reach a thickness such that the heat lost by conduction is equal to the heat input from plastic flow and frictional heating, i.e., an equilibrium condition is reached (Figure 1.4).

It is interesting to do some calculations on the time taken to reach this state of equilibrium. The actual rate of heat flow is very large in comparison with the small heat content of the plastic in the frozen layer. The result is that equilibrium is reached very quickly, often in a time measured in a few tenths of a second. As the total filling time is measured in seconds, the frozen layer reaches an equilibrium state early in the filling cycle.

It is useful to think about how the thickness of this frozen layer will vary. If the injection rate were slowed, less heat would be generated by friction along the flow path, with less heat input from the flow. The heat loss would be at the same rate, and with less heat input the frozen layer would grow in thickness. If the injection rate were raised, the frozen layer would be thinner (Figure 1.5). Similarly, higher melt and mold temperatures would reduce the thickness of the frozen layer. This can be seen experimentally using the two-color technique.

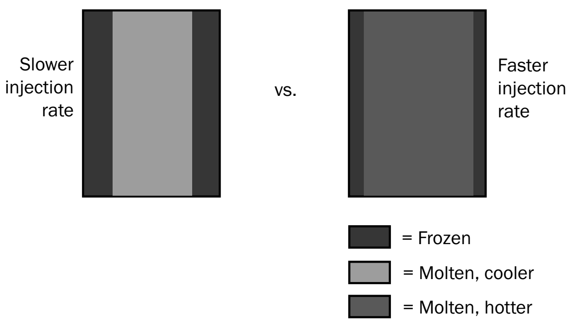

Figure 1.5 Influence of injection rate on frozen layer thickness

1.1.2.1 Flow Shear Stress

It is easy to get confused between the various stress levels and orientation of the polymer. As the plastic flows it is subject to *shear stress*, also called *flow shear stress*. This flow shear stress will orient the material, i.e., cause the molecules to align themselves in the general direction of flow.

The shear stress varies from a maximum at the outside, dropping off to zero at the center.

Shear stress is purely a function of force and area. This must not be confused with shear rate, which is the rate of plastic sliding over the next layer. Shear rate is zero at the outer edge where the plastic is frozen, rises to a maximum just inwards of the frozen layer, then drops toward the center, as shown in Figure 1.6.

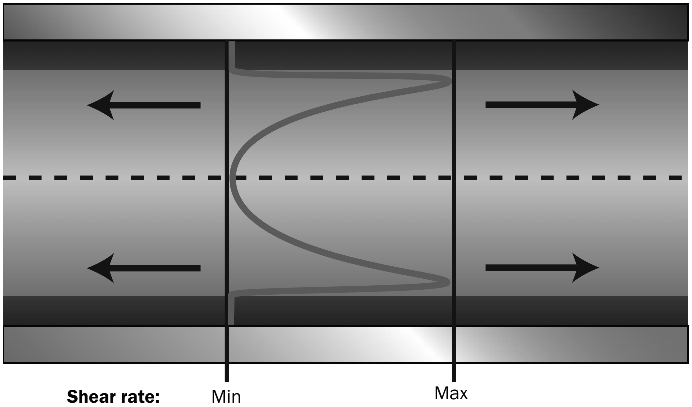

Figure 1.6 Shear rate distribution

If the flow were stopped and the plastic allowed to cool down very slowly, this orientation would have time to relax, giving a very low level of residual orientation. On the other hand, if the material were kept under stress and the plastic snap frozen, most of the orientation would be trapped in the frozen plastic (Figure 1.7).

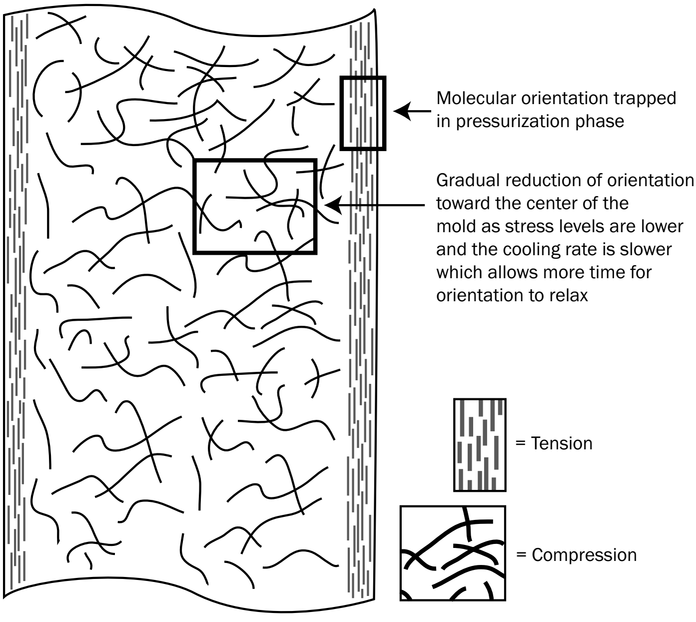

Figure 1.7 Molecular orientation through the thickness of the part

Now consider the orientation from the mold surface toward the center.

The frozen layer itself, formed with very little shear and therefore low orientation, immediately freezes, "setting" the low level of orientation.

The layer of plastic just on the inside of the frozen layer is subject to maximum shear stress and freezes the instant flow stops, trapping almost all the orientation.

This is the orientation pattern: the further toward the center, the more the shear stress drops and the slower the rate of cooling. This allows more time for the level of orientation to relax, so the residual orientation drops rapidly toward the center. Consider how this pattern will affect the residual stress level. Oriented material (normally) will shrink more than nonoriented material. On the inner surface of the original frozen layer, highly oriented material wants to shrink a great deal, but it is prevented from doing so by the less-oriented material. The highly oriented layer ends up being in tension, while the less-oriented material is in compression.

This residual stress pattern is a common cause of part warpage.

> ✎ There is a connection—through orientation—between the shear stress during filling (flow stress) and the residual stress in the final molded part. This means shear stress during filling, shown on Moldflow plots, can be used as a design parameter.

1.1.3 The Pressurization Phase

The pressurization phase—from the point of view of flow behavior—is very similar to the filling phase. The flow rate may drop somewhat as the mold builds up to pressure, resulting in an increase in the thickness of the frozen layer.

The main difference of course, is the increase in hydrostatic (isotropic) pressure. We shall see in chapter 2, section 2.4 Effect of Molding Conditions, that hydrostatic pressure in itself does not cause any residual stress.

1.1.4 The Compensation Phase

Compensating flow is unstable. Consider the plate molding again (see Figure 1.1). You would think that plastic flowing uniformly through the thin diaphragm would top up the thick rim. In practice, the plastic during the compensation phase flows in rivers that spread out like a delta, as illustrated in Figure 1.8. This may seem surprising at first, but it can be explained by temperature instability.

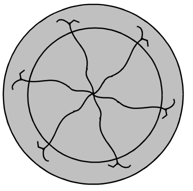

Figure 1.8 River flow

1.1.4.1 Temperature Variation

There is always some variation in melt temperature coming from the barrel of the injection machine. In exceptional cases, up to 40 °C variation has been measured using a high-speed thermocouple..

1.1.4.2 Natural Instability

However slight the temperature variation, natural instability will amplify it. If, for example, one part of the melt is slightly hotter than the rest, then the plastic flow in that area will be slightly greater, bringing hotter material into the area and maintaining the temperature. If, on the other hand, there is another area that is cooler, the flow will be less, so there will be less heat input, and the plastic will get colder until it eventually freezes off.

However balanced the initial conditions, this natural instability will result in a river-type flow. This is a very important consideration. The first material to freeze off will shrink early in the cycle. By the time the material in the river flows freezes, the bulk of the material will have already frozen off and shrinkage will have occurred. The rivers will shrink relative to the bulk of the molding, and because they are highly orientated, shrinkage will be very high. The result is high-stress tensile members throughout the molding, a common cause of warpage.

1.1.4.3 Optimum Part Quality

Most of the stress in plastic parts occurs during the compensation phase. By controlling flow and minimizing stress, it is possible to design for optimum part quality. This important point is at the heart of the Moldflow philosophy.

1.2 How Do Plastics Flow?

1.2.1 Material Behavior

Molten thermoplastics exhibit viscoelastic behavior, which combines flow characteristics of both viscous liquids and elastic solids. When a viscous liquid flows, the energy that causes the deformation is dissipated and becomes viscous heat. On the other hand, when an elastic solid is deformed, the driving energy is stored. For example, the flow of water is a typical viscous flow, whereas the deformation of a rubber cube falls into the elastic category.

1.2.2 Deformation

In addition to the two types of material flow behavior, there are two types of deformation: simple shear and simple extension (elongation), as shown in Figure 1.9 (a) and (b) below. The flow of molten thermoplastics during injection-molding filling is predominantly shear flow, as shown in Figure 1.9 (c), in which layers of material elements "slide" over each other. The extensional flow, however, becomes significant as the material elements undergo elongation when the melt passes areas of abrupt dimensional change (e.g., a gate region), as shown in Figure 1.9 (d).

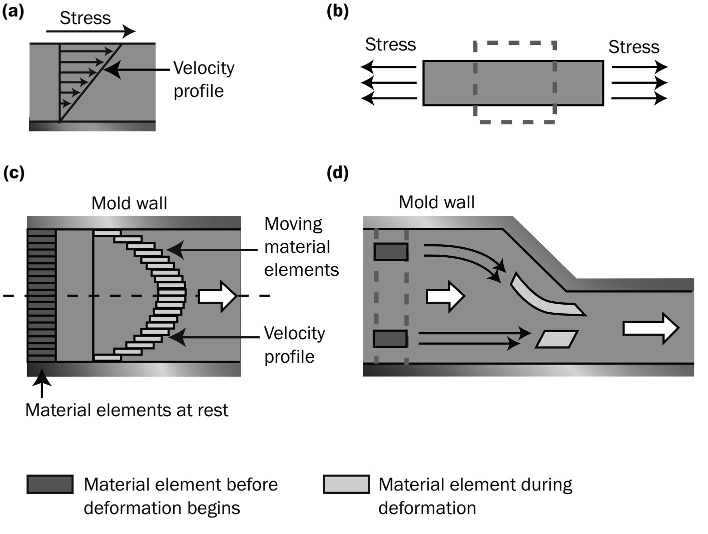

Figure 1.9 (a) Simple shear flow (b) Simple extensional flow (c) Shear flow in cavity filling (d) Extensional flow in cavity filling

1.2.3 Viscoelastic Behavior

In response to an applied stress (force per unit area), molten thermoplastics exhibit viscoelastic behavior, which combines characteristics of an ideal viscous liquid with those of an ideal elastic solid. In other words, under certain conditions, molten thermoplastics behave like a liquid and will continuously deform while shear stress is applied, as shown in Figure 1.10. Upon the removal of the stress, however, the materials behave somewhat like an elastic solid with partial recovery of the deformation, as shown in Figure 1.10 (b) and (c). This viscoelastic behavior stems from the random-coil configuration of polymer molecules in the molten state, which allows the movement and slippage of molecular chains under the influence of an applied load. However, the entanglement of the polymer molecular chains also makes the system behave like an elastic solid upon the application and removal of the external load. Namely, on removal of the stress, chains will tend to return to the equilibrium random-coil state and thus will be a component of stress recovery. The recovery is not instantaneous because of the entanglements still present in the system.

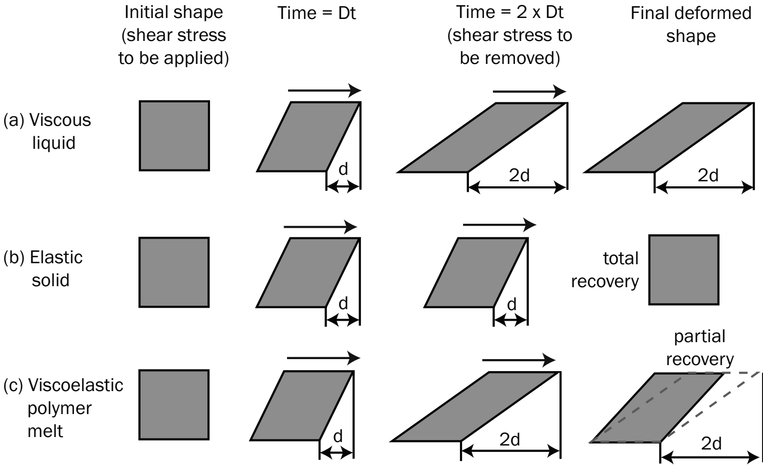

Figure 1.10 (a) Ideal viscous liquid deforms continuously under applied stress (b) Ideal elastic solid deforms immediately upon the application of stress, but fully recovers when the stress is removed (c) Molten thermoplastic deforms continuously under the applied stress (like a viscous liquid), but also recovers partially from the deformation upon removal of the applied stress (like an elastic solid)

1.2.4 Melt Shear Viscosity

1.2.4.1 What Is Shear Viscosity?

Melt shear viscosity is a material's resistance to shear flow. In general, polymer melts are highly viscous because of their long molecular chain structure. The viscosity of a polymer melt ranges from 2 to 3,000 Pa.s (water 10^-1 Pa.s, glass 10^20 Pa.s). Viscosity can be thought of as the thickness of a fluid, or how much it resists flow. Viscosity is expressed as the ratio of shear stress (force per unit area) to the shear rate (rate change of shear strain), as shown in Equation 1.1 and Figure 1.11: