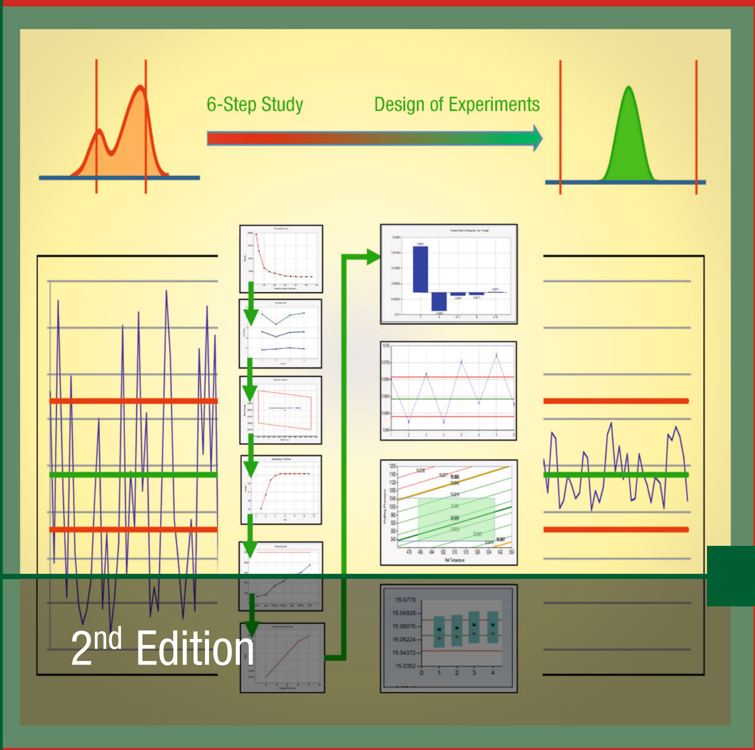
Suhas Kulkarni

# Robust Process Development and Scientific Molding

## Theory and Practice




2nd Edition

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Dedicated to my Parents

Dr. Mohan P Kulkarni

Jayashree M Kulkarni

# Preface to the Second Edition

As the saying goes "the only thing that is constant is change." It has been six years since the first edition of this book was published, and it has been very well received. Thank you to all its readers. Since then, I have continued my research to further understand the process of injection molding with the final goal of robust process development. As I kept publishing and teaching this new material, it became time to revise the book.

This second edition has new material in almost all the chapters. Some concepts, which were explained in the first edition, have been expanded upon and rewritten for better understanding. Several figures have been added to complement the explanations. Some of the chapters and text have been split up and rearranged to have a better flow of understanding. A complete chapter on "Basic Quality Concepts" has also been added.

The topic of process development is a complex one, but once the concepts are understood, implementation is easy. The key is to understand the basics first. Over the years, in my consulting business, I often get called on by companies to 'fix' their processes. I always go back to the basics and ask them several simple questions about their molds, machines, and processes to which they sometimes have no answer, or when they do answer my questions, they figure out the solution to the problem on their own. Their process development was probably done by throwing darts on a dartboard and hence the issues. This book is attempting to change that. By using the techniques described in this book, one can establish what I call *cruise control processes*: set the process, start molding, and never touch a setting until the run is done.

The topic of "Design of Experiments" (DOE) has great importance in injection molding. Many companies employ this technique, but not effectively. The reason is not because of their lack of knowledge of DOE, but because of their lack of understanding of the basics of molding, along with their choice of factors and levels for the DOE. This topic has been expanded in the new edition.

I would like to thank Hanser Publications and their staff for this opportunity to write the second edition. Mark Smith and Cheryl Hamilton have been very helpful

with the proofing and, moreover, very patient with all the delays from my side. I would also like to thank several other people who have helped me with the second edition. Lorena Castro who took all the bits and pieces of my writing and transformed it into readable flow needs a special mention and acknowledgement.

In the preface to the first edition, I failed to mention a very important place that also helped shape my career and my life. The National Chemical Laboratory (NCL), Pune, India, is where my dad worked all his life as a research scientist. I lived in the shadows of this great institution and its several researchers. My dad would often take me to his lab when he conducted his research, and that is where the seeds of my future were laid. I worked on a couple of projects during my college days in its Polymer Engineering Department, and that was my first personal exposure and involvement with research. It was my experience at NCL, which was one of the contributing factors that pushed me to study further.

My constant sources of inspiration and help include Tim and Violeta of Distinctive Plastics, who have opened their company for my research and seminars, my professor from college, Dr. Basargekar, my colleagues in the industry, Ravi Khare, Atul Khandekar, Vishu Shah, Vikram Bhargava, Randy Phillips, and my family.

To my mom, dad, and siblings, I will be forever indebted to you for all the support and inspiration you have given me over the years.

*Suhas Kulkarni*
October 2016

# Preface to First Edition

When I interviewed for my second job after I graduated, I was told that if the position was offered to me, I would have to spend my first three days at a seminar on Scientific Molding and Design of Experiments. It was all new to me then. My job was to implement this new technology as a standard across the company. The job was offered to me; I accepted and attended the seminar. Implementing the techniques on the first couple molds was a refreshing change from how I did it before. The scientific method of developing the process left no room for any guess work by applying the theories of polymer science and injection molding. Scientific evidence proved why parts could be or could not be molded consistently within the required specifications. My enthusiasm for the use of these techniques grew as I found more and more evidence of success. Over the next few years, I gave presentations at the local SPE chapter and the attendees wanted to learn more to make their operations efficient. In 2004 I decided to start consulting in the area of Scientific Processing, a term I coined to include all the processes that are involved in the transformation of the pellet to the final product that is shipped out to the customer. My research work on the 'overdrying' of PBT and Nylon was the main driving force to think of the process as being outside of the molding machine and not just what happens in the mold. As my consulting and teaching career expanded, I found many people looking for a resource to learn the basic underlying principles of polymers and plastics and apply them to injection molding. They wanted to understand the why, and then how of Scientific Processing. 'Where can I find this information?' was always a question that was asked. This book is the answer to their question.

Understanding the molding process from the scientific perspective helps in making better decisions to establish the parameters that are involved in controlling the journey of the pellet; from the warehouse to the molding machine and then to its conversion as a molded product. All the parameters are set on the basis of scientific knowledge and experience making the process efficient in terms of productivity. Higher yield, reduced scrap, robust processes, reduced quality inspection, reduced number of process changes leading to less human intervention are some of the benefits of Scientific Processing. This book details the theory and practice of Scientific Processing. There are a lot of 'rules of thumb' in injection molding. My mission is to eliminate them and present a scientific solution. A good example is the size of vents in the mold.

I hope my commitment to researching and understanding of the molding process will continue to give a better insight to the process. I hope to share those with you in the future editions of this book. There are a number of people who are part of the success of writing this book. Some gave me the knowledge, some inspired me to learn more while others gave me unconditional support in this endeavor. It is impossible to thank all of them individually but without all of them this project would not have been accomplished. First and foremost, special mention must be made of my father who introduced me to the fascinating world of chemical research. It is from here that I get my curiosity, creativity and my analytical abilities of problem solving. Thanks to my teachers and professors who not only imparted the knowledge but also instilled in me the value of education through the dedication to their students. It is from here that I get my inspiration to teach and spread my knowledge. Thanks to my family and friends who have supported me and believed in me. It is from them that I get my will power and courage to get past the current frontiers and take a step into an unknown future.

In the production of this book I would like to thank Christine Strohm and the management of Hanser Publications for publishing the book. The sections on cavity pressure sensing and the chapter on rheology were reviewed by Mike Groleau of RJG and John Beaumont of Beaumont Technologies respectively. Thanks to them for their valuable comments. Thanks also to Dave Hart for proofreading the text and making the matter an interesting technical read. Valuable comments from Ravi Khare of Symphony Technologies were included on the DOE chapter. Without the unconditional help of Tim and Violeta Curnutt of Distinctive Plastics I would have not had the chance to experiment with many of the theories and applications put forward in this book. Special thanks to them for letting me make Distinctive Plastics my home during the book writing process. I am often told I am an effective teacher with clear concepts in polymer science and rheology – I have picked the teaching skills and the knowledge from Prof. Basargekar – my sincere acknowledgements to him. Under the leadership of Vishu Shah I conducted a few successful seminars with the Society of Plastics Engineers. These seminars gave me the fuel and material for this book. Thanks to Vishu not only for the opportunities of the seminars but also for being a professional guide and a personal friend. I would also like to acknowledge the efforts of John Bozzelli and Rod Groleau for their pioneering work in Scientific Molding and raising its awareness in the molding community.

To my alma maters, Maharashtra Institute of Technology, Pune, India and University of Massachusetts, Lowell, USA: Hidden in one of your foundations' bricks are the enriching roots to my success. Thank You.

*Suhas Kulkarni*
FIMMTECH Inc.
Vista, CA.
January 2010

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# 1 Introduction to Scientific Processing

## 1.1 The Evolution and Progress of Injection Molding

Injection molding and extrusion are the most common techniques employed in the manufacture of plastic products. Injection molding of plastics began as an idea by the Hyatt brothers for the manufacture of billiard balls. The idea was borrowed based on a patent by John Smith to inject metal castings. Since then, injection molding of plastics has come a long way. The technique became a popular way to fabricate plastic parts because of the simplicity of the concept, efficiency of production, and the possibility of producing intricate parts with fine details.

The art of injection molding evolved to its present state due to a few key reasons. The requirements of the molded parts became more stringent because of the advances in the fields of science and technology. The demand for tighter tolerances and more complex parts increased and is ever increasing. A required tolerance of a couple thousandths of an inch on a one inch dimension is not uncommon these days. Parts requiring innovative designs, especially designed for assembly (DFA) or parts molded from different materials in the same mold (multi-material molding) are now commonplace. As polymer materials were developed for injection molding, the requirements of processing changed. The discovery of the different morphologies of polymers and the need for better melt homogeneity in molding led to the introduction of the injection screw. Various designs for material-specific screws have followed since. The use of high temperature materials that have high melting points and need high mold temperatures have led to the use of high-temperature ceramic heaters and mold temperature controllers providing higher heat capability. Innovations in electrical and electronic technologies paved the road for machines that could be better controlled, accurate, and efficient. Response times for hydraulic valves can be in milliseconds. All electric machines and hybrid machines are gaining popularity because of their consistency and accuracy. The real time processing parameters of a molding machine can now be viewed from any part of the world via an internet connection and therefore machine production can be monitored or machines can be debugged online. All these features are becoming a common practice among manufacturers. Even some auxiliary equipment can now be debugged and programmed by the suppliers via an internet connection. For the machines tied into the company ERP system, automated messages can be sent to the managers and supervisors about the machine status and quality issues. The need for efficiency and the requirements for advanced product features have dictated the need for innovations in injection molding over the years.

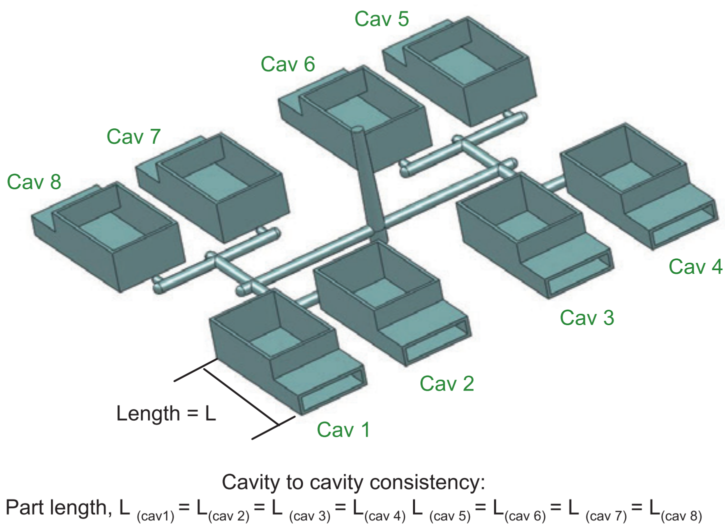
## ■ 1.2 The Molding Process

The actual molding process has been traditionally defined as the inputs to the molding machine. These are the settings of speeds, pressures, temperatures and times such as injection speeds, holding pressure, melt temperature and cooling time. These are inputs one would set at the molding machine and record on a sheet, commonly called the Process Sheet. However, the word process now needs to be redefined as the complete operation that encompasses all the activities the plastic is subjected to inside a molding facility–from when the plastic enters the molding facility as a pellet to when it leaves the facility as a molded part. For example, the storage of the plastic, the control of the drying of the plastic, and the post mold shrinkage of the part can have a significant influence on the quality of the part. During this journey of the pellet, every stage can have a significant effect on the final quality of the part or assembly. Naturally, understanding every stage now becomes imperative if we would like to control the quality of the molded part. Molding a part that meets the quality requirements is not the real challenge. The real challenge is molding parts consistently; cavity to cavity, shot after shot, and from one production run to another meeting all the quality requirements and with the least amount of effort and maximum efficiency.

## ■ 1.3 The Three Types of Consistencies Required in Injection Molding

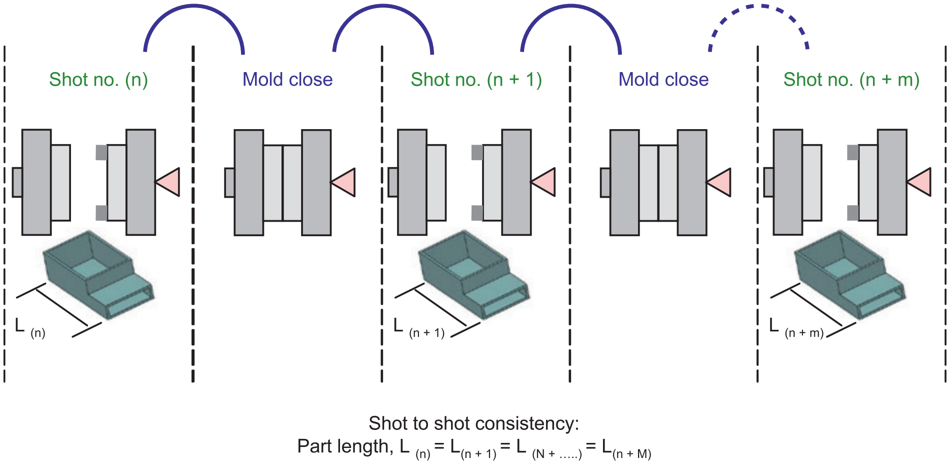
The aim of developing a molding process should be to develop robust processes that would not need any process modifications once the processes are set. Process consistency leads to quality consistency, see Figure 1.1. We look for three different types of consistencies: cavity-to-cavity consistency (Figure 1.1(a)), shot-to-shot consistency (Figure 1.1(b)), and run-to-run consistency (Figure 1.1(c)). Cavity-to-cavity consistency is required in multicavity molds so that each cavity is of the same quality level as the other cavities. Shot-to-shot consistency implies that every consecutive shot would be identical to the previous shot, or the first shot is identical to the last shot of the production run with the process parameters remaining the same during the entire production run. When the process parameters from two different runs are identical and they produce the same quality parts, then this is called run-to-run consistency. Robust and stable processes always yield consistent quality parts with one established process.

There can be several reasons for the three types of consistencies. A cavity-to-cavity inconsistency could be caused because of an error when cutting the steel in one of the cavities or by making one of the gates too large. A shot-to-shot inconsistency could be caused because of a damaged leaking check ring at the end of the molding screw. A run-to-run inconsistency can be caused because of a lack of a robust process or simply because the process was not accurately or completely documented in the previous run. The run to run consistency is the one that most companies struggle with. This book is deals in depth with process development of robust, repeatable and reproducible processes.

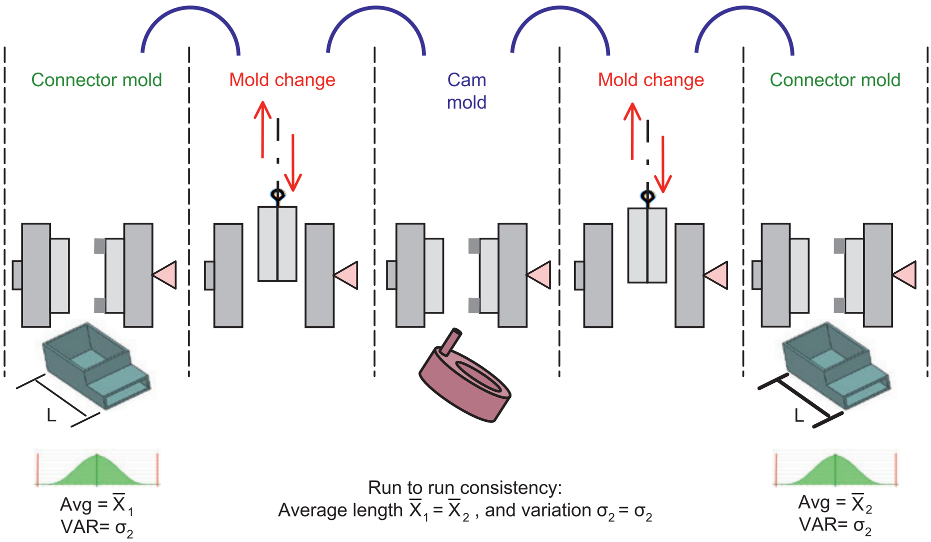



(a) Cavity to cavity consistency

**Figure 1.1** The three types of consistencies required in injection molding




(b) Shot to Shot consistency




(c) Run to run consistency

**Figure 1.1** The three types of consistencies required in injection molding *(continued)*

Another reason for inconsistencies and variations in the molded product is the nature of the shrinkage of plastics. When molten plastic is injected inside a mold it cools and freezes to form the product. There is a reduction in the volume of the melt when it cools inside the mold. This is called shrinkage. The magnitude of shrinkage determines the final dimensions of the part. However, this shrinkage is not easily predictable and depends on a number of factors. There is a range of shrinkage values available and that makes it difficult for a mold maker to select a shrinkage value. For example, the shrinkage value for a low density polyethylene is between 1.3 to 3.1 %, which is a wide range. Shrinkage also depends upon the processing conditions. For example, higher the melt temperature, the higher the shrinkage. Almost every processing parameter can affect the shrinkage to varying degrees. Refer to Figure 1.2, which shows the effect of the molding parameter on the length of the part. To increase or decrease the length of the part, several parameters can be increased or decreased.

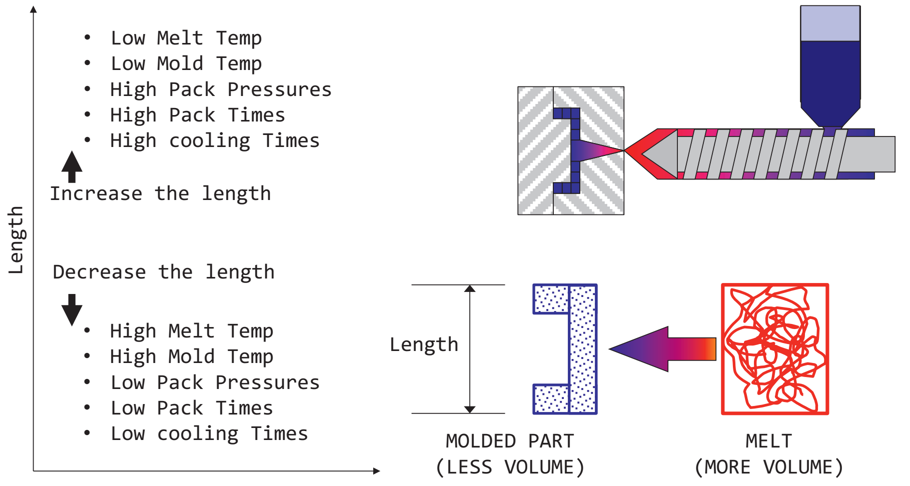



**Figure 1.2** Effect of molding parameters on shrinkage and dimension of a part

As seen in the figure, several parameters can have effect on the part dimension and quality. To increase the length of the part, some parameters need to be increased whereas some need to be decreased. Further, the magnitudes of change in length with change in the parameter varies from parameter to parameter. If the molding processes are not developed with these understandings, and in case the dimensions get out of specifications, each processor can work with any one of the parameters. The net result being that processes that were supposedly approved end up having completely different values in a matter of a few runs. When process sheets are compared, for example, from two years ago, there are hardly any numbers that match the current settings.

It should be the goal of every molder to develop an understanding of the molding process for the given mold. A systematic process development approach must be followed. The result of such an approach is a robust, repeatable and reproducible process: the 3 R's.

A process shown in Figure 1.3 is not acceptable because there is a lot of inefficiency in the system. Such processes result in defective parts, loss of material, loss of time, and not to mention the time and effort put in by the molding personnel. The parts can be remolded and shipped to the customer, however, the time and efforts lost cannot be recovered. The reputation of the molder is something that can also be permanently affected.

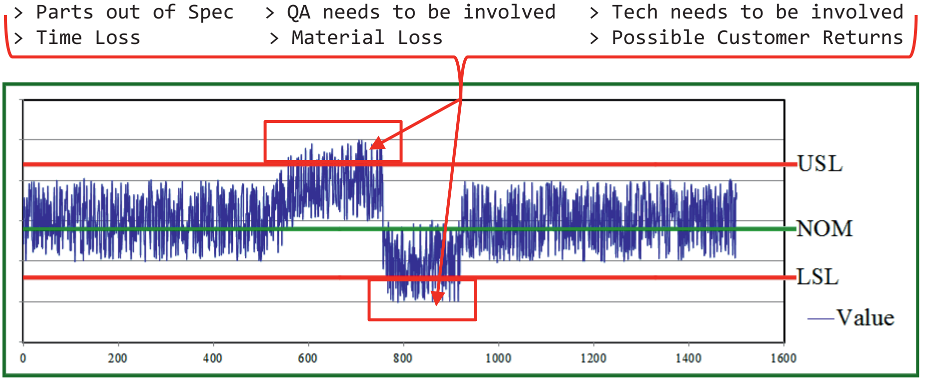



**Figure 1.3** Example of an inefficient process

## ■ 1.4 Scientific Processing

Scientific Processing is the process of achieving consistency in part quality via the application of the underlying scientific principles that control the parameters of the molding process. To achieve this consistency, we must be able to control every activity that is taking place in the process and to control every activity, we must understand the underlying scientific principles. The goal of scientific processing should be to achieve a robust process. Achieving robustness in each of the stages that the pellet travels through automatically translates to an overall robust process. The term consistency must not be confused with the parts being within the required specifications. A consistent process will produce parts that will reflect the consistency but the parts may be out of specifications. In this case, the mold steel must be adjusted to bring the parts within the required specifications and the process must not be altered.

The term *Scientific Molding* was coined and promoted by a two pioneers in the field of injection molding, John Bozzelli and Rod Groleau. Their principles are widely used today and are industry standards. Scientific molding deals with the actual plastic that enters the mold during the molding operation at the molding press.