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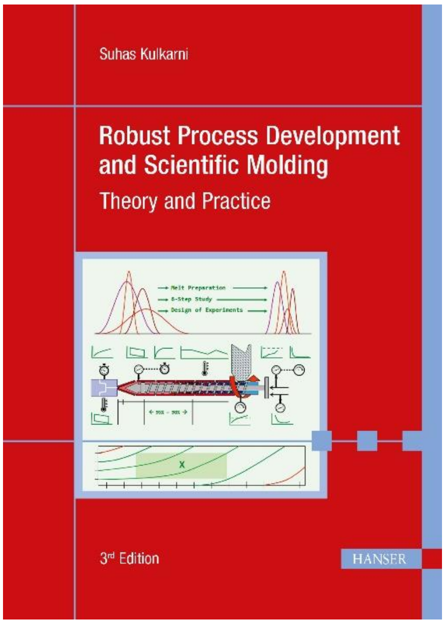

Sample Pages

Robust Process Development and Scientific Molding

Suhas Kulkarni

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The Author

Suhas Kulkarni is the founder and president of FimmTech Inc, an injection molding service-oriented firm focusing on Scientific Molding and Scientific Processing for injection molding. He has a bachelor's degree in polymer engineering from Pune, India and a master's degree in plastics engineering from UMass, Lowell, USA. FimmTech is based in San Diego, CA, USA.

Suhas has been associated with injection molding since 1993 with special focus on injection molding processing. He started his career with Republic Tool and Manufacturing in Carlsbad, CA, which is now a part of the Scotts Fertilizer company. He started as a setup and process technician, where he learnt all the nuts and bolts of injection molding. He later joined Molding International and Engineering in Temecula, CA and worked as a Process Engineer for 12 years before he started FimmTech in 2004. The main goal in starting FimmTech was to provide simple and easy-to-use tools for processors on the production floor for process development and troubleshooting. FimmTech has developed several custom tools that help molders develop robust processes and its seminars have trained individuals from hundreds of companies throughout the world. He is a regular contributor to the widely distributed Plastics Technology magazine and is also an adjunct faculty member at UMass, Lowell.

Preface to the Third Edition

It has been six years since the second edition of this book was published. In those six years my approach to process development has become increasingly streamlined and methodical, prompting the need for this third edition. Outdated sections have been deleted or revised and new insights have been incorporated based on my recent findings. My quest to set the value of every molding process parameter based on an experimental data continues. The basic molding principles and theories have remained unchanged but I have experimented and added a few more steps of process development.

A complete chapter on melt preparation has been added. This will help the reader understand the science and procedure of preparing the melt and setting the values for the barrel zone temperatures, the screw rotation speed, and the back pressure. Throughout the book, several existing figures were updated and several new ones were added to enhance the comprehension of the topics.

I extend heartfelt gratitude to my readers who have also encouraged me to take on this task. Special thanks to those who have sent me feedback on the book and mentioning some errors. This not only helps me but helps the readers to understand the subject and not be misguided.

I must express my gratitude to two individuals who were inadvertently omitted from previous editions' acknowledgments. First, Mr. Kirloskar of Kirloskar Kisan, Pune, India. It was in his company that I first saw an injection molding machine. The earliest seeds of my molding future were sown there. I was a summer intern student in my third year of engineering. Mr. Kirloskar was a towering figure but soft spoken with a pleasant smile. The first time I met him he was giving a solution to a molding problem which, at that time, I did not understand a word of. But I loved the technical talk which I am sure ignited the curiosity in me. As the 'Butterfly Effect' explains, an extra flap of a wing of a butterfly somewhere in South America can theoretically cre-

ate a storm in North America; one of those extra flaps is the internship that has led to the place I am today. I owe part of my success to Mr. Kirlosakar – thank you, sir.

Second is my dear friend Biff Lamkin, with whom I worked for 10 years in my second job. He was a genius who was an expert not only at molding but also in computers, IT, programming, and technology in general. He introduced me to a lot of concepts of molding in my early days. I can still remember him teaching me Pressure Drop Study, which is one of the most important studies in process development. He was also the one who came up with the idea of the melt probe preheater that I use in my courses. Thank you, Biff – I will forever be indebted to you.

A special thanks to my brother Sachin Kulkarni, who has supported and encouraged me all these years and to Ravi Khare of Symphony Technologies, who taught me statistics, DOE concepts, and now theories behind artificial intelligence and machine learning. The continued support of Prof. Basargekar, Tim, and Violeta of Distinctive Plastics, and my friends from UMass Lowell is a constant source of encouragement.

I would have never entered the world of plastics engineering had my dad not exposed me to chemistry as a young kid. I remember doing my high school homework sitting in his lab as he conducted his research. I will be forever indebted to my parents for the encouragement and the exposure at an early age.

A special thanks to my wife Neela for having sacrificed a vacation we were supposed to take as instead I ended up finishing up this third edition. She has always been patiently supportive of all my crazy ideas, work goals, irregular work hours, and last-minute schedule changes. I could not have released this edition on time without her support.

It is my commitment to continue enriching our industry and provide better and easier solutions not only to increase all efficiencies but also to build systems for a sustainable planet and future.

Thank you.

Suhas Kulkarni

June 2024

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 the 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

Contents

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 for 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 few microns on a 10 mm part, or 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.

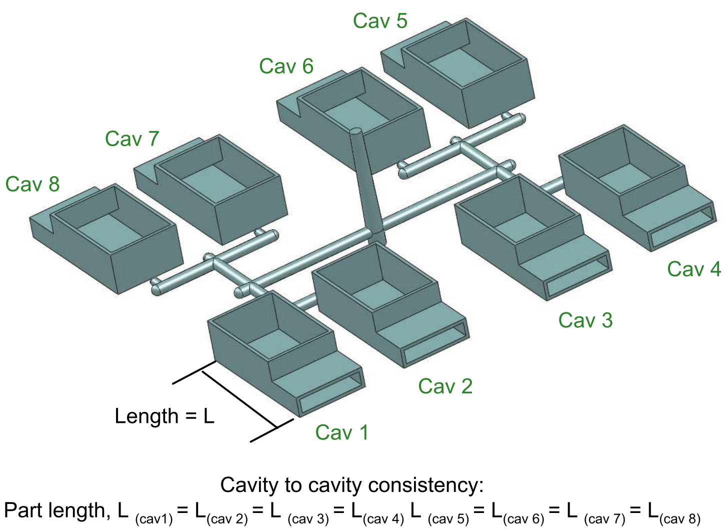
1.2 The Molding Process

The actual molding process has been traditionally defined as the inputs to the molding machine. These are the settings of speeds, pressures, temperatures, times and distances. Examples of these are injection speeds, holding pressure, mold temperature, cooling time and transfer position. 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 can be a challenge, but 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. We need to understand not just the inputs but also the outputs of the molding process. In fact, outputs are more important than the inputs.

The goal of this book is to explain to the reader all the molding process inputs, process outputs and provide process optimization techniques. There are several factors that contribute to each of these parameters and these factors will be discussed.

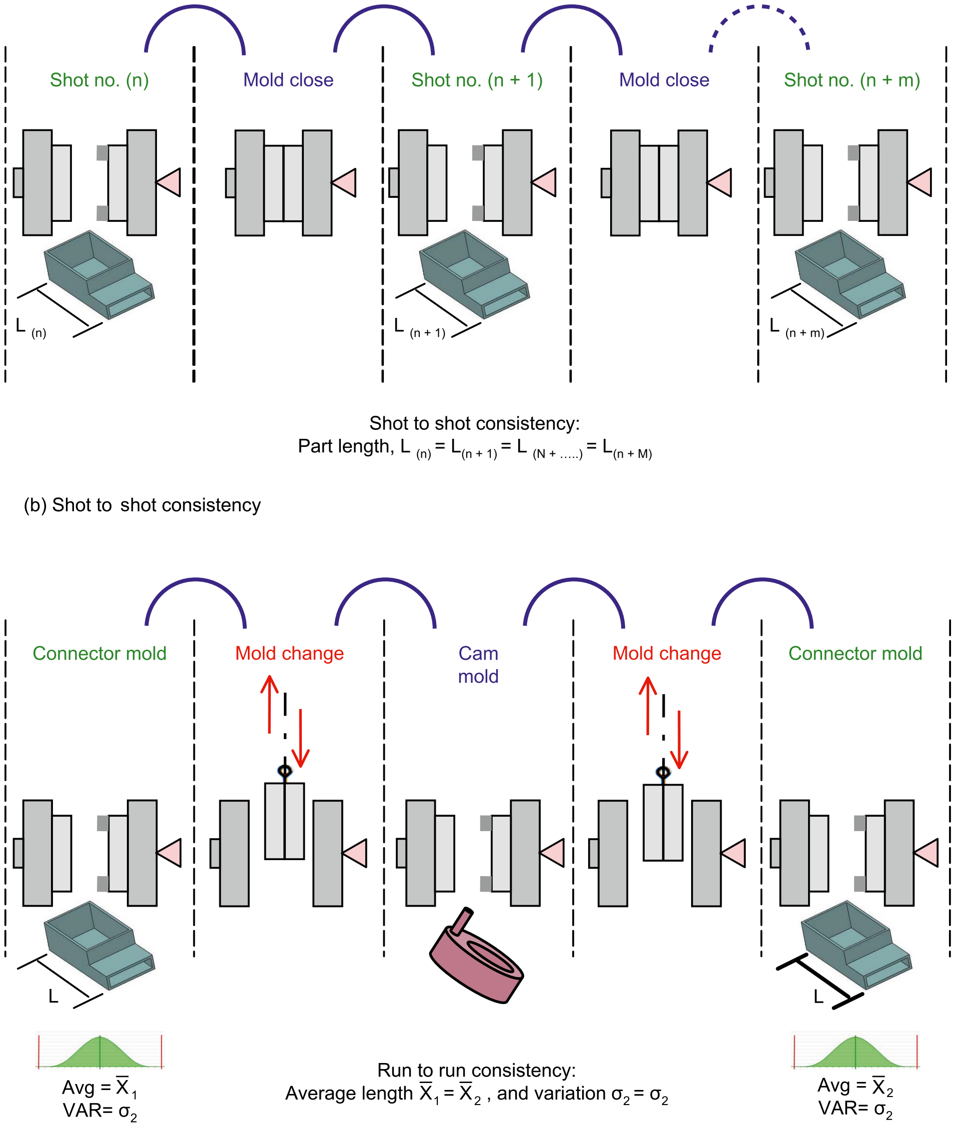
1.3 The Three Types of Consistencies Required in Injection Molding

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 as the other cavities. Shot-to-shot consistency implies that every consecutive shot would be identical in quality to the previous shot, or the first shot is identical to the last shot of the production run with the process parameters remaining identical during the entire production run. When the process parameters from two different runs are identical and they produce identical quality parts, then this is called run-to-run consistency. Robust and stable processes always yield consistent quality parts with one established process.



(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)*

There can be several reasons for not achieving the three types of consistencies. A cavity-to-cavity inconsistency could be caused because of an error when machining the steel in one of the cavities or by not making the gate sizes of the cavities identical to each other. A shot-to-shot inconsistency could be caused because of a damaged leaking check ring at the end of the molding screw or a problem with the hydraulic injection valve. 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 deals in depth with process development of robust, repeatable and reproducible processes.

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 and 3.1%, which is a wide range. Shrinkage also depends upon the processing conditions. For example, higher the melt temperature, the higher the shrinkage. 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.

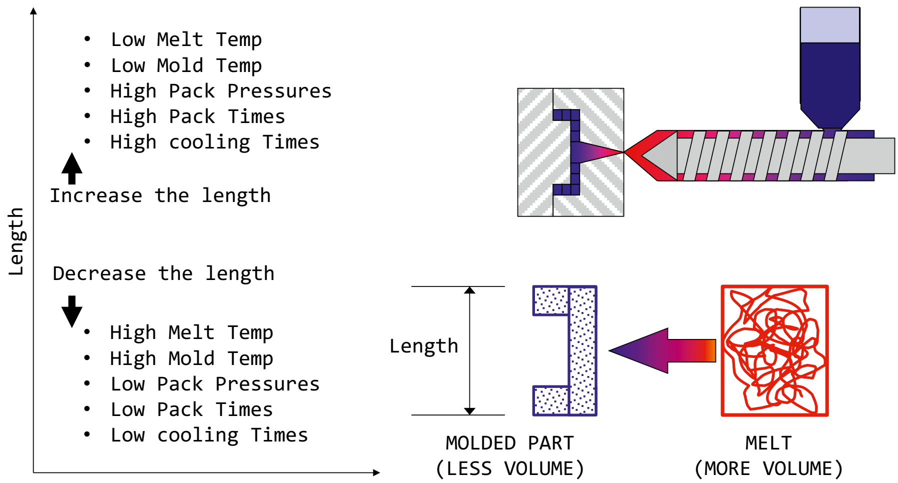


Figure 1.2 Effect of molding parameters on shrinkage and dimension of a part

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. The process also must be such that it can absorb the natural variations that are seen in the production environment such as temperature and humidity changes and even operator changes.

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, and loss of time, 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.

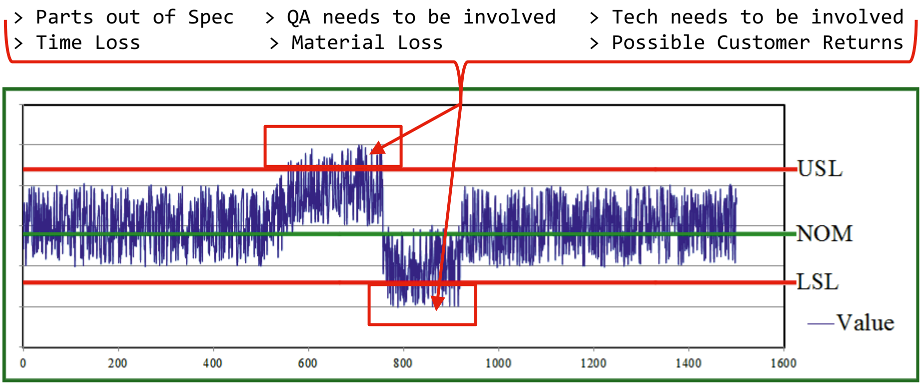


Figure 1.3 Example of an inefficient process

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 dimensions and/or the part specifications must be adjusted to bring the parts within the required specifications. The process must not be altered if the process is a robust process. Process robustness will be discussed at length in Chapter 8.

Consider that the task on hand is to drive a car in the cruise control mode at 120 km/h (75 mph) for 4 hours with no stops, every day for 365 days a year from location A to location B. There are two choices for the route between the two locations. The first is on a hilly terrain with the road on the edge of a cliff and the second on a wide lane highway as shown in Figure 1.4. Since this is a task to be done on a continuous basis it would be prudent to choose the wide lane highway since any small distractions at any time during the 4 hour daily drive, 365 days a year, could mean the car wavers some but because of the wide lanes the car would still be safe. However, driving the car at the edge of the cliff in the cruise control mode would need constant attention and there would be no chance of any error for the fear of driving off the cliff. For an efficient molding operation it is important to run the machines with no or the least amount of human interaction. In other words, the molding processes must run in a cruise control mode. The available tolerances should also support the natural variations that are seen in a molding environment. Figure 1.5 shows such a process where the part dimensions are well within specifications.

Winding road in the hills

Highway with wide lanes

Figure 1.4 Road options: edge of a cliff or wide lane highway? (Sources: George59/Pixabay; zdrsoft/Pixabay)

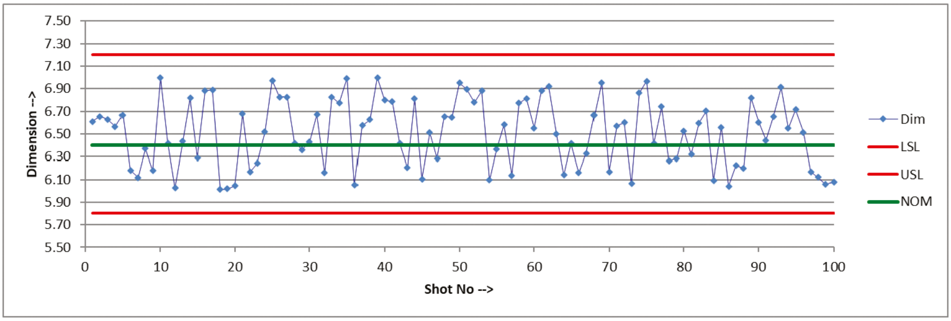


Figure 1.5 Cruise control process

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. Scientific processing is the complete process from when the pellet enters the facility and leaves the facility as a finished product. Figure 1.6 shows the journey of the pellet and how scientific molding is a subset of scientific processing.

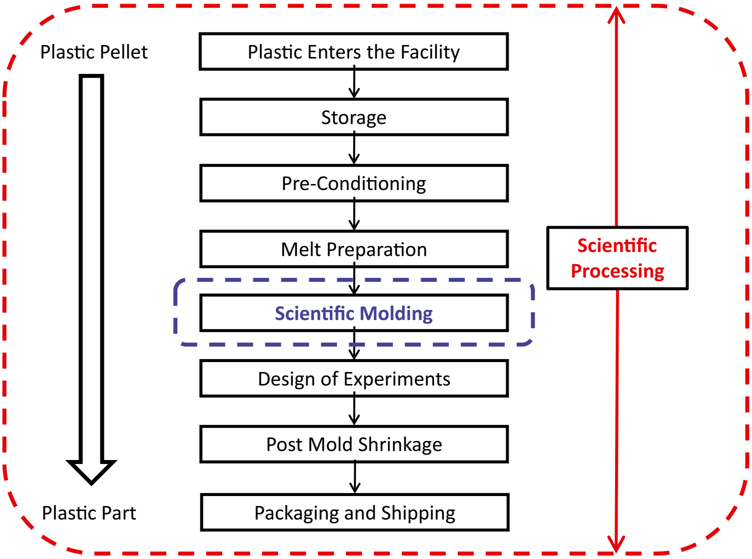


Figure 1.6 The journey of the pellet, Scientific Molding and Scientific Processing

1.5 The Five Critical Factors of Molding

For a part to be molded successfully, there are five factors that have to be considered. These factors, shown in Figure 1.7, are as follows.

1. Part design
2. Material selection
3. Mold design and construction
4. The choice of the molding machine
5. Molding process

Each of these factors plays a very important role in the production of the molded part and therefore every one of them has to be optimized for the production. It is not just the performance of the part but also being able to mold the parts consistently with all the part quality requirements being within the required specifications.

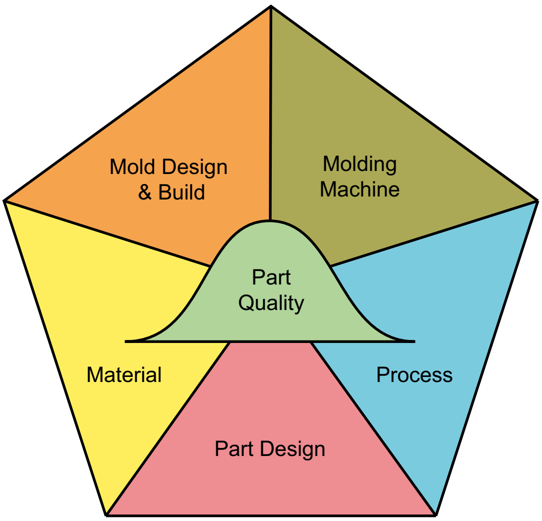


Figure 1.7
The five factors influencing part quality consistency and process robustness

1.5.1 Part Design

The concept of the part starts with the engineer designing it. The part must be designed for molding and all the design rules for plastics must be considered. Rules for plastic part design are considerably different than those used for metal part design because of the inherent nature of the plastic. For example, to avoid sink defects in the plastic part, thick sections cannot be present. Additionally, all corners must have a radius to avoid stress concentration and premature failure. With the growing cost of labor and the need for efficiency in the manufacturing process, the part designers now face the added challenges of designing parts for assembly along with those molded parts that utilize multiple materials, commonly referred to as multicomponent molding or multimaterial molding.

1.5.2 Material Selection

Based on the part design and the part performance requirements, the plastic material must be selected. These are functional requirements. The required tolerances should also be taken into consideration. For example, if a part is around the length of a ruler that is 30 cm (about 12 inches) long and needs to hold tight tolerances then a material of low shrinkage values must be selected. A polyethylene or a polypropylene material will not be able to hold the tolerances since the shrinkage values are high. A glass-filled polycarbonate could possibly work. The part design may require a special plastic material or a special additive to be added to the base plastic for performance. If a thick section must be present, a filled material may need to be selected or if there is a sliding surface, then an additive such as Teflon to reduce the coefficient of friction may need to be added to the plastic. Material selection should typically take place when the basic part design is done. Once the material is selected and the mold is built based on the shrinkage value for the material then changing the material will change the shrinkage and the mold will now not produce the parts to the required specifications. If the shrinkage values are the same, then it will be acceptable.

1.5.3 Mold Design and Construction

Once the part design and material selection is complete, the mold must be designed and constructed such that it is robust enough to withstand the molding process conditions and the plastic material. For example, during the molding process, the mold can be subjected to high mechanical stresses, especially during the plastic injection and the packing phases. The gates are high-wear areas and there are several places where the air needs to vent out for the plastic to enter the mold. Some plastic materials will require special attention and the mold must be specifically designed with the material in mind. Shrinkage may vary considerably from material to material. All these material specific factors must be considered. The required number of parts over the life of the mold is another factor that will dictate the actual materials of construction. Wear on the mold components must be considered, as the materials chosen to build the injection mold and mold cavities will impact the overall life of the mold and associated amount of maintenance required to keep it production worthy.

1.5.4 Machine Selection

Selecting the right machine for the mold should be done once the mold design is complete. It can be done concurrently during the mold construction stage. The machine plays a very important role in the stability of the molding process. For example, machines with large shot sizes must not be used to mold small shots because the part quality consistency will suffer. Vice versa, using a large percentage of the shot size can give rise to problems with melt homogeneity and therefore issues with fill and dimensions. Small molds must also not be mounted in large machines for fear of mold damage due to excessive clamp tonnage being applied.

1.5.5 Molding Process

Process optimization is the last step before the mold is released into production. This book will cover this topic in detail. If the above four factors and activities are not properly selected or performed, process optimization can be a challenge, if not impossible, without incurring significant cost and delay to the project. At this stage, it is usually very late in the project timeline to make any changes to the part design or mold design, especially because of the cost and time involved. An improperly constructed mold can have a very narrow process window leading to a process that will tend to be unstable. If the material selected is not capable of holding the tolerances, no process will be able to produce satisfactory parts. Molding processes should be robust, repeatable, and reproducible. Refer to Figure 1.8, which shows how the cost of making changes to the project changes and increases as the project progresses. For example, if a feature in the part design has to change after the first shots are taken, the cost is substantially higher since the mold design has to change, the mold will need to modified and then trialed again. The figure shows two dotted lines. The bottom line represents the line that shows that the costs will be minimal if all the first four elements are addressed and optimized before the first shots were taken.

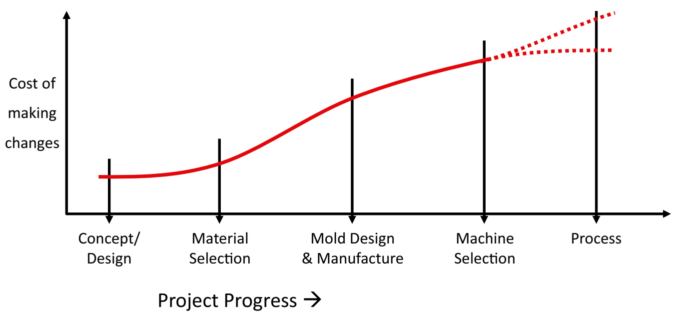


Figure 1.8 Cost of making changes as the each of the phases is completed

1.6 Concurrent Engineering

There are various departments involved in the production of the molded part and therefore regular meetings between the different departments must be held. Each department will have specific knowledge of the selection process and can contribute not just to the process but more importantly predict issues once the mold comes over to their department. For example, getting the process engineer involved in a mold design can help in part orientation in the mold for easy removal, or the mold maker can get help with vent locations based on the process engineer's experience. Involving the quality engineer can help the process engineer understand the required tolerances in the design stage. If the tolerances seem to be unrealistic, they can go back to the product designer for wider tolerances or a material change. There are a lot of benefits associated with implementing concurrent engineering in injection molding. A section is devoted to this topic in this book. Figure 1.9 shows how in the over the wall approach, all the bright people are each working in their own spaces without communicating whereas in the concurrent engineering approach, they are all discussing and contributing the project. The biggest advantage of concurrent engineering is the availability of and access to each member's experience. This contributes to the success of the project.

Over The Wall Engineering   Concurrent Engineering

Figure 1.9 Over the Wall and Concurrent Engineering

1.7 Variation

Variation is a natural phenomenon that is present in every process and activity. For example, the time it takes to drive to work has a number, but it can be an average that is collected over a certain period of time. There will be times that are lower than the average and there are times that are above the average. In injection molding, if the lengths of 100 parts are measured, then one could get an average number, but there will be parts below and above this number. Variation can never be eliminated, so the goal should be to minimize it. Variation should be measured in order to predict the quality of the molded parts. As shown in Figure 1.10, a molder could measure the part marked as A and decide that all the molded parts are within specification. However, only when the variation is measured can it be seen that there will be some parts, such as the one marked B, which are out of specification. Once the variation is known, it becomes important to make sure that this variation is always contained within the required specification limits before the mold is released into production.

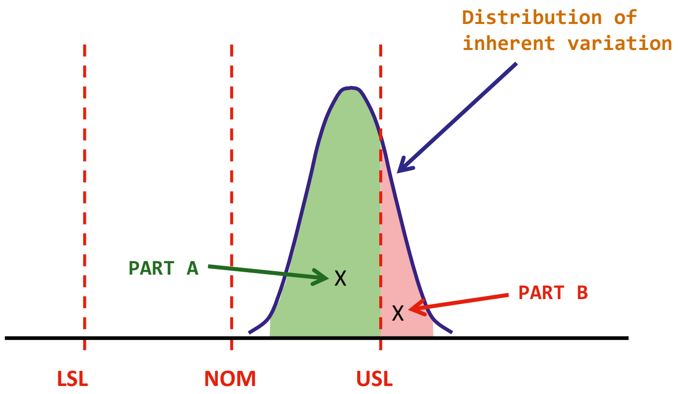


Figure 1.10 Reason to measure variation

A process is said to be capable when all the molded product variation is contained within the specification limits. This is shown in Figure 1.11. The concept of process capability will be discussed in detail in the chapter on quality concepts.

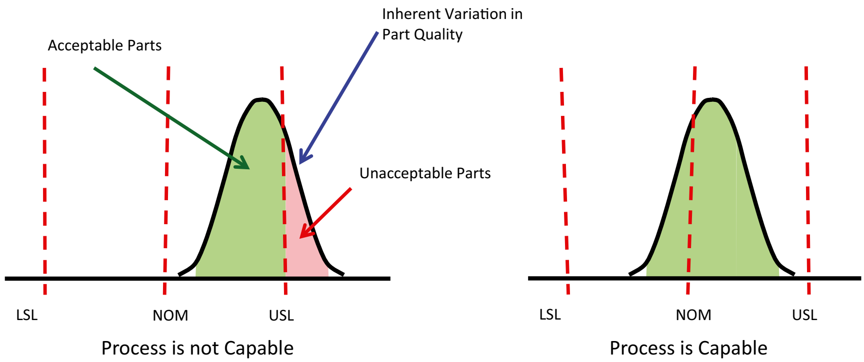


Figure 1.11 Process capability

Variation in injection molding can come from a number of sources, as shown in Figure 1.12. The variation in the molded product is the collective variation from each of these sources, plus many more. Controlling the variation in each source will help the reduction of the overall variation in the final product. The focus of this book will be to discuss the variations that arise from the molding process inputs and how to minimize these variations.

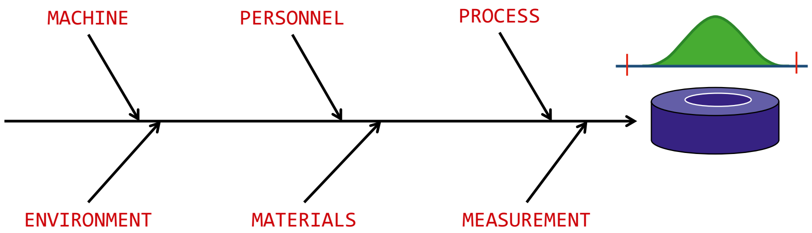


Figure 1.12 Some of the sources of variation in a molded part

In the chapters that follow, the reader will be introduced to the underlying scientific principles to achieve a robust molding process. This understanding will then help in the application of these principles, to develop a robust process and to troubleshoot problems that occur in production. The chapters have been written in a logical sequence to build the readers' knowledge as one would require it or should learn it. However, if the reader is familiar with the topic, he or she can bypass some in favor of other chapters containing the desired information.

1.8 The Molding Parameters and a Recommended Process Development Procedure

There are several process-related molding parameters that affect the part quality. These are shown in Figure 1.13. To achieve a robust process that will produce parts to the required specifications in the most efficient manner, one has to understand and implement a rigorous process development procedure. Note that the phrase is not 'follow' a rigorous procedure, but 'understand and implement' a rigorous procedure. This book will attempt to provide the basics of the molding parameters, what they are, how they can affect the molding process and then go on to explain how they can be optimized. A recommended procedure is shown in Figure 1.14.

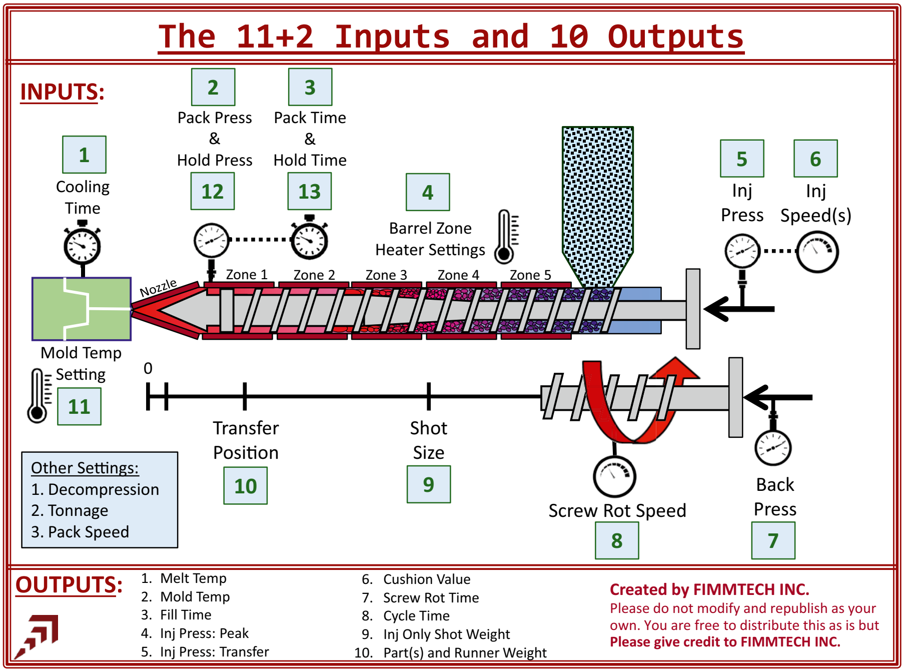


Figure 1.13 The process related molding parameters in injection molding

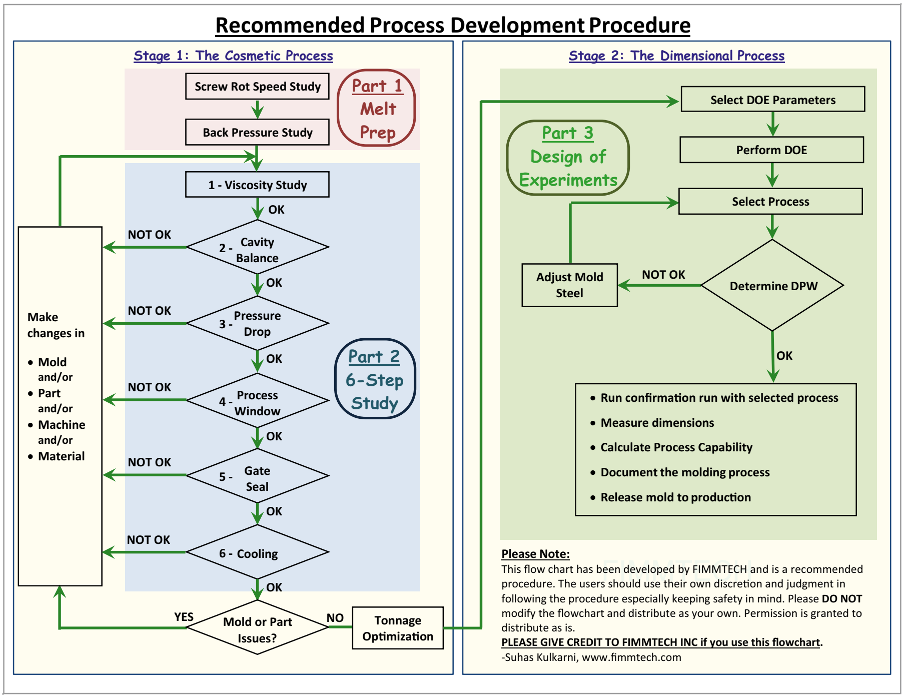


Figure 1.14 Recommended process development procedure

Suggested Reading

Osswald, T. A., Turng, L., Gramann, P. J. (Eds.), *Injection Molding Handbook* (2007) Hanser, Munich

Kulkarni, S. M., *Injection Molding Magazine* (June 2008) Cannon Publications, Los Angeles, USA

2 Properties of Polymers and Plastics That Influence Injection Molding

The term plastic is most commonly used when referring to injection molding materials. Plastics are a class of long-chain molecules called polymers. When polymers have certain properties they are called plastics. Since most of the commercially molded polymers fall under the classifications of plastics, we shall refer to these materials as plastics in this book. The other most commonly molded polymers are thermoplastic elastomers (TPEs) that have the same molding characteristics as plastics but different properties when molded. When referring to these materials, these will be mentioned as TPEs. To understand the concept of injection molding of plastics, a basic understanding about polymers, their properties, and the additives that are incorporated into them is required. This chapter will discuss the topic of polymers and their application to the injection molding process.

2.1 Polymers

Every particle in the universe is composed of atoms. Atoms in turn combine to form molecules. A molecule of water is made up of two atoms of hydrogen and one atom of oxygen. Polymers are very large molecules that have several identical molecules joined together. An ethylene molecule attaches itself to another ethylene molecule and when several thousands or millions of such molecules join with each other, a polyethylene molecule is formed. ‘Poly’ means many and ‘mer’ means part. A polymer is many parts chemically joined together. The basic single unit from which it is synthesized is called a monomer, ‘mono’ meaning one. Polymers are also called macromolecules. The process of converting monomers to polymers is called polymerization. Polymers can also be synthesized from multiple monomers. For example, ABS is synthesized from three different monomers, acrylonitrile, butadiene, and styrene.

Polymers have been around since the beginning of time. DNA, the basic unit of life, is a polymer found in all plants and animals and is a naturally occurring polymer. Today, almost all commercially available polymers are synthesized from natural ingredients. The first commercially synthesized polymers were materials such as ebonite in the late 1800s. Interestingly, the widely used polyolefins gained commercial importance only in the late 1950s, almost a couple decades after the introduction of polyvinyl chlorides, nylons, and polyesters. Recently introduced polymers are based on biomaterials and nanotechnology.

Polymers are synthesized from monomers via a chemical process. There are mainly two types of polymerization processes, the *addition polymerization* process and the *condensation polymerization* process. In the addition polymerization process, a catalyst initiates the polymerization reaction and each monomer adds onto the next monomer until all the monomers are polymerized. A common example of an addition polymer is polyethylene. Polyethylene is polymerized from ethylene monomer, which is a gas at room temperature. The double bond in the ethylene molecule breaks and a bond with an adjacent ethylene molecule is formed. The process continues and the result is a large molecule with high molecular weight. The polymerization process is shown in Figure 2.1.

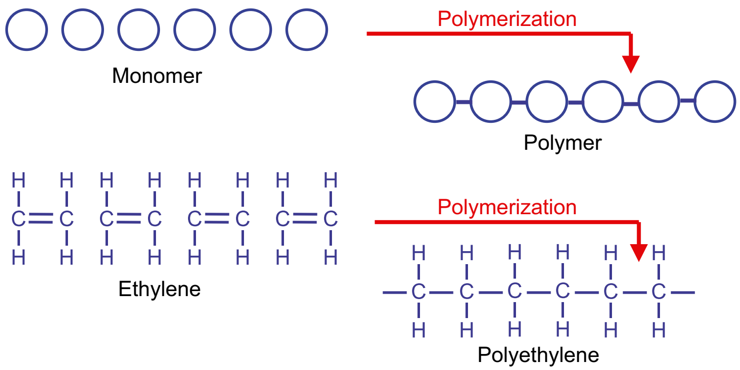


Figure 2.1 The process of polymerization and formation of polyethylene

In condensation polymerization too, each monomer adds on to the next monomer, but this chemical reaction also produces a low molecular weight byproduct that has to be continuously removed out of the system for the polymerization to continue. Condensation polymers are usually polymerized from two or more families of monomers. Nylons and polyesters are examples of condensation polymers. A nylon (chemical name: polyamide) is polymerized from the monomer families of diamines and diacids, as shown in the chemical reaction.

$$nH_2N - R - NH_2 + nHO_2C - R' - CO_2H \rightarrow$$
$$H - (- NH - R - NHCO - R' - CO -)_n - OH + (2n - 1)H_2O$$

R and R′ are the characteristic groups that are present in the monomer. In this case, water is the byproduct. Based on these groups, different types of nylons can be produced. The unit in parentheses repeats itself to form the polymer. If R is $(CH_2)_6$, then the first monomer is hexamethylene diamine and if R′ is $(CH_2)_4$, the second monomer is adipic acid. The polymer that is synthesized from these two monomers is poly(hexamethylene adipamide), commonly called nylon 66.

2.2 Molecular Weight and Molecular Weight Distribution

The repetition of the monomer units causes the molecular weight to increase. The number average molecular weight is the addition of the molecular weights of each of the molecules divided by the number of molecules. Most commercial polymers have a number average molecular weight between 40,000 and 200,000, with some having extremely high numbers. Ultra-high molecular weight polyethylene (UHMWPE) is an example for a molecular weight in the range of 1–6 million. Molecular weights for greases and soft waxes range between 500 and about 3000, whereas some tough and brittle waxes have molecular weights between 3000 and 10,000 [1]. When the attraction between the molecules (intermolecular forces) is high, the materials can gain sufficient mechanical properties at lower molecular weights. Polyamides and polyesters are examples of polymers with strong intermolecular forces. In materials such as polyethylene, where intermolecular forces are low, high molecular weights are required to achieve acceptable mechanical properties. In general terms, molecular weights for polyethylenes are higher those that for nylons or polyesters. UHMWPE was developed for applications in which polyethylenes were the right choice except for their mechanical properties. In most cases, the mechanical properties reach a plateau with increasing molecular weights. Other properties are also affected by molecular weight. Of particular interest to molders is the viscosity of the polymer where an increase in molecular weight results in the increase in viscosity. For melt processing, a certain minimum viscosity is essential for the formation of a processable and homogeneous melt. Processability increases with molecular weight but due to the increase in viscosity, the energy required to process also increases and reaches a point where the increase is not practical for melt processing, see Figure 2.2.

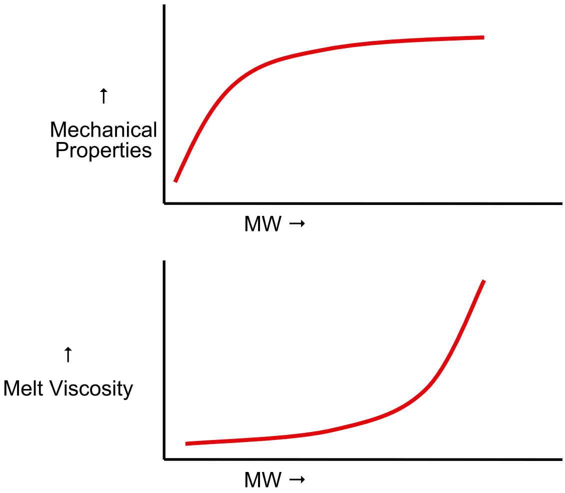


Figure 2.2 Effect of molecular weight on mechanical properties and the viscosity of polymers

The addition of the monomers during the polymerization process (both addition and condensation) is completely random. It is difficult to control the growth of the molecules, which results in molecules of various lengths and therefore varying molecular weights. This in turn leads to a distribution of the molecular weight in the polymer called the molecular weight distribution (MWD) of a polymer. The MWD is an important factor in processing. The lower molecular weight units melt faster than the high molecular weight units. In injection molding, the plastic needs to be injected into the mold as fast as possible to make sure the molecules do not freeze off in the cold mold during injection. If this happens, the part will not fill completely and/or will have built up internal stresses when ejected out of the mold. A narrow MWD ensures that all the molecules are molten during approximately the same period of time. When the residence time in the barrel of the injection molding machine reaches the upper limit, the possibility of molecular breakdown or degradation, resulting in the loss of properties in the final product, increases. This is another reason why a low MWD is desired. However, in the case of extrusion, melt strength is an important element of the process. In this case, the higher molecular weight units have higher viscosity and help to carry the molten lower molecular weight units to form the extrudate. Therefore, a broader MWD is preferred. A narrow MWD would result in the loss of melt strength, and therefore also in the loss of the shape and characteristics of the extrudate profile. The residence time inside the barrel of an extruder is short because extrusion is a continuous process and therefore the risk of degradation is low. This difference in MWD is the decisive factor whether a resin is an injection molding grade or an extrusion grade. Sometimes, extrusion grades are used in injection molding because the viscosity can be low enough to fill the cavities effectively and consistently. The oppo-

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