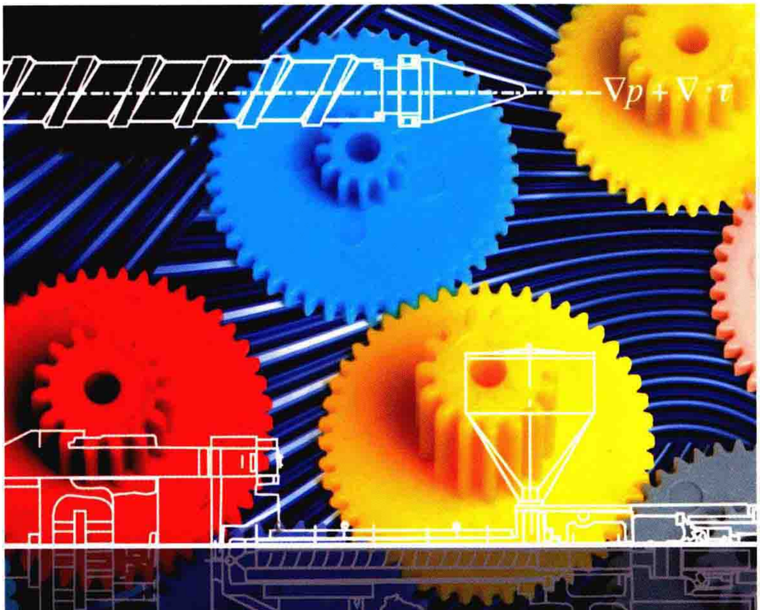
Tim A. Osswald

Understanding Polymer Processing

Processes and Governing Equations



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Osswald

Understanding Polymer Processing

In loving memory of Max Robert Osswald

In gratitude to Ronald L. Daggett,
the teacher and the plastics engineering pioneer,
for having the vision to develop and teach a plastics course in
mechanical engineering at the University of Wisconsin-Madison
in the fall of 1946.

Preface

This book provides the background for an understanding of the wide field of polymer processing. It is divided into three parts to give the engineer or student sufficient knowledge of polymer materials, polymer processing and modeling. The book is intended for the person who is entering the plastics manufacturing industry, as well as a textbook for students taking an introductory course in polymer processing.

Understanding Polymer Processing — Materials, Processes and Modeling is based on the 12 year-old Hanser Publisher's book *Polymer Processing Fundamentals*, as well as lecture notes from a 7-week polymer processing course taught at the University of Wisconsin-Madison.

The first three chapters of this book cover essential information required for the understanding of polymeric materials, from their molecule to their mechanical and rheological behavior. The next four chapters cover the major polymer processes, such as extrusion, mixing, injection molding, thermoforming, compression molding, rotomolding and more. Here, the underlying physics of each process is presented without complicating the reading with complex equations and concepts, however, helping the reader understand the basic plastics manufacturing processes. The last two chapters present sufficient background to enable the reader to carry out process scaling and to solve back-of-the-envelope polymer processing models.

I cannot possibly acknowledge everyone who helped in the preparation of this manuscript. First, I would like to thank all the students in my polymer processing course who, in the past two decades, have endured my experimenting with new ideas. I am also grateful to my polymer processing colleagues who taught the introductory polymer processing course before me: Ronald L. Daggett, Lew Erwin, Jay Samuels and Jeroen Rietveld. I thank Nicole Brostowitz for adding color to some of the original graphs, and to Katerina Sánchez for introducing and organizing the equations and for proofreading the final manuscript. I would like to thank Professor Juan Pablo Hernández-Ortiz, of the Universidad Nacional de Colombia, Medellín, for his input in Part III of this book. Special thanks to Wolfgang Cohnen for allowing me to use his photograph of Coyote Buttes used to exemplify the Deborah number in Chapter 3. My gratitude to Dr. Christine Strohm, my editor at Hanser Publishers, for her encouragement, support and patience. Thanks to Steffen Jörg at Hanser Publishers for his help and for putting together the final manuscript. Above all, I thank my wife Diane and my children Palitos and Rudi for their continuous interest in my work, their input and patience.

Summer of 2010
Tim A. Osswald

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Part I
Polymeric Materials

1 Introduction

Polymers
Macromolecules
Plastics

As the word suggests, polymers[1] are materials composed of molecules of high molecular weight. These large molecules are generally called *macromolecules*. The unique material properties of polymers and the versatility of their processing methods are attributed to their molecular structure. The ease with which polymers and *plastics*[2] are processed makes them, for many applications, the most sought after materials today. Because of their low density and their ability to be shaped and molded at relatively low temperatures, compared to traditional materials, such as metals, plastics. Polymers are the material of choice when integrating several parts into a single component — a design step usually called *part consolidation*. In fact, parts and components, traditionally made of wood, metal, ceramics, or glass, are frequently redesigned with plastics.

This chapter provides a general introduction to polymers and plastics, their molecular structure, their additives, as well as to other relevant topics, such as the plastics industry and plastics processes.

1.1 Historical Background

Natural polymeric materials, such as rubber, have been in use for thousands of years. Natural rubber also known as *caoutchouc* (crying trees) has been used by South American Indians in the manufacture of waterproof containers, shoes, torches, and squeeze bulb pumps. The first Spanish explorers of Haiti and Mexico reported that natives played games on clay courts with rubber balls [1]. Rubber trees were first mentioned in *De Orbe Novo*, originally published in Latin, by Pietro Martire d'Anghiera in 1516. The French explorer and mathematician Charles Maria de la Condamine, who was sent to Peru by the French *Academie des Sciences*, brought caoutchouc from South America to Europe in the 1740s. In his report [2] he mentions several rubber items made by native South Americans, including a piston-less pump composed of a rubber pear with a hole in the bottom. He points out that the most remarkable property of natural rubber is its great elasticity.

The first chemical investigations on *gummi elasticum* were published by the Frenchman Macquer in 1761. However, it was not until the 20th century that the molecular architecture of polymers was well understood. Soon after its introduction to Europe, various uses were found for natural rubber. Gossart manufactured the first polymer tubes in 1768 by wrapping rubber sheets around glass pipes. During the same time period small rubber blocks where introduced to erase lead pencil marks from paper. In fact, the word *rubber* originates from this specific application — *rubbing*.

1) From the Greek, *poli* which means many, and *meros* which means parts.
2) The term plastics describes the compound of a polymer with one or more additives.

These new materials slowly evolved from their novelty status as a result of new applications and processing equipment. Although the screw press, the predecessor of today's compression molding press, was patented in 1818 by McPherson Smith [3], the first documented *polymer processing* machinery dates to 1820 when Thomas Hancock invented a rubber masticator. This masticator, consisting of a toothed rotor in a toothed cylindrical cavity [4], was used to reclaim rubber scraps that resulted from the manual manufacturing process of elastic straps, perhaps the first recycling effort. In 1833 the development of the vulcanization process by Charles Goodyear [5] greatly enhanced the properties of natural rubber, and in 1836 Edwin M. Chaffee invented the two-roll steam heated mill, the predecessor of the calendar. It was used to continuously mix additives into rubber for the manufacture of rubber-coated textiles and leathers. As early as 1845, presses and dies were used to mold buttons, jewelry, dominoes, and other novelties out of shellac and gutta-percha. *Gutta-percha* (rubber clump), a gum found in trees similar to rubber, became the first wire insulation and was used for ocean cable insulation for many years.

The ram-type extruder was invented by Henry Bewley and Richard Brooman in 1845. The first *polymer processing* screw extruder, the most influential equipment in polymer processing, was patented by an Englishman named Mathew Gray in 1879 for the purpose of wire coating. However, the screw pump is attributed to Archimedes and the actual invention of the screw extruder by A. G. DeWolfe of the U. S. dates back to the early 1860s.

Cellulose nitrate plasticized by camphor, possibly the first thermoplastic, was patented by Isaiah and John Hyatt in 1870. Based on experience from metal injection molding, the Hyatt brothers built and patented the first injection molding machine in 1872 to mold cellulose materials [6].

With the mass production of rubber, gutta-percha, cellulose, and shellac articles during the height of the industrial revolution, the polymer processing industry after 1870 saw the invention and development of internal kneading and mixing machines for the processing and preparation of raw materials [7]. A notable invention was the Banbury mixer, developed by Fernley Banbury in 1916. This mixer, with some modifications, is still used for rubber compounding.

Bakelite, developed by Leo Baekeland in 1907, was the first synthetically developed polymer. Bakelite, also known as phenolic, is a thermoset resin that reacts by condensation polymerization occurring when phenol and formaldehyde are mixed and heated.

In 1924, Hermann Staudinger proposed a model that described polymers as linear molecular chains. Once this model was accepted by other scientists, the concept for the synthesis of new materials was realized. In 1927 cellulose acetate and polyvinyl chloride (PVC) [8] were developed. Because of its higher wear resistance, polyvinyl chloride replaced shellac for phonograph records in the early 1930s. Wallace Carothers pioneered condensation polymers such as polyesters and polyamides. It was not until this point that the scientific world was finally convinced of the validity of Staudinger's work. Polyamides, first called Nylon, were set into production in 1938. Polyvinyl acetate,