POLYMERIC FOAMS SERIES

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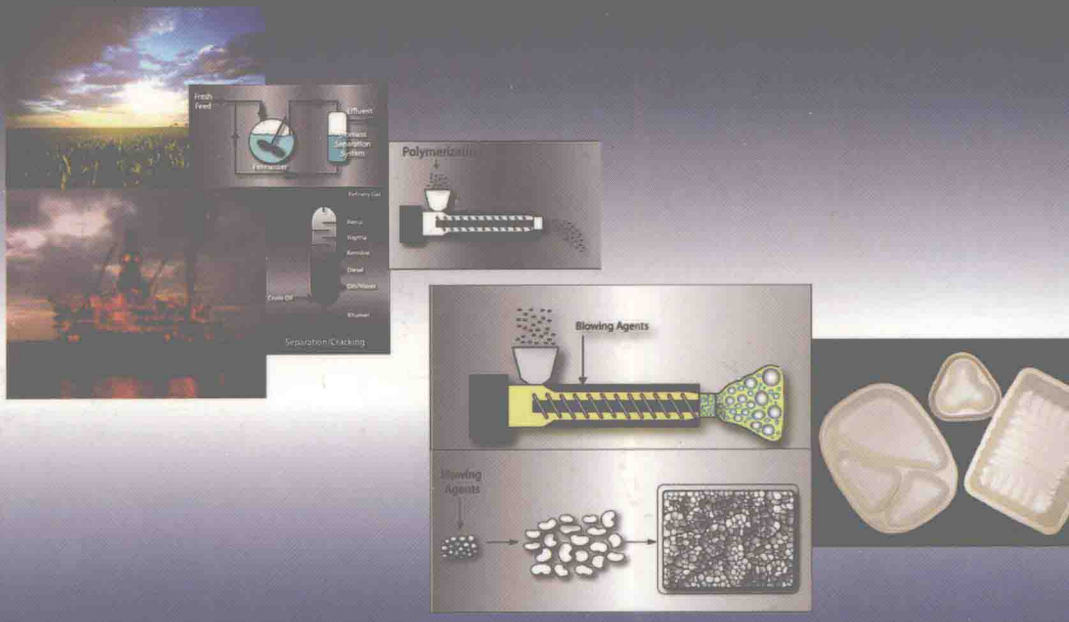
Science and Technology

Shau-Tarng Lee, Chul B. Park, and N.S. Ramesh



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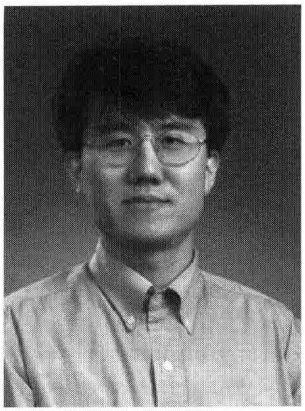
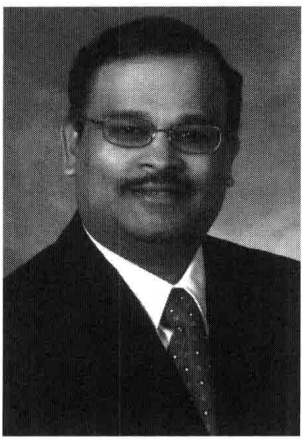


Chul B. Park received his Ph.D. from MIT in 1993. He is a professor and holder of the Canada Research Chair Tier I in Advanced Polymer Processing Technologies at the University of Toronto. He is also the founder and director of the Microcellular Plastics Manufacturing Laboratory, which enjoys the reputation of being one of the pioneering research institutions in refining various foaming technologies. As a Fellow of SPE, ASME, and CSME, Dr. Park is an accomplished scientist with international recognition in the field of polymer foam processing. He is the author or co-author of more than 300 publications including 15 patents and 110 journal papers. He is also active in professional activities. He is the editor-in-chief of the *Journal of Cellular Plastics* and serves as an advisory editorial board member of *Cellular Polymers and Advances in Polymer Technology.* As the Technical Program Chair, Dr. Park has been organizing the Foam Symposiums at PPS and the program of Foams TopCon 2006. He also serves as an active board member of the Thermoplastics and Foams Division of SPE. Currently, he resides with his wife Mindy, his son Joshua and his daughter Esther in Toronto, Ontario.



N.S. Ramesh is the Director of R&D of Specialty Materials Business at Sealed Air Corporation. He received his bachelor's degree in Chemical Engineering from the University of Madras, India and has master's and Ph.D. in Chemical Engineering from Clarkson University in Potsdam, New York. He attended the Summer Rheology Program at MIT and the executive management programs at University of Michigan (Ann Arbor) and SMU Cox (Dallas) business schools. Dr. Ramesh has worked in the area of polymeric foams and materials for 17 years and received Best Paper awards twice for his pioneering work on foams from the Society of Plastics Engineers (SPE). He has more than 50 publications, including 22 U.S. patents, two books, and two book chapters. The SPE elected him a Fellow of the Society in 2002 and he served as Technical Chair for the SPE Foams Conference from 1998–2004. He was inducted into Sealed Air's Hall of Fame in March 2006. His wife, Malathi Ramesh, teaches elementary school children; his oldest son, Deepak Ramesh, is a student at Rice University, and his second son, Vijay Ramesh, is a fourth grader. All are involved with local church and voluntary outreach activities. Without the support of his immediate family and parents, this book would not have been possible.

Acknowledgments

This book is a wonderful example of teamwork and learning experience. Communication, collaboration, and commitment were progressively improved in the last 4 years and are still improving. Although, frustrations, setbacks, and dead ends were inevitable; however, good eventually overcame evil; joy replaced suppression, and team effort overcame individual work. We thank God for the talents, support, cooperation, friendship, patience, perseverance, the ability to deal with uncertainties, and much more.

We acknowledge permission and support from Sealed Air Corporation and University of Toronto to allow the work to go to the public. The principal author is very thankful for the quality review comments from Dr. Masayuki Yamaguchi of Japan Advanced Institute of Sciences and Technology, Professor Masahiro Ohshima of Kyoto University, and Dr. Michel Huneault of Canadian Research Council, and the valuable marketing information from David Rives of Sealed Air Corporation. The extra hours from Hyun-Jung (Jenny) Jun, Kevin L. Lee, Slavec Kubicz, Arlene LaDuca, Nancy Demains at Sealed Air Corporation and from Guanming Li, Remon Pop-Iliev, and Gangjian Guo at University of Toronto are deeply appreciated. Special appreciation goes to Leonard Kareko, whose diligence and dedication in the final stages of this book greatly helped the delivery of the undertaking. Without their faithful dedication in making drawings, scanning charts, checking references, designing the cover, formatting manuscripts and making revisions, we most certainly would have compromised the quality of the book and delayed printing.

Our gratitude goes to our wives: Mrs. Mindy Park, Mrs. Malathi Ramesh, and Mrs. Mjau-Lin Lee. Their unconditional support and willingness to endure the somewhat rough preparation process are especially acknowledged. We also acknowledge our gratitude to all our family members for their love and for providing us with the best education since our childhood days. May God use this book to enlighten the readers, and may their growth become our reward and a benefit to the next generation in which the truth will continue to expand and to shine.

Dedication

To the Lord, who gave us the spirit of power, of love, and of a sound mind.

Series Statement

The bubble is a wonderful creation: a perfect spherical shape, a beautiful arch in various degrees of curvature, and minimum surface area per given volume. Without the bubble, both art and science would definitely have a narrower scope. In fact, the bubble consists of a weak phase surrounded by and sustained in a strong phase. It is like a traditional Chinese virtue, Qian Xu (謙虛), or "empty inside" for receiving. Foam simply combines art, science, and philosophy, whereas, we admit, foaming could be one of the most mysterious phenomena in the universe. Fortunately, researchers and practitioners were able to turn that into advantageous technologies. Nowadays, foamed products are generally indispensable in our daily life.

It is known that foaming in the polymers involves delicate scientific mechanisms, subtle processing accuracies, unique morphology transformation and structure formation. It simply combines material principles, engineering designs, processing methodologies, and property characterization. Polymeric foams ride on the 20th century polymer industry high route to a fascinating success. Within a quarter of a century, the technology evolved from lab scale product to pilot line sample, then to commercial success. Today, it is viewed not only as a technique, but a well-established industry. Through challenges, such as ozone depletion, recycling and environmental regulation, in addition to upgrades, it became a strong industry.

Since polymeric foams encountered various upgrades—material/technology, emission/environment, property/application—it is crucial to maintain cohesiveness of polymeric foam by looking at it from various perspectives. This series is to cover material/mechanism, science/technologies, structure/property, application/post-usage, etc. The reader will gain an overall view as well as fascinating aspects of polymeric foam. We have to admit foaming is still mysterious in quite a few areas. It is my hope that a healthy and cohesive understanding can not only strengthen the structure of the existing polymeric foam industry, but generate further developments to reveal the basic truth. Let us not forget life and truth should go hand in hand.

S.T. Lee, Series editor
Sealed Air Corp., New Jersey

Preface

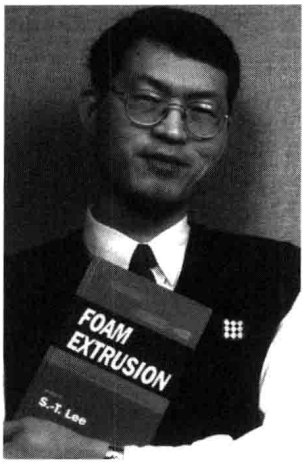
Polymeric foam exhibits enough extraordinary properties to differentiate it from the unique polymeric materials, which allows it to penetrate into almost all aspects of our daily life. Improvement of process technology, equipment and raw material availability made it possible to generate useful articles. Although the foam industry went through many challenges in the past decades it seems to be growing steadily due to better infrastructure, opportunities and global communication.

As we look back, it is amazing how polymeric foams have evolved from scientific concepts to lab research, then to pilot success, and finally to commercialization and a part of life in the last three quarters of a century. At present, foam researchers agree that foaming mechanisms remain somewhat mysterious, but the nucleation of spherical shape alone, a combination of science and art, is a fascinating truth. When a plethora of bubbles join together within a polymeric matrix to form a cellular structure, a collection of biblical principles, philosophy and sociology are nicely involved. It is important to understand that scientific research and application are two different areas, but they both are equally challenging and may share resources for breakthroughs.

Our attempt is very simple. Science and technology should be complementary to each other for a balanced and mutually beneficial growth. One without the other may cause an imbalanced outcome, and then self-destructive conflicts. When science and technology go hand in hand, they can withstand future challenges. From the 1930s to the 1950s, scientists laid the foundation of the foam industry, trailblazing foam technology in the 1960s through the 1980s. Since then, teamwork was acknowledged in dealing with ozone and application issues. Regulation and performance continue to be the main driving force for the global foam industry. From the Montreal protocol to the Kyoto protocol, the challenge of the global foam industry becomes even greater. A healthy future must be based on a solid science and technology foundation.

This book offers a clear guideline to link the basic science and foaming technologies. The first three chapters of this book cover the scientific principles and fundamental foaming mechanisms. The next three chapters are dedicated to general foaming technologies and product applications. Chapters 7 and 8 cover recent developments in the composite and degradable fields, which not only serve as current examples of using mechanisms and technologies to meet application needs, but show the role that polymeric foam is playing in the future developments of the global material realm. This book could be used as a supplementary book for seniors in chemical

Authors



Shau-Tarng Lee, who was born and raised in Taipei, Taiwan, ROC, received his Bachelor of Engineering degree from the National Tsing-Hua University. He joined graduate school in the Chemical Engineering department at Stevens Institute of Technology in 1980 under Professor Joseph Biesenberger's guidance in foam enhanced devolatilization, and, in 1981 and 1982, spent summer internships with Farrel Company to investigate bubble phenomena in devolatilization. He also received a Stanley fellowship and grant from the National Science Foundation (NSF) to support his research works at Stevens. After earning his master's degree in Engineering and his Ph.D., he joined Sealed Air Corporation in 1986. Since then, he has specialized in foam extrusion research, development, and production support as Development Engineer, Assistant Research Director, and presently Research Director.

Dr. Lee has accomplished more than 100 publications, including 26 U.S. patents, and was elected to the Fellow of Society of Plastics Engineers in 2001. He was inducted to Sealed Air's Inventor Hall of Fame in 2003. He is the editor for *Foam Extrusion; Principles and Practice*, published by Technomic Publishing Co. (now Taylor & Francis) in July, 2000, and is also Polymeric Foam Series editor for CRC Press (now Taylor & Francis), with two volumes published in 2004: *Mechanisms and Materials* (edited by S.T. Lee and N.S. Ramesh), and *Thermoplastic Foam Processing* (edited by R. Gendron). Dr. Lee and his wife, Mjau-Lin Tsai, have three children, Joseph, Matthew, and Thomas. Currently, they reside in Oakland, New Jersey. He is a local church elder, and is actively involved in mission works in Asia.

POLYMERIC FOAMS

series editor Shau-Tarng Lee

INCLUDED TITLES

Polymeric Foams: Mechanisms and Materials
Edited by Shau-Tarng Lee and N. S. Ramesh

Thermoplastic Foam Processing: Principles and Development
Edited by Richard Gendron

Polymeric Foams: Science and Technology
Shau-Tarng Lee, Chul B. Park, and N.S. Ramesh

engineering, mechanical engineering, and material science. For polymer science and engineering, this book can be considered as a co-text book for graduate school.

S.T. Lee

C.B. Park

N.S. Ramesh

Table of Contents

1

Introduction to Polymeric Foams

1.1 Basic Considerations on Foams, Foaming, and Foamed Polymers

Matter generally assumes one of three forms (or phases): gas, liquid, or solid. Gases are essentially shapeless and formless, and naturally or artificially exist or co-exist with the other two phases, such as in sponge, cork, aerogel, cake, for example. In fact, gas molecules are capable of penetrating into a liquid or solid phase to create mixtures. Table 1.1 presents a summary of typical gas/liquid and gas/solid mixtures.

The word "foam" derives from the medieval German word *veim* for "froth" [1]. "Foam" refers to spherical gaseous voids dispersed in a dense continuum. There are a number of common natural and artificial foamed products, ranging from foamed pumice to seat cushions [2,3] (see Table 1.2).

TABLE 1.1

Typical Two-Phase Systems

Phenomena	Terminology
Gas bubbles on top of liquid	Froth
Gas bubbles dispersed in liquid	Emulsion Bubble
Liquid bubbles in liquid	Emulsion Liquid
Liquid bubbles in solid	Jelation
Gas Bubbles in solid	Foam

TABLE 1.2

Common Foamed Products

Natural:	Pumice, Tree Trunk, Wood, Cork, Marine Organisms
Synthetic:	
Food:	Steamed Rice, Flour Dough, Popped Cereal...
Plastic:	Seat Cushion, Life Jacket, Insulation Board...
Automotive:	Arm-rest, Liner, Bumper...
Sports:	Helmet Pad, Knee Protection, Surfing Board
Medical:	Tape, Gasket Seal...