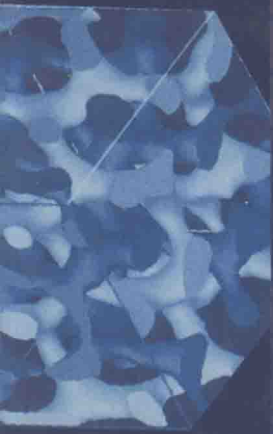

Polymer Foams Handbook

Engineering and Biomechanics Applications and Design Guide

Nigel Mills

Polymer Foams Handbook

Engineering and Biomechanics Applications and Design Guide

N J Mills

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Butterworth-Heinemann is an imprint of Elsevier

BH

Butterworth-Heinemann is an imprint of Elsevier
Linacre House, Jordan Hill, Oxford OX2 8DP
30 Corporate Drive, Suite 400, Burlington, MA 01803

First edition 2007

British Library Cataloguing in Publication Data
Mills, N. J. (Nigel J.)
Polymer foams handbook : engineering and biomechanics applications and design guide
1. Plastic foams
I. Title
668.4'93

Library of Congress Number: 2006939882

ISBN-13: 978-0-7506-8069-1
ISBN-10: 0-7506-8069-5

For information on all Butterworth-Heinemann publications visit our web site at http://books.elsevier.com

Typeset by Charon Tec Ltd (A Macmillan Company), Chennai, India
www.charontec.com
Printed and bound in Great Britain

07 08 09 10 10 9 8 7 6 5 4 3 2 1

Foreword

This book explores the applications of polymer foams. It attempts to explain their mechanical properties in terms of polymer properties and the foam microstructure. The first chapter introduces geometrical concepts that are used throughout the book. The subsequent three chapters deal separately with the microstructure and processing of polyurethane foams, foamed thermoplastics, and bead-foam mouldings. Their different processing routes and microstructures mean that a combined treatment would be confusing. Surface tension may mainly determine the microstructure of PU foams, but high-stress melt flow is more important for foamed thermoplastics. Concepts in the mechanical property area are introduced in Chapter 5 before Chapter 6 covers finite element analysis (FEA) for the complex geometries of many foam products.

Case studies are included for two reasons. Firstly, they are increasingly used to motivate students to study the relevant theory and to understand major industries; a variety of activities such as literature searches and product dismantling can be used as the basis for student presentations. Secondly, specialised foam-based industries tend to remain compartmentalised, but could learn a lot from each other. Thus the areas of foam seating, protective packaging, safety helmets are included; each is associated with one or more theory chapters. There are two strategies for reading this book. One is to read the case studies alone, and use the computer programs to illustrate the foam selection and properties. The other is to read a case study together with the appropriate background theory on the mechanics and materials science. If the reader's background is weak in polymer materials science, it is recommended that he/she should read a general textbook, such as the authors *Plastics*.

This book is intended to compliment previous books with different approaches. Mustin (1968)[1] viewed foam packaging from the military engineering viewpoint; how to design packaging so that supplies could survive air-drops. Hilyard's (1982)[2] multi-author book reviewed many areas of mechanical properties, but concentrated on polyurethane systems. Gibson and Ashby's (1988)[3] book, which surveyed all cellular solids, contains many interesting ideas. However it gives the impression that the mechanical properties of foams are fully explained. It uses a dimensional approach to avoid full analyses of deformation, which are now available. Some of the proposed deformation mechanisms are less important than suggested, and some are not observed in polymer foams. Hilyard and Cunningham's (1994)[4] book contains a good review of the micromechanics of foam elasticity by Kraynik and Warren, and useful chapters on the mechanisms of heat transfer and gas diffusion. Finally Klempner and Sendijarevic (2004)[5] book reviews the chemistry and processing of all the major polymer families.

This book covers the principles which provide a framework for foam developments. It has become easy to search and access literature electronically, but the user should be aware of the advantage and shortcomings of databases such as Google

Scholar, Science Direct, and RAPRA databases in keeping their coverage of the foam literature up to date.

Writing this book has been a voyage of discovery. I am grateful to the efforts of collaborators such as Adam Gilchrist and Miguel Rodriguez-Perez, and to PhD students, in particular Hanzing Zhu, Stephanie Ankrah, Raquel Verdejo, Yago Masso-Moreu, Iona Lyn, and Catherine Fitzgerald.

Nigel Mills
September 2006

Notes

1. Mustin G.S. (1968) *Theory and Practise of Cushion Design*, Shock and Vibration Information Center, US Department of Defence.
2. Hilyard N.C. Ed. (1982) *Mechanics of Cellular Plastics*, Macmillan, London.
3. Gibson L.J. & Ashby M.F. (1988) *Cellular Solids*, Pergamon, Oxford. (2nd Edn., Cambridge University Press, Oxford, 1997).
4. Hilyard N.C. & Cunningham A. Eds. (1994) *Low Density Cellular Plastics*, Chapman and Hall, London.
5. Klempner D. & Sendijarevic V. Eds. (2004) *Handbook of Polymeric Foams and Foam Technology*, 2nd Edn., Hanser, Munich.

Acknowledgements

Figures 1.2a and 7.17 Reproduced from Youssef S. et al. (2005) Finite element modelling of the actual structure of cellular materials determined by X-ray tomography, *Acta Mater.* **53**, 719–730, with permission from Elsevier Ltd.

Figure 1.2b Reproduced from Kraynik et al. (1999) 'Foam micromechanics' p. 274, Figure 10, in *Foams and Emulsions*, Eds. Sadoc J.F. & Rivier N., Nato ASI Series E, Vol. 354, with permission from Kluwer.

Figure 1.2c Reproduced from Kusner R. & Sullivan J.M. (1966) Comparing the Weaire–Phelan equal-volume foam to Kelvin's foam, of Forma, 11, 233–242, with permission from Scipress, Toyko.

Figure 1.2d Reproduced from Weaire et al. (1999) The structure and geometry of foams', in *Foams and Emulsions*, Eds. Sadoc J.F. & Rivier N., Nato ASI Series E, Vol. 354, with permission from Kluwer.

Figure 1.3 Reproduced from Gong L. et al. (2005) Compressive response of open-cell foams. Part 1. Morphology and elastic properties, *Int. J. Solids Struct.* **42**, 1355, with permission from Elsevier Ltd.

Figures 1.7 and 7.4 Reproduced from Elliott J.A. et al. (2002) In-situ deformation of an open-cell flexible polyurethane foam characterised by 3D computed tomography, *J. Mater. Sci.* **37**, 1547–1555, with permission from Kluwer.

Figure 1.8 Reproduced from Schulmeister V. (1998) *Modelling of the mechanical properties of low-density foams*, Ph.D. thesis, Technical University of Delft, with permission from Shaker Publishing, Maastricht.

Figures 1.11 and 1.12 Reproduced from Kraynik A.D. et al. (2003) Structure of monodisperse foam, *Phys. Rev. E* **67**, with permission from The American Physical Society.

Figures 2.1 and 2.2 Reproduced from Herrington R. & Hock K. (1997) *Dow polyurethanes: flexible foams* (2nd edn), with permission from Dow Chemical Company.

Figure 2.3 Reproduced from Neff R. & Macosko C.W. (1995) A model for modulus development in flexible polyurethane foam, *Proc. Polyurethanes* September, 344–352, with permission from Society of the Plastics Industry.

Figure 2.4 Reproduced from Klemperer D. & Frisch, K. Eds. (2001) Advances in urethane science and technology, chapter 2 by A. Weier and G. Burkhardt, with permission from Rapra.

Figures 2.4b and 2.12 Reproduced from Yasunaga K. et al. (1996) Study of cell opening in flexible polyurethane foam, *J. Cell. Plast.* **32**, 427–448, with permission from Sage Publications.

Figure 2.6 Reproduced from Kaushiva B.D. & Wilkes G.L. (2000) Alteration of polyurea hard domain morphology by diethanol amine in molded polyurethane foams, *Polymer* **41**, 6981–6986, with permission from Elsevier Ltd.

Figure 2.8 Reproduced with permission from Dow Chemical Company.

Figure 2.9 Reproduced from Van der Heide E., van Asselen O.L.J. et al. (1999) Tensile deformation behaviour of the polymer phase of flexible polyurethane foams and polyurethane elastomers, *Macromol. Symp.* **147**, 127–137, with permission from Wiley & Sons Inc.

Figure 2.10 Reproduced from Qi H.J. & Boyce M.C. (2005) Stress–strain behaviour of thermoplastic polyurethanes, *Mech. Matl.* **37**, 817–839, with permission from Elsevier Ltd.

Figure 2.11 Reproduced from Van der Schuur M. et al. (2004) Elastic behaviour of flexible polyether(urethane–urea) foam materials, *Polymer* **45**, 2721–2727, with permission from Elsevier Ltd.

Figure 2.13 Reproduced from Kleiner G.A. et al. (1984) *J. Cell. Plast.* 49–57, with permission from Sage Publications.

Figure 2.14 Reproduced with permission from Dow Chemical Company.

Figure 3.2 Reproduced from Guan and Pitchumani (2007) A micromechanical model for the elastic properties of semicrystalline thermoplastic polymers, *Poly. Eng. Sci.* **44**, 433, with permission from Wiley & Sons Inc.

Figures 3.5 and 3.6 Reproduced from Ruinaard H. (2006) Elongational viscosity as a tool to predict the foamability of polyolefins, *J. Cell. Plast.* **42**, 207–220, with permission from Society of Plastic Engineers.

Figure 3.9b Reproduced from Koopmans R.J. et al. (2000) Modelling foam growth in thermoplastics, *Adv. Mater.* **12**, 1873, with permission from Wiley & Sons Inc.

Figure 3.10 Reproduced from Everitt S.L. et al. (2006) Competition and interaction of polydisperse bubbles in polymer foams, *J. Non-Newt. Fluid Mech.*, with permission from Elsevier Ltd.

Figure 3.15 Reproduced from Rodriguez-Perez M.A. et al. (2005) Characterisation of the matrix polymer morphology of polyolefin foams by Raman spectroscopy, *Polymer* **46**, 12093–12102, with permission from Elsevier Ltd.

Figures 3.16 and 3.17 Reproduced from Almanza O, Rodriguez-Perez M.A. et al. (2005) Comparative study on the lamellar structure of polyethylene foams, *Euro. Poly. J.* **41**, 599–609, with permission from Elsevier Ltd.

Figure 4.1b Reproduced from Cigna G. et al. (1986) Morphological and kinetic study of EPS pre-expansion and effects on foam properties, *Cell. Polym.* **5**, 241–268, with permission from Rapra.

Figures 4.1a and 4.2 Reproduced from Fen-Chong T. et al. (1999b) Viscoelastic characteristics of pentane-swollen polystyrene beads, *J. Appl. Polym. Sci.* **73**, 2463–2472, with permission from J Wiley & Sons Inc.

Figure 4.3a Reproduced from Tuladhar T.R. & Mackley M.R. (2004) Experimental observations and modelling related to foaming and bubble growth from pentane loaded polystyrene melts, *Chem. Eng. Sci.* **59**, 5997–6014, with permission from Elsevier Ltd.

Figure 4.7 Reproduced from Rossacci J. & Shivkumar S. (2003) *J. Mater. Sci.* **38**, 201, with permission from Kluwer.

Figures 4.9 and 4.10 Reproduced from Jarvela P. et al. (1986a) A method to measure the fusion strength of EPS beads, *J. Mater. Sci.* **21**, 3139, with permission from Kluwer.

Figure 5.7 Reproduced from Wada A. et al. (2003) A method to measure shearing modulus of the foamed core for sandwich plates, *Compos. Struct.* **60**, 385–390, with permission from Elsevier Ltd.

Figures 6.13 and 6.14 Reproduced from Deshpande V.S. & Fleck N. (2001) Multiaxial yield behaviour of polymer foams, *Acta. Mater.* **49**, 1859–1866, with permission from Elsevier Ltd.

Figure 7.10 Reproduced from Laroussi M. et al. (2002) Foam mechanics: nonlinear response of an elastic 3D-periodic microstructure, *Int. J. Solids Str.* **39**, 3599–3623, with permission from Elsevier Ltd.

Figure 7.16 Reproduced from Zhu H.X. & Windle A.H. (2002) Effects of cell irregularity on the high strain compression of open-cell foams, *Acta Mater.* **50**, 1041–1052, with permission from Elsevier Ltd.

Figure 7.18 Reproduced from Gong L. et al. (2005b) On the stability of Kelvin cell foams under compressive loads, *J. Mech. Phys. Solids* **53**, 771–794, with permission from Elsevier Ltd.

Figures 8.1a and 8.17 Reproduced from Cummings A. & Beadle S.P. (1993) Acoustic properties of reticulated plastic foams, *J. Sound Vibr.* **175**, 115, with permission from Academic Press.

Figure 8.3 Reproduced from Hilyard N.C. & Collier P. (1987) A structural model for air-flow in flexible PU foams, *Cell. Polym.* **6**, 9–26, with permission from Rapra.

Figure 9.1 Reproduced from Hubbard R.P. et al. (1993) New biomechanical models for automotive seat design, SAE SP-963, *Seat System Comfort and Safety*, pp. 35–42, with permission from SAE.

Figure 9.4 Reproduced from Setyabudky R.F., Ali A. et al. (1997) Measuring and modelling of human soft tissue and seat interaction, SAE SP-1242, *Progress with Human Factors in Automotive Design*, pp. 135–142, with permission from SAE.

Figure 9.6b Reproduced from Kinkelaar M.R. et al. (1998) Vibrational characterization of various polyurethane foams employed in automotive seating applications, *J. Cell. Plast.* **34**, 155–173, with permission from Sage Publications.

Figure 9.11 Reproduced from Cavender K.D. & Kinkelaar M.R. (1996), Real time dynamic comfort and performance factors of polyurethane foam in automotive seating, SP-1155 SAE, *Automotive Design Advancements in Human Factors*, with permission from SAE.

Figure 9.13 Reproduced from Shen W. & Vertiz A.M. (1997) Redefining seat comfort, SAE SP-1242, *Progress in Human Factors in Automotive Design*, pp. 161–168, with permission from SAE.

Figure 9.14 Reproduced from Bouten C.V. et al. (2003) The etiology of pressure ulcers: skin deep or muscle bound? *Arch. Phys. Med. Rehabil.* **84**, 616–619, with permission from American Congress of Rehabilitation Medicine.

Figure 9.15 Reproduced from Verver M.M., van Hoof J. et al. (2004) A FE model of the human buttocks for prediction of seat pressure distributions, *Comp. Meth. Biomech. Biomed. Eng.* 7, 193, with permission from Taylor & Francis.

Figure 9.16 Reproduced from Broos R. et al. (2001) Endurance of PU automotive seating foam under various temperature and heating conditions, *Cell. Polym.* **19**, 169–204, with permission from Rapra.

Figure 11.15b Reproduced with permission of McKown S.

Figure 11.17 Reproduced from Viot P. & Bernard D. (2005) Impact test deformations of polypropylene foam samples followed by microtomography, *J. Mater. Sci.* **41**, 1277–1279, with permission from Kluwer.

Figure 12.3 Reproduced from Sek M.A. & Kirkpatrick J. (1997) Prediction of the cushioning properties of corrugated cardboard. *Pack. Sci. Tech.* **10**, 91, Figure 6, Comparison of simulated and experimental cushioning curves, with permission from Wiley & Sons Inc.

Figure 12.4 Reproduced with permission from Zotefoams Brochure for LD24 cushion curve.

Figure 12.15 Reproduced from Totten T.L. et al. (1990) The effects of multiple impacts on the cushioning properties of closed cell foams, *Pack. Tech. Sci.* **3**, 117–122, with permission from Wiley & Sons Inc.

Figure 13.13 Adapted from Misevich K.W. & Cavanagh P.R. (1984) Material aspects of modeling shoe/foot interaction, p. 58 Figure 10, in Sports Shoes and Playing Surfaces, Frederick E.C. Ed. Human Kinetics Publishers Inc. © Nike.

Figure 13.16 Reproduced from Kinoshita H. & Bates B.T. (1996) The effect of environmental temperature on the properties of running shoes, *J. Appl. Biomech.* **12**, 258–268, with permission from Human Kinetics Publishers Inc.

Figure 14.3 Reproduced from Smith T.A. et al. (1994) Evaluation and replication of impact damage to bicycle helmets, *Accid. Anal. Prev.* **26**, 795–802, with permission from Elsevier Ltd.

Figure 14.4 Reproduced from L.B. Larsen et al. (1991) Epidemiology of bicyclist's injuries, *Conference IRCOBI*, 217–230, with permission from IRCOBI.

Figure 15.1 Reproduced from Stupak P.R. et al. (1991) The effect of bead fusion on the energy absorption of polystyrene foam, *J. Cell. Plast.* **27**, with permission from Sage Publications.

Figure 15.12 Reproduced from Choi S. & Sankar B.V. (2005) A micromechanical method to predict the fracture toughness of cellular materials, *Int. J. Solids Struct.* **42**, 1797, with permission from Elsevier Ltd.

Figure 15.14 Reproduced from McIntyre A. & Anderson G.E. (1979) Fracture properties of a rigid PU foam over a range of densities, *Polymer* **20**, 247–253, with permission from Elsevier Ltd.

Figure 15.15 Reproduced from Zenkert D. & Bäcklund J. (1989) PVC sandwich core materials: mode I fracture toughness, *Comp. Sci. Tech.* **34**, 225–242, with permission from Elsevier Ltd.

Figures 15.16 and 18.2 Reproduced from Danielsson M. (1996) Toughened rigid foam core material for use in sandwich construction, *Cell. Polym.* **15**, 417–435, with permission from RAPRA.

Figure 15.17 Reproduced from Stupak P.R. et al. (1991) The effect of bead fusion on the energy absorption of polystyrene foam. Part 1. Fracture toughness, *J. Cell. Plast.* **27**, 484, with permission from Sage Publications.

Figure 16.15 Reproduced from Kostopoulos V. et al. (2002) FEA of impact damage response of composite motorcycle safety helmets, *Composites Part B* **33**, 97–107, with permission from Elsevier Ltd.

Figure 17.1 Reproduced from Okuizumi H., Harada A. et al. (1998) Effect on the femur of a new hip fracture preventative system using dropped-weight impact testing, *J. Bone Miner. Res.* **13**, 1940–1945, with permission from American Society for Bone and Mineral Research.

Figure 17.2a Reproduced with permission from Dr Jones, Imperial College, London, UK.

Figure 17.2b Reproduced from Bousson V. et al. (2004) Cortical bone in the human femoral neck: 3D appearance and porosity using synchrotron radiation, *J. Bone Min. Res.* **19**, 794–801, with permission from American Society for Bone and Mineral Research.

Figure 17.5 Reproduced from Robinovitch S.N. et al. (1994) Force attenuation in trochanteric soft tissues during impact from a fall, *J. Orthopaed. Res.* **13**, 956–962, with permission from Orthopaedic Research Society.

Figure 17.6 Redrawn from Askegaard V. & Lauritzen J.B. (1995) Load on the hip in a stiff sideways fall, *Eur. J. Muscoloskel. Res.* **4**, 111–115, Scandinavian University Press.

Figures 17.7 and 21.2 Reproduced from Ellis H. et al. (1991) *Human Cross-Sectional Anatomy*, with permission from Elsevier Ltd.

Figures 17.9 and 17.11 Reproduced from Robinovitch S.N. et al. (1995) Energy shunting hip padding system attenuates femoral impact force in a simulated fall, *J. Biomech. Eng. Trans* ASME, **117**, 409–413, with permission from ASME.

Figures 17.9b and 17.12a Reproduced from Derler S. et al. (2005) Anatomical hip model for the mechanical testing of hip protectors, *Med. Eng. Phys.* **27**, 475, with permission from Elsevier Ltd.

Figure 17.12b Reproduced from Van Schoor N.M., van der Veen A.J. et al. (2006) Biomechanical comparison of hard and soft hip protectors, and the influence of soft tissue, *Bone* **39**, 401–407, with permission from Elsevier Ltd.

Figure 18.3 Reproduced from Thomas T., Mahfuz H. et al. (2004) High strain rate response of crosslinked and linear PVC cores, *J. Reinf. Plast. Compos.* **23**, 739–749, with permission from Sage Publications.

Figure 18.4a Reproduced from Microstructures of H130 and H130 PVC foams (Kanny K., Mahfuz H. et al. (2004) Static and dynamic characterization of polymer foams under shear loads, *J. Comp. Matl.* **38**, 629), with permission from Sage Publications.

Figure 18.4b Redrawn from Gundberg T. (2002) Foam cores in the marine industry: www.boatdesign.net

Figures 18.10 and 18.11 Reproduced from Kim J. & Swanson S.R. (2001) Design of sandwich structures for concentrated loading, *Comp. Str.* **52**, 365–373, with permission from Elsevier Ltd.

Figure 18.13 Reproduced from Magnitude of residual dent vs. indentation magnitude for H60 PVC foam core (Zenkert D., Shipska A. & Persson K. (2004) Static indentation and unloading response of sandwich beams, *Composites B* **35**, 511), with permission from Elsevier Ltd.

Figure 18.14 Adapted from Rizov V., Shipsha A. & Zenkert D. (2005) Indentation study of core sandwich composite panels, *Compos. Struct.* **69**, 95–102. Elsevier Ltd.

Figure 18.15 Reproduced from Eeckhaut G. & Cunningham A. (1996) The elimination of radiative heat transfer in fine celled PU rigid foams, *J. Cell. Plast.* **32**, 528–552.

Figure 18.16 Reproduced from Ahern A. et al. (2005) The conductivity of foams: a generalisation of the electrical to the thermal case, *Coll. Surf.* **263**, 275–279, with permission from Elsevier Ltd.

Figure 18.17 Reproduced from Quenard D. et al. (1998) Heat transfer in the packing of cellular pellets: microstructure and apparent thermal conductivity, *14th ECTP Proceedings*, 1089–1095, with permission from Pion Ltd.

Figure 18.18 Reproduced from Wilkes K.E., Yarborough D.W. et al. (2002) Aging of polyurethane foam insulation in simulated refrigerator panels- 3-year results with third generation blowing agents, with permission from Alliance for the Polyurethanes Industry.

Figures 19.17 and 19.18 Reproduced from Rodriguez-Perez M.A., Ruiz-Herrero J.L. et al. (2006) Gas diffusion in polyolefin foams during creep tests, *Cell. Polym.* **25**, 221–236, with permission from Rapra.

Figure 20.3 Reproduced from Shafee E.E. & Naguib H.F. (2003) Water sorption in cross-linked poly(vinyl alcohol) networks, *Polymer* **44**, 1647–1653, with permission from Elsevier Ltd.

Figure 20.4 Reproduced from www.foamex.com/technical/resanddel.asp SIP felt oil wicking as a function of firmness with permission from Foamex.

Figure 20.5a Reproduced from Chen J., Park H., Park K. (1999) Synthesis of superporous hydrogels: hydrogels with fast swelling and superabsorbent properties, *J. Biomed. Res.* **44**, 53–62, with permission from Wiley & Sons Inc.

Figure 20.5b Reproduced from Braun J. et al. (2003) Non-destructive, 3D monitoring of water absorption in PU foams using MRI, *Poly. Test* **22**, 761–767, with permission from Elsevier Ltd.

Figure 20.10 Reproduced from Duškov M. (1997) Materials research on EPS 20 and EPS15 under representative conditions in pavement structures, *Geotext. Geomembr.* **15**, 147–181, with permission from Elsevier Ltd.

Figure 20.11 Reproduced from Gnip I.Y., Kersulis V. et al. (2006) Water absorption of expanded polystyrene boards, *Poly. Test.* **25**, 635–641, with permission from Elsevier Ltd.

Figure 20.13 Reproduced from Ojanen T. & Kokko E. (1997) Moisture performance analysis of EPS frost insulation, in *STP 1320 Insulation Materials, Testing and Applications*, pp. 442–455, with permission from ASTM.

Figure 20.14 Reproduced from Dement'ev A.G. et al. (1996) Diffusion and sorption of water vapour in polyurethane foam, *Polym. Sci. USSR* **31**, 2291–2296, with permission from Elsevier Ltd.

Figure 20.15 Reproduced from Mondal P. & Khakhar D.V. (2004) Regulation of cell structure in water-blown rigid polyurethane foam, *Macromo. Symp.* **216**, 241–254, with permission from Iupac.

Figure 21.19a Reproduced from McIntosh A., McCrory P. & Finch C.F. (2004) Performance enhanced headgear: a scientific approach to the development of protective headgear, *Br. J. Sports Med.* 38, 46–49, with permission from BMJ Ltd.

Contents

Foreword	xvii
Acknowledgements	xix
1. Introduction to polymer foam microstructure	1
1.1 Open- and closed-cell foams	2
1.2 Relative density: wet and dry foams	3
1.3 Edges	5
1.4 Vertices	6
1.5 Faces	7
1.6 Cell geometry	8
1.7 Cells	9
1.8 Foam microstructural models	12
1.8.1 Lattice micromechanics models	12
1.8.2 Cell (bubble) growth	13
1.8.3 Irregular models	14
1.9 Bead foams	17
References	17
2. Polyurethane foams: processing and microstructure	19
2.1 Introduction	20
2.2 PU chemistry	20
2.3 PU foam processes	21
2.3.1 Slabstock foam	21
2.3.2 Moulded PU foam	24
2.3.3 Slow-recovery foams	25
2.4 PU microstructure	26
2.5 Effect of microstructure on mechanical properties	27
2.6 PU foam microstructure	29
2.6.1 Slabstock PU foams	30
2.6.2 Moulded foams	30
2.6.3 Rebonded PU foams	32
2.6.4 Slow-recovery PU foams	33
Summary	35
References	36
3. Foamed thermoplastics: microstructure and processing	39
3.1 Introduction	40
3.2 Polyolefins	41

3.2.1 PEs and copolymers 41
3.2.2 Blends 44
3.2.3 Ethylene styrene 'interpolymers' 44
3.2.4 Ethylene–propylene–diene monomer 46
3.2.5 Polypropylenes 46
3.3 Processing 46
3.3.1 Extrusion of thermoplastic foam sheet 47
3.3.2 Melt rheology suitable for foaming 48
3.3.3 Stages in closed-cell foam development 53
3.3.4 Post-extrusion shrinkage 58
3.3.5 Oriented PP foams – Strandfoam 61
3.4 Foam crystallinity and crystal orientation 62
Summary 64
References 64

4. Bead foam microstructure and processing 69
4.1 Introduction 70
4.2 Processing 70
4.2.1 Bead preparation 70
4.2.2 Steam moulding 71
4.2.3 Dimensional stability post-moulding 74
4.3 Microstructure 74
4.3.1 Bead shape and fusion 74
4.3.2 Density variations in large mouldings 75
4.3.3 The effects of processing on properties 75
4.3.4 Bead shape variation 79
4.3.5 Microstructural models 80
4.4 Specific bead foams 80
4.4.1 PP bead foam: EPP 80
4.4.2 PS bead foam: EPS 81
References 82

5. Simple mechanical tests 85
5.1 Introduction 86
5.2 Stiffness and strength of structures 87
5.3 Stress–strain responses and material parameters 88
5.3.1 Linearly elastic and isotropic 88
5.3.2 Elastically non-linear and isotropic 89
5.3.3 Anisotropic and elastic 89
5.3.4 Elastic–plastic 89
5.3.5 Elastic–brittle 90
5.3.6 Viscoelastic materials 90
5.3.7 Viscoelastic phenomena 91
5.3.8 Temperature-dependent properties 92

5.4 Test types 93
5.4.1 Uniaxial compressive tests 93
5.4.2 Simple shear tests 95
5.4.3 Bend tests 99
5.4.4 Torsion tests 105
5.5 Testing products with a density gradient 105
5.5.1 Tensile or compression tests on EPS 105
5.5.2 Bend tests on EPS 106
5.6 Test equipment 107
5.6.1 Compressive impact 108
5.6.2 Tensile or shear impact 110
5.6.3 Creep 110
5.6.4 Compression set 112
5.6.5 Poisson's ratio 112
5.6.6 Humidity and temperature control 113
References 113

6. Finite element modelling of foam deformation 115
6.1 Introduction 116
6.1.1 FEA packages 116
6.1.2 Static vs. dynamic FEA 116
6.1.3 FEA material models 117
6.2 Elastic foams 117
6.2.1 Curve fitting vs. strain energy functions 117
6.2.2 Strain energy function for rubbers 118
6.2.3 Ogden strain energy function for elastic foams 119
6.2.4 Validation of FEA: plane-strain indentation of flexible foams 125
6.3 Crushable foams 127
6.3.1 Yield surfaces 127
6.3.2 Crushable foam model in ABAQUS 128
6.3.3 Response of crushable foam model in simple deformations 130
6.3.4 Experimental data 131
6.3.5 Validation of FEA models 138
6.4 Dynamic FEA (explicit) 140
6.4.1 Computing issues 140
6.4.2 Simulation of foam compressive impact tests 141
Summary 143
References 144

7. Micromechanics of open-cell foams 147
7.1 Introduction 148
7.1.1 Concepts and approaches 148
7.1.2 Observations of cell deformation 149

7.2 Edge geometry and stiffness 151
7.3 Regular polyhedral-cell models 153
7.3.1 Gibson and Ashby model 153
7.3.2 Kelvin cell model 156
7.4 Elastic moduli of the Kelvin foam 156
7.4.1 Uniform edge cross-sections 156
7.4.2 Non-uniform edge cross-sections 159
7.5 Compression of the Kelvin foam with uniform edges 160
7.5.1 History of modelling 160
7.5.2 Stress–strain response 160
7.5.3 Long range buckling 162
7.6 FEA model of wet Kelvin foam 163
7.6.1 [001] direction compression 163
7.6.2 [111] direction compression 164
7.7 Irregular foam models 167
7.8 Anisotropic cell shapes 169
7.9 Non-linear polymer response 170
7.10 Strain localisation 171
7.11 Modelling edge touching 171
7.12 Comparison with experiment 172
References 173

8. Air flow in open-cell foams 177
8.1 Introduction 178
8.2 Air-flow measurement 178
8.2.1 Equipment 178
8.2.2 Data treatment 179
8.2.3 Data for PU foams with fully open cells 179
8.2.4 Data for compressed PU foams with fully open cells 181
8.2.5 Data for PU foams with partly open cells 182
8.3 Models for air-flow resistance 184
8.3.1 Gent–Rusch model 184
8.3.2 Gent–Rusch model with distorted faces 186
8.3.3 Fourie and Du Plessis model 187
8.3.4 CFD of Kelvin foam model 187
8.3.5 CFD of bead foam channels 190
8.3.6 CFD of the Weaire–Phelan model 192
8.4 Air flow during foam impact compression 192
8.4.1 Air pressure changes during compressive impacts 192
8.4.2 Air-flow modelling 193
8.5 Sound absorption in foams 198
8.6 Filters 200
References 201

9. Seating case study 205
9.1 Introduction 206
9.2 Biomechanics of sitting in chairs 206
9.2.1 Seating posture and mannikins 206
9.2.2 Pressure sores and ischaemia 207
9.2.3 Measuring seating pressure distributions 209
9.2.4 Comparative deformation of the thigh and foam cushion 210
9.2.5 Moisture and heat transmission to the seat 211
9.2.6 Design of wheelchair seats 212
9.2.7 Mattresses and sleep comfort 213
9.3 Car seats 214
9.3.1 Types of car seat 214
9.3.2 Comfort 214
9.3.3 Vibration transmission 215
9.3.4 Crash safety 216
9.4 Foam selection 217
9.4.1 Foam grades and the indentation force deflection test 217
9.4.2 FEA of IFD experiments 218
9.4.3 Comparison with experimental IFD pressure fields 221
9.4.4 Foam selection factors 222
9.4.5 High resilience PU foams 223
9.4.6 Ultra-low resilience PU foams 223
9.5 Seat design 225
9.5.1 Uniform uniaxial compression 225
9.5.2 Indentation with a rigid butt-form 225
9.5.3 Indentation with a compliant dummy 226
9.5.4 FEA of buttock and foam deformation 227
9.6 Other foam mechanical properties 228
9.6.1 Mechanical fatigue 228
9.6.2 Hydrolysis 229
9.6.3 Additives to provide fire resistance 230
Summary 230
References 230

10. Sport mat case study 235
10.1 Introduction 236
10.1.1 Mats used in sport 236
10.1.2 Foam materials 236
10.1.3 Head impacts 236
10.2 Modelling of impacts 237
10.2.1 Type of analysis 237
10.2.2 Hyperfoam model parameters for FEA 238