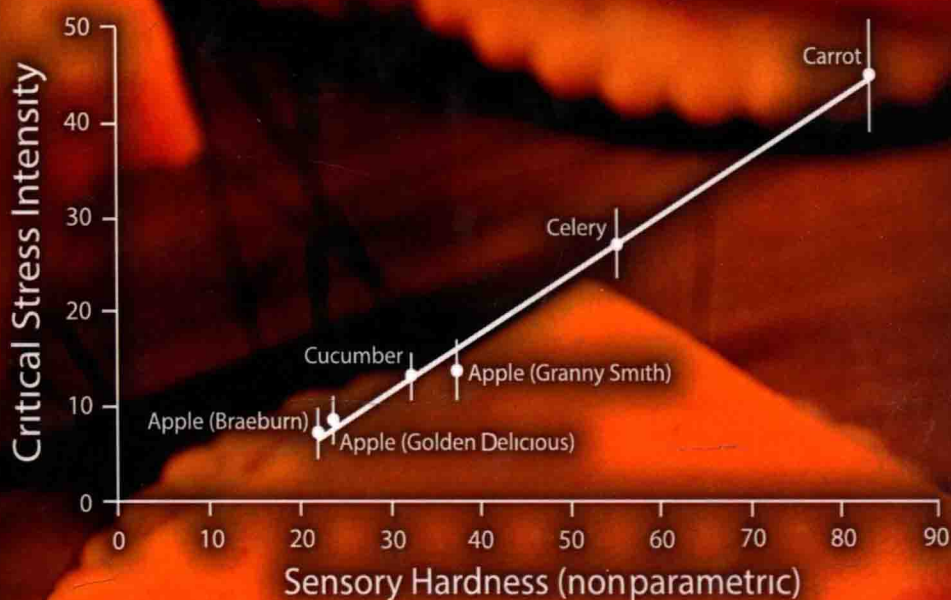


TON VAN VLIET

RHEOLOGY and FRACTURE MECHANICS of FOODS



CRC Press
Taylor & Francis Group

TON VAN VLIET

RHEOLOGY and FRACTURE MECHANICS of FOODS



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Cover design, reprinted with permission from Elsevier, includes a figure from J. F. V. Vincent, Application of fracture mechanics to the texture of food, *Engineering Failure Analysis*, 11, (2004): 695–704.

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2014 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper
Version Date: 20130726

International Standard Book Number-13: 978-1-4398-2703-1 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Vliet, Ton van.
Rheology and fracture mechanics of foods / Ton van Vliet.
pages cm
"A CRC title."
Includes bibliographical references and index.
ISBN 978-1-4398-2703-1 (alk. paper)
1. Food texture. 2. Food--Composition. 3. Rheology. I. Title.

TX531.V45 2013
664'.07--dc23

2013006493

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

RHEOLOGY and FRACTURE MECHANICS of FOODS

Preface

The main theme of this book is the rheological and fracture behavior of foods. The focus is on the basic principles of this behavior, the determination of rheological and fracture properties, and the relation between these properties and the structure of model food products.

People working in the field of food production have realized for quite some time that the mechanical properties of food are essential quality characteristics of these products. These properties play an important role during the manufacture of food and intermediate products, their storage, handling, and last but not least during consumption.

Initially, mainly empirical approaches were used for determining the mechanical properties of food. This was especially the case with respect to getting instrumentally an impression of humans' perception of these properties during consumption and meal preparation. Less than a century ago, scientists generally considered sensory perception of the mechanical properties of food during handling and consumption so subjective and unreliable that it could not be studied seriously in a profound way.

On the other hand, process engineers started to realize quite soon the great value of determining the rheological properties of liquid and liquid-like food products for improving existing processes of food production and developing new ones. For this purpose, they could make use of series of measuring methods and sets of equations describing the flow of liquids under various conditions that were developed outside food science and technology. However, many liquid and liquid-like foods are structurally very complex. The description of the flow behavior of these products turned out to be more complex than, for instance, that of simple polymer solutions. Moreover, the relation between the rheological

properties of foods and their sensory properties turned out to be very complicated. Pioneering work on the rheology of food products was carried out by the famous British scientist, Scott Blair, and his coworkers.

It was the valuable contribution of Alina Szczesniak and coworkers and many other scientists that highlighted the essential role that the mechanical (both rheological and fracture) properties of food (food texture) play with respect to the appreciation of solid and solid-like food products. Moreover, after 1960 more and more methods became available for determining these properties in such a way that the results obtained were relevant for estimating the texture perception of food products. In addition, there was a growing awareness of the importance of many more aspects of the fracture behavior of food products for texture perception of solid and solid-like foods than originally thought.

Initially, the fracture behavior of brittle (hard solid) food products was characterized relatively simply by determining the stress at which the product fractured. However, for soft solid products such as margarines, butter, gels, various cheeses, jellies, dough, meat and meat products, fracture behavior was observed to be much more complex than that of materials usually studied in the field of fracture mechanics. Fracture behavior was observed to depend on certain factors such as speed and the way of deformation. It turned out that for a profound characterization of the mechanical properties of soft solid products, concepts developed in the fields of rheology and fracture mechanics are required.

There are several good books available that discuss the rheology of foods. Mostly they are limited to liquid and liquid-like food products. Furthermore, there are several good books that discuss food texture and how to measure it using instruments and/or human panels. In some of these books, some aspects of fracture mechanics are also discussed. In addition, there are various books on fracture mechanics of engineering materials and/or polymer systems. However, as discussed above, for a profound analysis of the mechanical properties of many food products, one needs a basic understanding of rheology and fracture mechanics as well as the ability to combine concepts from both science fields. With this book, I have attempted to provide basic knowledge of both rheology and fracture mechanics to enable the readers to gain a profound understanding of the mechanical behavior of various classes of food products. Moreover, a discussion is given on the relation between mechanical properties and the structure of food products at various length scales. In the last chapter, a short discussion is given on the relation between rheological and fracture characteristics of foods and texture perception.

The book can be used as a course book for food science majors and for students with a minor in food engineering. I realize that for both purposes, a selection has to be made of the topics discussed to let the content fit better with the background of the students following the

course. The book is primarily written as a textbook; a second aim is that it can be used as a reference book by people working in the field of food research and development. I have tried to keep the mathematics at a relatively low level (no tensor calculus). In places where a derivation is given for a relatively complicated equation, I have tried to do so in such a way that one can understand the most important steps in this derivation without being able to follow the mathematics in detail.

For several chapters, I used parts of the chapter on rheology that I wrote together with Hans Lyklema for volume IV of his book, *Fundamentals of Interface and Colloid Science*. In addition, extensive use was made of the numerous lectures that I have given as part of the courses on rheology and fracture behavior of foods for undergraduate, graduate, and postdoctoral students at Wageningen University and abroad and for industries.

As mentioned above, I have made no attempt to cover all aspects of rheology and fracture mechanics of foods. Had I done so, the size of this book would have doubled at least. Self-evidently, the selection of the topics is colored by my experience and opinions and the extent to which topics have been discussed in the literature. This is especially the case for the choice of examples illustrating the relation between food structure and their rheological and fracture behavior.

Acknowledgments

Several colleagues have contributed to this book in a direct or indirect way. First of all I am indebted to the late Prof. Pieter Walstra for the many discussions we had on rheology and fracture mechanics of foods. I also want to especially thank Prof. Tiny van Boekel, Wageningen University, who has read and commented on all chapters. I am likewise grateful to Prof. Allen Foegeding, Raleigh, North Carolina, USA, who scrutinized several chapters and provided good suggestions that improved the manuscript. Without the contributions of my PhD and postdoctoral students and coworkers to the development of various parts of the knowledge discussed in this book, I would never have been able to write it.

I am greatly indebted to Marlies Meijer for all the computer work she did, which was necessary to enhance the figures from the basic ones I prepared. And last, but not least, I am very grateful to my wife, Willemien, for her understanding, love, and support.

Author

Ton van Vliet graduated with a degree in food technology from Wageningen University in 1973. He earned his PhD in physical chemistry and colloid sciences from the same university in 1977. After a post-doctoral fellowship at the Weizmann Institute of Science in Israel, he became an assistant professor at Wageningen University in the Food Physics Group, and in 1984 he became an associate professor. From 1998 until his retirement in 2010, he worked as a project leader at the Top Institute Food and Nutrition (TIFN).

His main research interest is rheology and fracture mechanics of food systems, in terms of their composition, structure, and physical stability. In his research, a range of rheological techniques were used in addition to techniques such as microscopy, permeametry, x-ray diffraction, and pulse nuclear magnetic resonance (NMR). He tries to bridge the gap between fundamental and predominantly curiosity-driven research and research resulting from problems in the food industry.

At TIFN, Dr van Vliet was the project leader of large projects on the stability of emulsions and foams, crispy/crunchy behavior of cellular solid foods, and effects of water migration in solids.

During his career, he has worked with scientists from various disciplines, and has published about 300 scientific papers on many topics in the field of food physics in a wide variety of journals. He taught at the university holding lectures for undergraduate and graduate students, and was responsible for establishing experimental courses, and thesis supervision for many MSc and PhD students. He also conducted various post-doctoral courses at the university as well as in industry on a contractual basis both in the Netherlands and abroad.

Dr. van Vliet served as the editor of the *Journal of Texture Studies* for 14 years. In 2008, he received the Carl Wilhelm Brabender award from the American Association of Cereal Chemists (AACC) for his outstanding contribution to the field of rheology as applied to the milling and baking industry (this award is presented every 3 years), is listed by Thomson ISI as a highly cited researcher, and is an elected member of the International Academy of Food Science and Technology (IAFoST).

Contents

Preface xi
Acknowledgments xv
Author xvii

PART I Introduction

1 Rheology and Fracture Mechanics in Food Science and Technology. 3
 1.1 *Structure of This Book* 6
 Reference 8

PART II Phenomenology

2 Basic Notions 11
 References 15

3 Rheological Quantities, Types of Deformation . . . 17
 3.1 *Well-Defined Types of Deformation* 17
 3.1.1 *All-Sided, or Isotropic, Compression* 18
 3.1.2 *Uniaxial Compression or Extension* 18
 3.1.3 *Shear* 19

3.2	Relationship between Rheological Quantities	21
3.3	Types of Flow	24
3.4	Definitions of Stress and Strain at Large Deformations ...	29
	References	31

4 Descriptive Rheology 33

4.1	Classification of Materials According to Their Rheological Behavior	33
4.1.1	Equilibrium Behavior	33
4.1.2	Nonequilibrium Behavior	39
4.2	Dynamics: The Role of Time Scale	40
4.3	Descriptive Modeling of Rheological Behavior	45
4.3.1	Modeling of Liquid Flow Behavior in Shear Flow	45
4.3.2	Modeling Stress versus Strain Curves of Solids ...	47
	References	48

5 Fracture and Yielding Behavior 49

5.1	Basic Notions	50
5.2	Fracture Mechanics	52
5.2.1	Linear Elastic or Brittle Fracture	54
5.2.1.1	Effects due to Stress Concentration	54
5.2.1.2	Notch Sensitivity in Relation to Material Structure	56
5.2.1.3	Crack Propagation	59
5.2.2	Elastic Plastic Fracture	62
5.2.3	Time-Dependent Fracture	64
5.2.3.1	Effects due to Viscoelasticity	68
5.2.3.2	Effects due to Friction between Structural Elements as a Result of Inhomogeneous Deformation	70
5.2.4	Halting Crack Propagation	73
5.2.5	Fracture Stress, Work of Fracture, Toughness, and Fracture Toughness	74
5.2.6	Fracture or Yielding	78
5.3	Strain Hardening and Stability against Fracture in Extensional Deformation	79
5.4	Concluding Remarks	81
	References	81

PART III Experimental Evaluation

6 Selection of Instrumental Method. 85

Reference 89

7 Measuring Methods. 91

7.1 Tests at Constant Strain, Stress Relaxation 91

7.2 Tests at Constant Stress, Creep Test 94

 7.2.1 Analysis of Creep Curves in Terms of Retardation Spectra..... 97

7.3 Tests at Constant Strain Rate..... 99

7.4 Oscillatory Tests 101

 7.4.1 Analysis Oscillatory Data in Terms of Relaxation Spectra..... 105

References..... 107

8 Measuring Apparatus 109

8.1 Tube Viscometers 109

 8.1.1 Flow Equations 110

 8.1.1.1 Non-Newtonian Liquids 112

 8.1.2 Instruments 115

 8.1.2.1 Entrance Effect..... 117

 8.1.2.2 Kinetic Energy Correction 117

 8.1.2.3 Turbulence..... 117

 8.1.2.4 Particle Migration 118

 8.1.2.5 Wall Slip..... 118

 8.1.2.6 Viscous Heating 118

8.2 Rotational Rheometers 118

 8.2.1 Concentric Cylinder Geometry..... 119

 8.2.1.1 Sources of Errors 124

 8.2.2 Cone and Plate Geometry..... 128

 8.2.3 Plate-Plate Geometry 130

 8.2.4 Torsion Tests 132

8.3 Tension Compression Apparatus 134

 8.3.1 Uniaxial Compression Tests 135

 8.3.2 Uniaxial Extension Tests 138

 8.3.3 Bending Tests 140

 8.3.4 Comparison of Compression, Tension, and Bending Tests for Determining Fracture Behavior 143

 8.3.5 Controlled Fracture Tests 144

 8.3.6 Biaxial Extension Tests 147

8.4 Empirical Tests..... 149

8.4.1	Empirical Tests Primarily Suited for Liquids and Semisolids.....	150
8.4.1.1	Flow Funnels.....	150
8.4.1.2	Vane Rotational Measuring Geometry	152
8.4.1.3	Spreading Consistometers	153
8.4.1.4	Penetrometer Tests	153
8.4.2	Empirical Tests Primarily Suited for Solids	155
8.4.2.1	Puncture Tests.....	155
8.4.2.2	Compression Extrusion Tests.....	156
8.4.2.3	Texture Profile Analysis	157
	References.....	159

PART IV Relation between Structure and Mechanical Properties

9 General Aspects 163

Reference	165
-----------------	-----

10 Viscosity of Dispersions of Particles 167

10.1	Dilute Dispersions	167
10.1.1	Quantities Characterizing Viscosity Increment due to Particles Added	171
10.2	Concentrated Dispersions	173
10.2.1	Viscosity of Concentrated Dispersions of Fruit Cells.....	177
10.3	Effects of Colloidal Interaction Forces between Particles	181
10.3.1	Colloidal Interaction Forces	181
10.3.1.1	van der Waals Attraction	181
10.3.1.2	Electrostatic Interaction	182
10.3.1.3	Steric Interaction.....	182
10.3.1.4	Hydrodynamic Force	183
10.3.2	Effect of Colloidal Forces on Viscosity.....	183
10.3.3	Relation Aggregate Structure and Shear Thinning Behavior	189
	References.....	192

11 Viscosity of Macromolecular Solutions 193

11.1	Very Dilute and Dilute Macromolecular Solutions	195
11.1.1	Intrinsic Viscosity.....	196

11.1.2 Nonideal Macromolecules	199
11.1.2.1 Nonrandom Coil Macromolecules ...	199
11.1.2.2 Hetero-Macromolecules	200
11.1.2.3 Polyelectrolytes	200
11.1.3 Concentration Effects	201
11.1.3.1 Dilute Solutions	201
11.1.3.2 Transition to Semidilute Solutions ...	202
11.2 Semidilute and Concentrated Macromolecular Solutions	203
11.2.1 Gel-Like Properties	209
References	212

12 Solids and Solid-Like Materials 215

12.1 Rheological Behavior of Elastic Materials at Small Deformations	216
---	-----

13 Gels 219

13.1 Introduction	219
13.2 Polymer Networks	223
13.2.1 Large Deformation Behavior of Polymer Gels...	226
13.2.2 Polysaccharide Gels	227
13.3 Particle Networks	229
13.3.1 Large Deformation Behavior of Particle Gels ..	239
13.4 Comparison of Polymer and Particle Gels	241
13.5 Heat-Set Protein Gels	243
13.6 Plastic Fats	248
13.6.1 Small Deformation Properties of Plastic Fats ...	250
13.6.2 Large Deformation Properties of Plastic Fats ...	255
13.7 Weak Particle Networks	259
References	263

14 Composite Food Products. 265

14.1 Layered Composite Products	266
14.2 Filled Composite Products	268
14.2.1 Large Deformation Behavior of Filled Composite Products	275
References	279

15 Gel-Like Close Packed Materials 281

15.1 Gels of Swollen Starch Granules	281
15.2 Close Packed Foams and Emulsions	287
References	291

16 Cellular Materials 293
16.1 Dry Cellular Materials 293
16.2 Wet Cellular Materials 301
References..... 303

17 Hard Solids 305

PART V Relationships among Food Structure, Mechanical Properties, and Sensory Perception

18 Texture Perception. 309
18.1 Liquids and Semisolid Products..... 312
18.2 Soft Solids..... 316
18.2.1 Creaminess of Soft Solids 318
18.2.2 Crumbliness 319
18.3 Hard Solids..... 322
18.4 Concluding Remarks 327
References..... 328

Appendix A 331
Appendix B. 335
Appendix C. 337
Index 339



Introduction