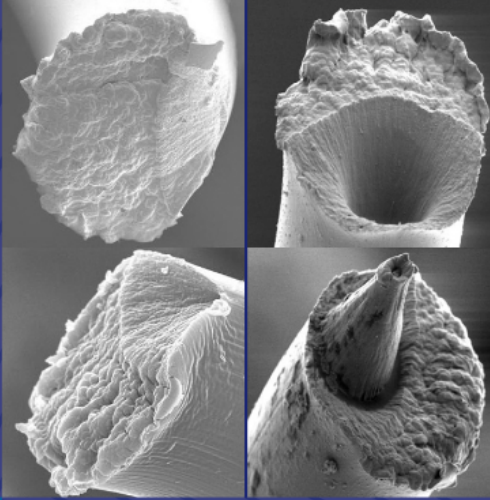


WOODHEAD PUBLISHING IN TEXTILES



Handbook of tensile properties of textile and technical fibres

Edited by A. R. Bunsell



The Textile Institute

WP

Handbook of tensile properties of textile and
technical fibres

The Textile Institute and Woodhead Publishing

The Textile Institute is a unique organisation in textiles, clothing and footwear. Incorporated in England by a Royal Charter granted in 1925, the Institute has individual and corporate members in over 90 countries. The aim of the Institute is to facilitate learning, recognise achievement, reward excellence and disseminate information within the global textiles, clothing and footwear industries.

Historically, The Textile Institute has published books of interest to its members and the textile industry. To maintain this policy, the Institute has entered into partnership with Woodhead Publishing Limited to ensure that Institute members and the textile industry continue to have access to high calibre titles on textile science and technology.

Most Woodhead titles on textiles are now published in collaboration with The Textile Institute. Through this arrangement, the Institute provides an Editorial Board which advises Woodhead on appropriate titles for future publication and suggests possible editors and authors for these books. Each book published under this arrangement carries the Institute's logo.

Woodhead books published in collaboration with The Textile Institute are offered to Textile Institute members at a substantial discount. These books, together with those published by The Textile Institute that are still in print, are offered on the Woodhead web site at www.woodheadpublishing.com. Textile Institute books still in print are also available directly from the Institute's website at: www.textileinstitutebooks.com.

A list of Woodhead books on textile science and technology, most of which have been published in collaboration with The Textile Institute, can be found on pages xv-xxi.

Woodhead Publishing in Textiles: Number 91

Handbook of tensile properties of textile and technical fibres

Edited by

A. R. Bunsell



The Textile Institute



CRC Press

Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Oxford Cambridge New Delhi

Published by Woodhead Publishing Limited in association with The Textile Institute
Woodhead Publishing Limited, Abington Hall, Granta Park, Great Abington
Cambridge CB21 6AH, UK
www.woodheadpublishing.com

Woodhead Publishing India Private Limited, G-2, Vardaan House, 7/28 Ansari Road,
Daryaganj, New Delhi – 110002, India
www.woodheadpublishingindia.com

Published in North America by CRC Press LLC, 6000 Broken Sound Parkway, NW,
Suite 300, Boca Raton, FL 33487, USA

First published 2009, Woodhead Publishing Limited and CRC Press LLC
© Woodhead Publishing Limited, 2009
The authors have asserted their moral rights.

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. Reasonable efforts have been made to publish reliable data and information, but the authors and the publishers cannot assume responsibility for the validity of all materials. Neither the authors nor the publishers, nor anyone else associated with this publication, shall be liable for any loss, damage or liability directly or indirectly caused or alleged to be caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming and recording, or by any information storage or retrieval system, without permission in writing from Woodhead Publishing Limited.

The consent of Woodhead Publishing Limited does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from Woodhead Publishing Limited for such copying.

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

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data

A catalog record for this book is available from the Library of Congress.

Woodhead Publishing ISBN 978-1-84569-387-9 (book)
Woodhead Publishing ISBN 978-1-84569-680-1 (e-book)
CRC Press ISBN 978-1-4398-0145-1
CRC Press order number N10032

The publishers' policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp which is processed using acid-free and elemental chlorine-free practices. Furthermore, the publishers ensure that the text paper and cover board used have met acceptable environmental accreditation standards.

Typeset by Replika Press Pvt Ltd, India

Printed by TJ International Limited, Padstow, Cornwall, UK

Contents

<i>Contributor contact details</i>	<i>xi</i>
<i>Woodhead Publishing in Textiles</i>	<i>xv</i>
<i>Acknowledgements</i>	<i>xxii</i>
1 Introduction to fibre tensile properties and failure A. R. BUNSELL, Ecole des Mines de Paris, France	1
1.1 Introduction	1
1.2 Units of measure for fibres and their structures	2
1.3 Fineness and flexibility	3
1.4 Typical fibre properties	8
1.5 Statistical nature of fibre properties	9
1.6 Markets	15
1.7 Conclusions	17
2 Tensile testing of textile fibres A. R. BUNSELL, Ecole des Mines de Paris, France	18
2.1 Introduction	18
2.2 Determination of fibre dimensions	19
2.3 Surface analysis	28
2.4 Internal structure	29
2.5 Mechanical characterisation	40
2.6 High temperature characterisation	43
2.7 Conclusions	46
2.8 References and further reading	46
Part I Tensile properties and failure of natural fibres	
3 Tensile properties of cotton fibers R. FARAG and Y. ELMOGAHZY, Auburn University, USA	51
3.1 Introduction	51

vi	Contents	
3.2	Fiber tensile behavior during cotton handling	53
3.3	The contribution of cotton fiber tensile behavior to yarn strength	55
3.4	Cotton fiber structure	55
3.5	The tensile behavior of cotton fiber	58
3.6	Conclusions	71
3.7	References	71
4	Tensile properties of hemp and <i>Agave americana</i> fibres T. THAMAE, S. AGHEDO, C. BAILLIE and D. MATOVIC, Queens University, Canada	73
4.1	Introduction	73
4.2	The experiment	75
4.3	Results and discussion	78
4.4	Conclusions	96
4.5	References	97
5	Tensile failure of wool M.G. HUSON, CSIRO Materials Science and Engineering, Australia	100
5.1	Introduction	100
5.2	Structure of wool	101
5.3	Models and theories of strength	110
5.4	Methods of measurement	112
5.5	Tensile failure	118
5.6	Applications and examples	131
5.7	Future trends	133
5.8	Sources of further information and advice	134
5.9	References	135
6	Types, structure and mechanical properties of silk V. JAUZEIN, Mines de Paris (ENSMP), France and P. COLOMBAN, CNRS and Université Pierre et Marie Curie (Paris 6), France	144
6.1	Introduction	144
6.2	Silks	151
6.3	Mechanical properties and microstructure	159
6.4	Conclusions	172
6.5	Acknowledgements	172
6.6	References	172
7	Structure and behavior of collagen fibers F. H. SILVER, UMDNJ-Robert Wood Johnson Medical School, USA and M. JAFFE, New Jersey Institute of Technology, USA	179
7.1	Introduction	179

7.2	Collagen fiber structure	182
7.3	Chemical structure of collagen fibers	182
7.4	Collagen fibrillar structure	184
7.5	Collagen self-assembly	185
7.6	Viscoelastic behavior of tendon	185
7.7	Viscoelasticity of self-assembled type I collagen fibers	188
7.8	Collagen fiber failure	189
7.9	Conclusions	191
7.10	References and further reading	192

Part II Tensile properties and failure of synthetic fibres

8	Manufacturing, properties and tensile failure of nylon fibres S. K. MUKHOPADHYAY, AEL Group, South Africa	197
8.1	Introduction	197
8.2	Raw materials and mechanisms of polymerisation	198
8.3	Manufacturing of nylon 6 and nylon 6.6 fibres	200
8.4	Fibre structure and properties of nylon 6 and nylon 6.6	204
8.5	Preparation and properties of other nylons	211
8.6	Tensile fracture and fatigue failure of nylon fibres	213
8.7	Market trends of nylon 6 and nylon 6.6 fibres	217
8.8	Application of nylon 6 and nylon 6.6 fibres	219
8.9	References	221
9	The chemistry, manufacture and tensile behaviour of polyester fibers J. MLITKÝ, Technical University of Liberec, Czech Republic	223
9.1	Introduction	223
9.2	Chemistry and production of polyester fibers	225
9.3	Modified poly(ethylene terephthalate) (PET) fibers	231
9.4	Processing and structure evolution in polyester fibers	238
9.5	Spinning	239
9.6	Drawing	244
9.7	Heat treatment	251
9.8	Structure of polyester fibers	259
9.9	Mechanical behavior of polyester fibers	265
9.10	Tensile strength of polyester fibers	292
9.11	Failure mechanisms of polyester fibers	298
9.12	Conclusions	300
9.13	References	301

10	Tensile properties of polypropylene fibres E. RICHAUD, J. VERDU and B. FAYOLLE Arts et Métiers ParisTech, France	315
10.1	Introduction	315
10.2	Polypropylene (PP) structure and properties	316
10.3	Polypropylene (PP) fibre processing	318
10.4	Initial tensile properties	319
10.5	Fibre durability	322
10.6	Conclusions	325
10.7	References	326
11	Tensile fatigue of thermoplastic fibres A. R. BUNSELL, Ecole des Mines de Paris, France	332
11.1	Introduction	332
11.2	Principles of tensile fatigue	333
11.3	The tensile and fatigue failures of thermoplastic textile fibres produced by melt spinning	335
11.4	Mechanisms involved in fibre fatigue	342
11.5	Tensile and fatigue failure at elevated temperatures and in structures	347
11.6	Conclusions	352
11.7	Acknowledgements	352
11.8	References	352
12	Liquid crystalline organic fibres and their mechanical behaviour A. PEGORETTI and M. TRAINA, University of Trento, Italy	354
12.1	Introduction	354
12.2	Liquid crystalline (LC) aromatic polyamide fibres	357
12.3	Liquid crystalline (LC) aromatic heterocyclic fibres	387
12.4	Liquid crystalline (LC) aromatic copolyester fibres	403
12.5	Applications and examples	422
12.6	References	426
13	The manufacture, properties and applications of high strength, high modulus polyethylene fibers M. P. VLASBLOM, DSM Dyneema, The Netherlands and J. L. J. van Dingenen, DSM Dyneema (retired), The Netherlands	437
13.1	Introduction	437
13.2	Manufacture	438
13.3	Fiber characteristics	443
13.4	Properties	444
13.5	Processing	467

13.6	Applications	475
13.7	References	483
14	Tensile failure of polyacrylonitrile fibers B. S. GUPTA and M AFSHARI North Carolina State University, USA	486
14.1	Introduction	486
14.2	Preparation of acrylonitrile	488
14.3	Polymerization of acrylonitrile polymer	489
14.4	Stereoregularity and chain conformation of polyacrylonitrile	498
14.5	Acrylic fiber manufacturing	500
14.6	Structure of acrylic fibers	506
14.7	Physical properties of acrylic fibers	508
14.8	Carbon fiber precursor	511
14.9	Failure mechanisms of acrylic fibers	513
14.10	Conclusions	524
14.11	References	525
15	Structure and properties of glass fibres F. R. JONES, The University of Sheffield, UK and N. T. HUFF, Owens Corning, USA	529
15.1	Introduction	529
15.2	Historical perspective	529
15.3	The nature of glass	532
15.4	Fibre manufacture	544
15.5	Strength of glass fibres	548
15.6	Conclusions	570
15.7	References	571
16	Tensile failure of carbon fibers Y. MATSUHISA, Toray Industries Inc., Japan and A. R. BUNSELL, Ecole des Mines de Paris, France	574
16.1	Introduction	574
16.2	Carbon fibers	575
16.3	Carbon fibers produced from polyacrylonitrile (PAN) precursors	577
16.4	Carbon fibers produced from pitch precursors	595
16.5	Carbon fibers produced from regenerated cellulose	598
16.6	Conclusions	600
16.7	References	601

x	Contents	
17	The mechanical behaviour of small diameter silicon carbide fibres	603
	A. R. BUNSELL, Ecole des Mines de Paris, France	
17.1	Introduction	603
17.2	First generation fine silicon carbide (SiC) fibres	604
17.3	Second generation small diameter silicon carbide (SiC) fibres	610
17.4	Third generation small diameter silicon carbide (SiC) fibres	616
17.5	Conclusions	623
17.6	Acknowledgements	623
17.7	References	624
18	The structure and tensile properties of continuous oxide fibers	626
	D. WILSON, 3M Company, USA	
18.1	Introduction	626
18.2	Sol/gel processing and technology	627
18.3	Heat treatment and fiber microstructure	628
18.4	Comparative properties of oxide fibers	631
18.5	Fiber strength and properties	637
18.6	High temperature fiber properties	643
18.7	Conclusions and future trends	647
18.8	Sources of further information and advice	649
18.9	References	649
	<i>Index</i>	651

Contributor contact details

(* = main contact)

Chapters 1, 2, 11 and 17

Dr Anthony R. Bunsell
Ecole des Mines de Paris
Centre des Matériaux
10 rue Desbruyères
BP87, 91003 Evry Cedex
France

E-mail: anthony.bunsell@ensmp.fr

Chapter 3

Dr Ramsis Farag* and Dr Yehia
Elmogahzy
Auburn University
Auburn
Alabama 36849
USA

E-mail: faragra@auburn.edu
elmogy@auburn.edu

Chapter 4

Thimothy Thamae*, Stanley
Aghedo, Caroline Baillie and
Darko Matovic
Department of Chemical
Engineering
Queens University
Kingston
Ontario K7L 3N6
Canada

E-mail: thimothy.thamae@chee.queensu.ca
cbaille@post.queensu.ca

Chapter 5

Dr Mickey G. Huson
CSIRO Materials Science and
Engineering
PO Box 21
Belmont
Geelong
Victoria 3216
Australia

E-mail: mickey.huson@csiro.au

Chapter 6

Mr Vincent Jauzein*
Centre des Matériaux
Mines de Paris (ENSMF)
Paristech
UMR 7633 CNRS
10 rue Desbroyères
91003 Evry
France

E-mail: vincent.jauzein@ensmf.fr

Dr Philippe Colombar
Laboratoire de Dynamique
Interactions et Réactivité (Ladir)
UMR 7075 CNRS
Université Pierre et Marie Curie
(Paris 6)
2 rue Henry-Dunant
94320 Thiais
France

E-mail: philippe.colombar@glvt-cnrs.fr

Chapter 7

Dr Frederick H. Silver*
Department of Pathology and
Laboratory Medicine
UMDNJ-Robert Wood Johnson
Medical School
675 Hoes Lane
Piscataway NJ 08854
USA

E-mail: fhsilver@hotmail.com

Professor Michael Jaffe
Department of Biomedical
Engineering
New Jersey Institute of Technology
University Heights
New Jersey 07102
USA

E-mail: jaffe@adm.njit.edu

Chapter 8

Dr Samir K. Mukhopadhyay
8 Isabel Avenue
Claremont
Cape Town 7708
South Africa

E-mail: samirmuk@mweb.co.za

Chapter 9

Professor Jiri Militký
Technical University of Liberec
Textile Faculty, Department of Textile
Materials
Studentska Street No. 2
46117 Liberec
Czech Republic

E-mail: jiri.militky@tul.cz

Chapter 10

Dr Emmanuel Richaud, Professor
Jacques Verdu and Dr Bruno
Fayolle*
Arts et Metiers ParisTech
CNRS
PIMM
151 bd de l'Hôpital
75013 Paris
France

E-mail: emmanuel.richaud@paris.
ensam.fr
jacques.verdu@paris.ensam.fr
bruno.fayolle@paris.ensam.fr

Chapter 12

Professor Alessandro Pegoretti* and
Matteo Traina
University of Trento
Department of Materials Engineering
and Industrial Technologies
via Mesiano 77
38123 – Trento
Italy

E-mail: alessandro.pegoretti@unitn.
itmatteo.traina@unitn.it

Chapter 13

Martin P. Vlasblom
DSM Dyneema
PO Box 1163
6160 BD Geleen
The Netherlands

E-mail: martin.vlasblom@dsm.com

Chapter 14

Professor Bhupender S. Gupta* and
Dr Mehdi Afshari
Department of Textile Engineering,
Chemistry and Science
College of Textiles
North Carolina State University
Raleigh
NC 27695-8301
USA

E-mail: bgupta@ncsu.edu
mafshar2@ncsu.edu

Chapter 15

Professor Frank R. Jones*
The University of Sheffield
Department of Engineering
Materials
Sir Robert Hadfield Building
Mappin Street
Sheffield S1 3JD
UK

E-mail: f.r.jones@sheffield.ac.uk

Dr Norman T. Huff
Owens Corning
46500 Humbolt Drive
Novi, MI 48377-2434
USA

E-mail: tom.huff@owenscorning.com

Chapter 16

Yoji Matsuhisa*
ACM Technology Department
Toray Industries Inc.
Head Office
Tokyo
Japan

E-mail: Yoji_Matsuhisa@nts.toray.co.jp

Anthony R.Bunsell
Ecole des Mines de Paris
Centre des Matériaux
10 rue Desbruyères
BP 87, 91003 Evry Cedex
France

E-mail: anthony.bunsell@ensmp.fr

Chapter 18

David Wilson
3M Company
High Capacity Conductor Program
251-2A-39 3M Center
St. Paul, MN 55144-1000
USA

E-mail: davidwilson@mmm.com

Woodhead Publishing in Textiles

- 1 **Watson's textile design and colour Seventh edition**
Edited by Z. Grosicki
- 2 **Watson's advanced textile design**
Edited by Z. Grosicki
- 3 **Weaving Second edition**
P. R. Lord and M. H. Mohamed
- 4 **Handbook of textile fibres Vol 1: Natural fibres**
J. Gordon Cook
- 5 **Handbook of textile fibres Vol 2: Man-made fibres**
J. Gordon Cook
- 6 **Recycling textile and plastic waste**
Edited by A. R. Horrocks
- 7 **New fibers Second edition**
T. Hongu and G. O. Phillips
- 8 **Atlas of fibre fracture and damage to textiles Second edition**
J. W. S. Hearle, B. Lomas and W. D. Cooke
- 9 **Ecotextile '98**
Edited by A. R. Horrocks
- 10 **Physical testing of textiles**
B. P. Saville
- 11 **Geometric symmetry in patterns and tilings**
C. E. Horne
- 12 **Handbook of technical textiles**
Edited by A. R. Horrocks and S. C. Anand

- 13 **Textiles in automotive engineering**
W. Fung and J. M. Hardcastle
- 14 **Handbook of textile design**
J. Wilson
- 15 **High-performance fibres**
Edited by J. W. S. Hearle
- 16 **Knitting technology Third edition**
D. J. Spencer
- 17 **Medical textiles**
Edited by S. C. Anand
- 18 **Regenerated cellulose fibres**
Edited by C. Woodings
- 19 **Silk, mohair, cashmere and other luxury fibres**
Edited by R. R. Franck
- 20 **Smart fibres, fabrics and clothing**
Edited by X. M. Tao
- 21 **Yarn texturing technology**
J. W. S. Hearle, L. Hollick and D. K. Wilson
- 22 **Encyclopedia of textile finishing**
H.-K. Rouette
- 23 **Coated and laminated textiles**
W. Fung
- 24 **Fancy yarns**
R. H. Gong and R. M. Wright
- 25 **Wool: Science and technology**
Edited by W. S. Simpson and G. Crawshaw
- 26 **Dictionary of textile finishing**
H.-K. Rouette
- 27 **Environmental impact of textiles**
K. Slater
- 28 **Handbook of yarn production**
P. R. Lord

- 29 **Textile processing with enzymes**
Edited by A. Cavaco-Paulo and G. Gübitz
- 30 **The China and Hong Kong denim industry**
Y. Li, L. Yao and K. W. Yeung
- 31 **The World Trade Organization and international denim trading**
Y. Li, Y. Shen, L. Yao and E. Newton
- 32 **Chemical finishing of textiles**
W. D. Schindler and P. J. Hauser
- 33 **Clothing appearance and fit**
J. Fan, W. Yu and L. Hunter
- 34 **Handbook of fibre rope technology**
H. A. McKenna, J. W. S. Hearle and N. O'Hear
- 35 **Structure and mechanics of woven fabrics**
J. Hu
- 36 **Synthetic fibres: nylon, polyester, acrylic, polyolefin**
Edited by J. E. McIntyre
- 37 **Woollen and worsted woven fabric design**
E. G. Gilligan
- 38 **Analytical electrochemistry in textiles**
P. Westbroek, G. Priniotakis and P. Kiekens
- 39 **Bast and other plant fibres**
R. R. Franck
- 40 **Chemical testing of textiles**
Edited by Q. Fan
- 41 **Design and manufacture of textile composites**
Edited by A. C. Long
- 42 **Effect of mechanical and physical properties on fabric hand**
Edited by H. M. Behery
- 43 **New millennium fibers**
T. Hongu, M. Takigami and G. O. Phillips
- 44 **Textiles for protection**
Edited by R. A. Scott

- 45 **Textiles in sport**
Edited by R. Shishoo
- 46 **Wearable electronics and photonics**
Edited by X. M. Tao
- 47 **Biodegradable and sustainable fibres**
Edited by R. S. Blackburn
- 48 **Medical textiles and biomaterials for healthcare**
Edited by S. C. Anand, M. MirafTAB, S. Rajendran and J. F. Kennedy
- 49 **Total colour management in textiles**
Edited by J. Xin
- 50 **Recycling in textiles**
Edited by Y. Wang
- 51 **Clothing biosensory engineering**
Y. Li and A. S. W. Wong
- 52 **Biomechanical engineering of textiles and clothing**
Edited by Y. Li and D. X.-Q. Dai
- 53 **Digital printing of textiles**
Edited by H. Ujiie
- 54 **Intelligent textiles and clothing**
Edited by H. Mattila
- 55 **Innovation and technology of women's intimate apparel**
W. Yu, J. Fan, S. C. Harlock and S. P. Ng
- 56 **Thermal and moisture transport in fibrous materials**
Edited by N. Pan and P. Gibson
- 57 **Geosynthetics in civil engineering**
Edited by R. W. Sarsby
- 58 **Handbook of nonwovens**
Edited by S. Russell
- 59 **Cotton: Science and technology**
Edited by S. Gordon and Y-L. Hsieh
- 60 **Ecotextiles**
Edited by M. MirafTAB and A. Horrocks

- 61 **Composite forming technologies**
Edited by A. C. Long
- 62 **Plasma technology for textiles**
Edited by R. Shishoo
- 63 **Smart textiles for medicine and healthcare**
Edited by L. Van Langenhove
- 64 **Sizing in clothing**
Edited by S. Ashdown
- 65 **Shape memory polymers and textiles**
J. Hu
- 66 **Environmental aspects of textile dyeing**
Edited by R. Christie
- 67 **Nanofibers and nanotechnology in textiles**
Edited by P. Brown and K. Stevens
- 68 **Physical properties of textile fibres Fourth edition**
W. E. Morton and J. W. S. Hearle
- 69 **Advances in apparel production**
Edited by C. Fairhurst
- 70 **Advances in fire retardant materials**
Edited by A. R. Horrocks and D. Price
- 71 **Polyesters and polyamides**
Edited by B. L. Deopora, R. Alagirusamy, M. Joshi and B. S. Gupta
- 72 **Advances in wool technology**
Edited by N. A. G. Johnson and I. Russell
- 73 **Military textiles**
Edited by E. Wilusz
- 74 **3D fibrous assemblies: Properties, applications and modelling of three-dimensional textile structures**
J. Hu
- 75 **Medical textiles 2007**
Edited by J. Kennedy, A. Anand, M. Miraftab and S. Rajendran
- 76 **Fabric testing**
Edited by J. Hu