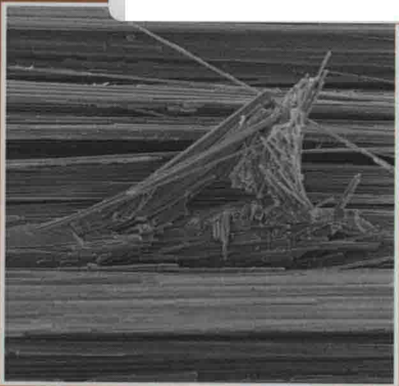
WOODHEAD PUBLISHING SERIES IN COMPOSITES SCIENCE AND ENGINEERING



Toughening Mechanisms in Composite Materials

Edited by
Qinghua Qin and
Jianqiao Ye

WP
WOODHEAD
PUBLISHING

Woodhead Publishing Series in Composites Science and Engineering: Number 55

Toughening Mechanisms in Composite Materials

Edited by

Qinghua Qin and Jianqiao Ye

ELSEVIER

AMSTERDAM • BOSTON • CAMBRIDGE • HEIDELBERG
LONDON • NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Woodhead Publishing is an imprint of Elsevier

WP
WOODHEAD PUBLISHING

Woodhead Publishing is an imprint of Elsevier
80 High Street, Sawston, Cambridge, CB22 3HJ, UK
225 Wyman Street, Waltham, MA 02451, USA
Langford Lane, Kidlington, OX5 1GB, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Control Number: 2015931787

ISBN 978-1-78242-279-2 (print)
ISBN 978-1-78242-291-4 (online)

For information on all Woodhead Publishing publications visit our website at http://store.elsevier.com/

Printed in the United States of America

Toughening Mechanisms in Composite Materials

Related titles

Composite joints and connections
(ISBN 978-1-84569-990-1)

Composite reinforcements for optimum performance
(ISBN 978-1-84569-965-9)

Non-crimp fabric composites
(ISBN 978-1-84569-762-4)

List of contributors

G. Allegri Imperial College London, London, UK

S. Araby School of Engineering, University of South Australia (UniSA), Salisbury, SA, Australia

C. B. Emrullahoglu Abi Afyon Kocatepe University, Afyonkarahisar, Turkey

K. Bilge Sabanci University, Istanbul, Turkey

M. Esmkhani Iran University of Science and Technology, Tehran, Iran

S.M. Ghoreishi Iran University of Science and Technology, Tehran, Iran

M. Kašiarová Slovak Academy of Sciences, Košice, Slovak Republic

V. Kompiš University of Žilina, Žilina, Slovakia

T. Kusaka Ritsumeikan University, Kusatsu, Japan

J.K. Lander Rolls-Royce Plc, Derby, UK

X. Lin University of New South Wales, Canberra, ACT, Australia

X. Liu Beijing University of Technology, Beijing, China

J. Ma School of Engineering, University of South Australia (UniSA), Salisbury, SA, Australia

Q. Meng School of Engineering, University of South Australia (UniSA), Salisbury, SA, Australia

Z. Mouti Eaton, West Midlands, UK

Z. Murčinková Technical University, Košice, Slovakia

J. Njuguna Robert Gordon University, Aberdeen, UK

M. Papila Sabanci University, Istanbul, Turkey

I.K. Partridge University of Bristol, Bristol, UK

Q.H. Qin Australian National University, Acton, ACT, Australia

M. Quaresimin University of Padova, Vicenza, Italy

M. Salviato University of Padova, Vicenza, Italy, and Northwestern University, Evanston, IL, USA

M.M. Shokrieh Iran University of Science and Technology, Tehran, Iran

P. Tatarko Slovak Academy of Sciences, Košice, Slovak Republic, and Queen Mary University of London, London, UK

H. Tian The University of New South Wales, Canberra, ACT, Australia

K. Westwood Eaton, West Midlands, UK

Q.-S. Yang Beijing University of Technology, Beijing, China

M. Yasaee University of Bristol, Bristol, UK

M. Zappalorto University of Padova, Vicenza, Italy

Y.X. Zhang The University of New South Wales, Canberra, ACT, Australia

M. Žmindák University of Žilina, Žilina, Slovakia

Woodhead Publishing Series in Composites Science and Engineering

1 **Thermoplastic aromatic polymer composites**
F. N. Cogswell
2 **Design and manufacture of composite structures**
G. C. Eckold
3 **Handbook of polymer composites for engineers**
Edited by L. C. Hollaway
4 **Optimisation of composite structures design**
A. Miravete
5 **Short-fibre polymer composites**
Edited by S. K. De and J. R. White
6 **Flow-induced alignment in composite materials**
Edited by T. D. Papthanasiou and D. C. Guell
7 **Thermoset resins for composites**
Compiled by Technolex
8 **Microstructural characterisation of fibre-reinforced composites**
Edited by J. Summerscales
9 **Composite materials**
F. L. Matthews and R. D. Rawlings
10 **3-D textile reinforcements in composite materials**
Edited by A. Miravete
11 **Pultrusion for engineers**
Edited by T. Starr
12 **Impact behaviour of fibre-reinforced composite materials and structures**
Edited by S. R. Reid and G. Zhou
13 **Finite element modelling of composite materials and structures**
F. L. Matthews, G. A. O. Davies, D. Hitchings and C. Soutis
14 **Mechanical testing of advanced fibre composites**
Edited by G. M. Hodgkinson
15 **Integrated design and manufacture using fibre-reinforced polymeric composites**
Edited by M. J. Owen and I. A. Jones
16 **Fatigue in composites**
Edited by B. Harris
17 **Green composites**
Edited by C. Baillie

18 **Multi-scale modelling of composite material systems**
Edited by C. Soutis and P. W. R. Beaumont
19 **Lightweight ballistic composites**
Edited by A. Bhatnagar
20 **Polymer nanocomposites**
Y-W. Mai and Z-Z. Yu
21 **Properties and performance of natural-fibre composite**
Edited by K. Pickering
22 **Ageing of composites**
Edited by R. Martin
23 **Tribology of natural fiber polymer composites**
N. Chand and M. Fahim
24 **Wood-polymer composites**
Edited by K. O. Niska and M. Sain
25 **Delamination behaviour of composites**
Edited by S. Sridharan
26 **Science and engineering of short fibre reinforced polymer composites**
S-Y. Fu, B. Lauke and Y-M. Mai
27 **Failure analysis and fractography of polymer composites**
E. S. Greenhalgh
28 **Management, recycling and reuse of waste composites**
Edited by V. Goodship
29 **Materials, design and manufacturing for lightweight vehicles**
Edited by P. K. Mallick
30 **Fatigue life prediction of composites and composite structures**
Edited by A. P. Vassilopoulos
31 **Physical properties and applications of polymer nanocomposites**
Edited by S. C. Tjong and Y-W. Mai
32 **Creep and fatigue in polymer matrix composites**
Edited by R. M. Guedes
33 **Interface engineering of natural fibre composites for maximum performance**
Edited by N. E. Zafeiropoulos
34 **Polymer-carbon nanotube composites**
Edited by T. McNally and P. Pötschke
35 **Non-crimp fabric composites: Manufacturing, properties and applications**
Edited by S. V. Lomov
36 **Composite reinforcements for optimum performance**
Edited by P. Boisse
37 **Polymer matrix composites and technology**
R. Wang, S. Zeng and Y. Zeng
38 **Composite joints and connections**
Edited by P. Camanho and L. Tong
39 **Machining technology for composite materials**
Edited by H. Hocheng
40 **Failure mechanisms in polymer matrix composites**
Edited by P. Robinson, E. S. Greenhalgh and S. Pinho
41 **Advances in polymer nanocomposites: Types and applications**
Edited by F. Gao

42 **Manufacturing techniques for polymer matrix composites (PMCs)**
Edited by S. Advani and K-T. Hsiao
43 **Non-destructive evaluation (NDE) of polymer matrix composites: Techniques and applications**
Edited by V. M. Karbhari
44 **Environmentally friendly polymer nanocomposites: Types, processing and properties**
S. S. Ray
45 **Advances in ceramic matrix composites**
Edited by I. M. Low
46 **Ceramic nanocomposites**
Edited by R. Banerjee and I. Manna
47 **Natural fibre composites: Materials, processes and properties**
Edited by A. Hodzic and R. Shanks
48 **Residual stresses in composite materials**
Edited by M. Shokrieh
49 **Health and environmental safety of nanomaterials: Polymer nanocomposites and other materials containing nanoparticles**
Edited by J. Njuguna, K. Pielichowski and H. Zhu
50 **Polymer composites in the aerospace industry**
Edited by P. E. Irving and C. Soutis
51 **Biofiber reinforcement in composite materials**
Edited by O. Faruk and M. Sain
52 **Fatigue and fracture of adhesively-bonded composite joints: Behaviour, simulation and modelling**
Edited by A. P. Vassilopoulos
53 **Fatigue of Textile Composites**
Edited by V. Carvelli and S. V. Lomov
54 **Wood Composites – From Nanocellulose to Superstructures**
Edited by M. Ansell
55 **Toughening Mechanisms in Composite Materials**
Edited by Q. Qin and J. Ye

Contents

Introduction to the composite and its toughening mechanisms

1

Q.H. Qin
Australian National University, Acton, ACT, Australia

1.1 Basic concepts

The word "composite" usually signifies that two or more separate materials are combined on a macroscopic scale to form a structural unit for various engineering applications. Each of the material components may have distinct thermal, mechanical, electrical, magnetic, optical, and chemical properties. It is noted that a composite composed of an assemblage of these different materials gives us a useful new material whose performance characteristics are superior to those of the constituent materials acting independently (Ye, 2003; Qin and Yang, 2008). One or more of the material components is usually discontinuous, stiffer, and stronger and known as the reinforcement; the less stiff and weaker material is continuous and called the matrix. Sometimes, because of chemical interactions or other processing effects, an additional distinct phase, called an interphase, exists between the reinforcement and the matrix (Damiel and Ishai, 2006). Composite materials have some advantages when compared to their components or metal parts. Some material properties that can be improved by forming a composite material are (Jones, 1999):

- Strength
- Stiffness
- Wear resistance
- Weight
- Fatigue life
- Extreme temperature response
- Thermal insulation or conduction
- Electrical insulation or conduction
- Acoustical insulation or conduction
- Response to nuclear, X-ray, or magnetic radiation
- Chemical response or inertness to an environment (corrosion resistance)
- Electromagnetic and radar insulation or conduction
- Crack (fracture) resistance and arrest
- Cost
- Fabrication
- Temperature-dependent behavior
- Attractiveness.

Further, composite materials have the following advantages: (1) composites can have unique properties (e.g., specific strength and modulus) that are significantly better

Toughening Mechanisms in Composite Materials. http://dx.doi.org/10.1016/B978-1-78242-279-2.00001-9

than their metal, polymer, and ceramic counterparts; (2) composites offer a greater flexiblity in designing and manufacturing a specific engineering structure; (3) composites can be fabricated to a final product from raw materials; and (4) composites can be tailored to have given properties required by the end users.

1.1.1 Matrix materials

Polymers, metals, and ceramics are all used as matrix materials in composites. They are the constituents that are continuously distributed in a composite. Examples of matrix materials are (1) polymers: epoxies, polyesters, phenolics, silicone, polyimide, nylon, polyethelene, polystyrene, and polycarbonate. The first five belong to the category of thermoset plastic, which is the material that can be melted and shaped only once (if it is heated a second time, it tends to crack or disintegrate); whereas the last four are categorized as thermoplastic, which is, in contrast, a material that can be melted and shaped over and over again; (2) metals: steel, iron, aluminum, zinc, carbon, copper, nickel, silver, titanium, and magnesium; and (3) ceramics: alumina, silicon carbide, aluminum nitride, silicon nitride, zirconia, and mullite. The functions of the matrix are to transmit forces between fibers, hold fibers in proper orientations, protect fibers from the environment, and stop cracks from spreading between fibers. To effectively realize those functions, a desired matrix material should have good ductility, high toughness and interlaminar shear strength, stable temperature properties, and high moisture/environmental resistance. In addition, a strong interface bond between the fiber and matrix materials is desirable, so the matrix must be capable of developing a mechanical or chemical bond with the fiber (Gibson, 2012).

1.1.2 Reinforcement materials

Reinforcement materials usually add rigidity and greatly impede crack propagation. In particular, they enforce the mechanical properties of the matrix and, in most cases, are harder, stronger, and stiffer than the matrix. The reinforcement can be divided into four basic categories: fibers, particulates, fillers, and flakes.

Flakes are in flat platelet form and have a primarily two-dimensional geometry with strength and stiffness in two directions. They can form an effective composite material when suspended in a glass or plastic. Ordinarily, flakes are packed parallel to one another with a resulting higher density than fiber-packing concepts. Typical flake materials are mica, aluminum, and silver. Mica flakes embedded in a glassy matrix provide composites that can be machined easily and are used in electrical applications. Aluminum flakes are commonly used in paints and other coatings in which they orient themselves parallel to the surface of the coating. Silver flakes are used where good conductivity is required.

Fillers are particles or powders added to material to change and improve the physical and mechanical properties of composites. They are also used to lower the consumption of a more expensive binder material. In particular, fillers are used to modify or enhance properties such as thermal conductivity, electrical resistivity, friction, wear resistance, and flame resistance. Typical fillers are calcium carbonate,