Thomas Böhlke · Frank Henning
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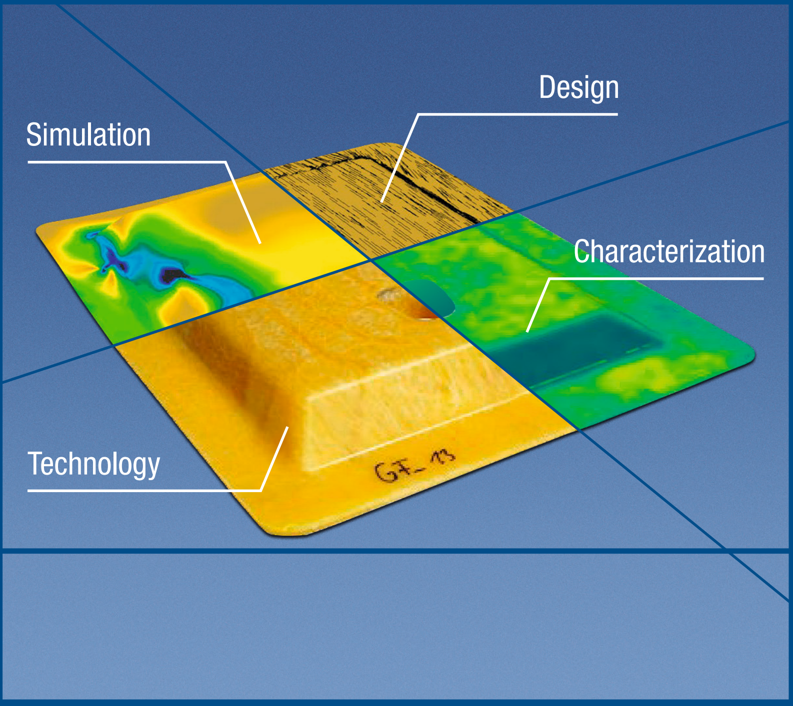
Kay A. Weidenmann · Jeffrey T. Wood (Eds.)
Musa R. Kamal (Series Editor)

Continuous – Discontinuous Fiber-Reinforced Polymers

An Integrated Engineering Approach



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Foreword

The editors are deeply grateful to Dr. Tarkes Dora Pallicity for his exceptional commitment to this collective work and for the very effectively organized coordination in gathering and arranging all information for the potential audience.

Dr. Tarkes Dora Pallicity has played one of the key roles in this book by coordinating and unifying all the contributions made by the authors from Germany and Canada within the International Research Training Group (IRTG) consortium.

He is currently a post-doctoral employee within the IRTG at the Institute of Engineering Mechanics (ITM), Karlsruhe Institute of Technology (KIT), Karlsruhe. He received his doctoral degree from Indian Institute of Technology Madras (2017), postgraduate degree from the National Institute of Technology, Trichy (2011), and undergraduate degree in Mechanical Engineering from the Biju Patnaik University of Technology (2009), Rourkela, India. His research interests are in the area of multi-physics and multi-scale simulations. He is currently working in the area of multi-scale simulations of residual stress in fiber-reinforced composites during composite processing. His doctoral research work was in the area of the measurement and simulation of residual stress in an optical glass lens manufactured by a precision glass molding process.

Acknowledgments

This volume summarizes the research of the first generation of doctoral researchers of the International Research Training Group "Integrated engineering of continuous–discontinuous long fiber-reinforced polymer structures" (GRK2078) from April 2015 to March 2018. This research was fully funded by the German Research Foundation (DFG). This financial support is gratefully acknowledged.

The editors of the book sincerely thank Prof. Musa R. Kamal (Editor of Progress in Polymer Processing (PPP) series) for the opportunity to publish this book as part of the PPP series. We are also thankful to Hanser Publishers and Dr. Mark Smith (Editorial Office, Hanser Publishers) for their constant and efficient support.

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Preface

Hybrid materials, i.e., composites made or joined from several materials, including fiber-reinforced composites with different fiber architectures, play an increasingly important role in industrial applications. The general aim of a hybrid lightweight design is the mass reduction of lightweight structures and simultaneously the increase of performance of the construction, which is reflected in a higher strength, stiffness, or in an improved fatigue strength. Nevertheless, the combination of different materials in hybrid composites results in the evolution of a process-related, hierarchical microstructure, which defines the composite's performance. Hence, designing high performance hybrid materials needs a holistic approach in the interaction between product design, processing technologies, material science, and engineering mechanics.

The relevance of hybrid materials in lightweight structures in industry has increased during the last years. The BMW electric car concept featuring a CFRP-based life module and the use of composites in the aircraft industry are prominent examples for the enhanced used of high-performance composites in vehicle structures. Composite use in aircraft cumulates today in the design of the Boeing 787 featuring a composite-based fuselage concept. Nevertheless, such designs mainly based on the use of continuous carbon fibers are expensive in comparison to metal-based solutions and the design freedom is also limited. Consequently, hybrids based on a combination of cost-efficient long fiber-reinforced plastics and high-performance continuous fiber-reinforced plastics – so-called continuous–discontinuous fiber-reinforced polymers (CoDiCoFRP) – can help to overcome disadvantages and enables an economical lightweight design approach.

In this book, the editors present the results of a transatlantic research cooperation under the leadership of Karlsruhe Institute of Technology (KIT), Germany, and University of Western Ontario, Canada, directly focusing on the new material class of CoDiCoFRP bringing together scientists from production science and development, lightweight technology, mechanics, and material science. This International Research Training Group, "Integrated engineering of continuous-discontinuous long fiber-reinforced polymer structures" (GRK2078), has been fully funded by the German Research Foundation (DFG).

Divided between thematic chapters on technology (Chapter 2), characterization (Chapter 3), simulation (Chapter 4), and design (Chapter 5), the results from the first generation of doctoral researchers at KIT are presented. Especially, Chapter 6, on establishing the process chain for a demonstrator product, clearly shows the benefit of very strong interactions between all disciplines involved to realize a holistic approach.

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List of Symbols

Symbol	Definition
α	Coefficient of thermal expansion
β	Coefficient of chemical shrinkage
$\boldsymbol{\varepsilon}$	Infinitesimal strain tensor
$\bar{\boldsymbol{\varepsilon}}$	Infinitesimal effective strain tensor
$\boldsymbol{\varepsilon}_{\mathrm{cu}}$	Curing strain tensor
$\boldsymbol{\varepsilon}_{\mathrm{e}}$	Elastic strain tensor
$\boldsymbol{\varepsilon}_{\mathrm{th}}$	Thermal strain tensor
$\boldsymbol{\varepsilon}_{\mathrm{v}}$	Viscous strain tensor
θ	Absolute temperature
θ_{g}	Glass transition temperature
ν_{f}	Poisson's ratio of the fiber
ν_{m}	Poisson's ratio of the matrix
$\boldsymbol{\sigma}$	Cauchy stress tensor
$\bar{\boldsymbol{\sigma}}$	Effective Cauchy stress tensor
ρ	Mass density
τ	Relaxation time
$a, b, A, B...$	Scalar quantities
$\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, ...$	First-order tensors
$\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, ...$	Second-order tensors
$\mathbb{A}, \mathbb{B}, \mathbb{C},...$	Fourth-order tensors
$\mathbb{A}$	Strain localization tensor
$\mathbb{B}$	Stress localization tensor
c_{f}	Fiber volume fraction
c_{m}	Matrix volume fraction
$\mathbb{C}$	Stiffness tensor
$\mathbb{C}_{\mathrm{f}}$	Stiffness tensor for fiber
$\mathbb{C}_{\mathrm{m}}$	Stiffness tensor for matrix
$\bar{\mathbb{C}}$	Effective stiffness tensor

Symbol	Definition
d	Scalar damage variable
E_{f}	Elastic modulus of the fiber
E_{m}	Elastic modulus of the matrix
$f(\boldsymbol{n})$	Fiber orientation distribution function
$\boldsymbol{n}$	Fiber orientation
$\boldsymbol{N}$	Fiber orientation tensor of second order
$\mathbb{N}$	Fiber orientation tensor of fourth order
$\mathbb{P}_1$	First isotropic projector tensor
$\mathbb{P}_2$	Second isotropic projector tensor
$\boldsymbol{I}$	Second-order identity tensor
$\mathbb{I}$	Fourth-order identity tensor
q	Degree of cure
$\dot{q}$	Curing rate
R	Universal gas constant
t	Time
$\boldsymbol{u}$	Displacement vector
$\mathbb{V}$	Viscosity tensor

List of Acronyms

Acronym	Expanded form
2D	Two-dimensional
3D	Three-dimensional
CT	Computed tomography
CoFRP	Continuous fiber-reinforced polymer
CoDiCoFRP	Discontinuous fiber-reinforced polymer with continuous fiber
CoDiCoFRTP	Discontinuous fiber-reinforced thermoplastic with continuous fiber
CoDiCoFRTS	Discontinuous fiber-reinforced thermoset with continuous fiber
CoFRTP	Continuous fiber-reinforced thermoplastic
CoFRTS	Continuous fiber-reinforced thermoset
DiCoFRP	Discontinuous fiber-reinforced polymer
DiCoFRTS	Discontinuous fiber-reinforced thermoset
DiCoFRTP	Discontinuous fiber-reinforced thermoplastic
FAST	Institute of Vehicle System Technology
FEM	Finite element method
FFT	Fast Fourier transformation
FODF	Fiber orientation distribution function
FOD	Fiber orientation distribution at material point
FPC	Fraunhofer Project Center
GF	Glass fiber

Acronym	Expanded form
IAM-WK	Institute for Applied Materials – Materials Science and Engineering
IAM-CMS	Institute for Applied Materials – Computational Materials Science
ICT	Fraunhofer Institute for Chemical Technology
IFM	Institute of Mechanics
IPEK	Institute of Product Engineering
ITM	Institute of Engineering Mechanics
IWM	Fraunhofer Institute for Mechanics of Materials IWM
KIT	Karlsruhe Institute of Technology
LFTP	Long fiber-reinforced thermoplastic
PA6	Polyamide-6
RVE	Representative volume element
SMC	Sheet molding compound
TP	Thermoplastic material
TS	Thermoset material
UPPH	Unsaturated polyester polyurethane hybrid
UoW	University of Windsor
UT	University of Toronto
UWO	University of Western Ontario
wbk	Institute of Production Science

Contents

1

Introduction to Continuous–Discontinuous Fiber-Reinforced Polymer Composites

Thomas Böhlke, Andrew Hrymak, Luise Kärger,
Tarkes Dora Pallicity, Kay A. Weidenmann, Jeffrey T. Wood

1.1 Fiber-Reinforced Composite Materials

Composite materials have ushered in a new era in materials science and engineering, allowing the design of engineered materials with superior mass-specific mechanical properties. Current demand in the transportation and energy sectors to reduce carbon dioxide emissions has motivated designs with such materials, a trend expected to increase in the coming years. Fiber-reinforced plastics (FRP) are an important class of such materials that have gained increasing attention due to their characteristics of light weight, high strength, and stiffness [1, 2]. These materials are made of two constituents – fiber and matrix – that differ in their mechanical properties. The role of the matrix is primarily to bind the fibers together, transfer loads, and protect fibers from abrasion and the environment. The matrix material is usually either a thermoset (TS) or thermoplastic (TP). The fibers primarily carry the load transferred from the matrix and hence provide macroscopic stiffness and strength to the structure. Glass fiber and carbon fiber are the two most widely used reinforcements in FRP composites.

FRP materials can be broadly categorized as discontinuous FRP (DiCoFRP) and continuous FRP (CoFRP), based on the length of the fibers. Further, these can be either the TS or TP type, based on the matrix material used in the composite. CoFRP consists of aligned fibers similar in length to the dimensions of the structural component. The alignment of fibers along the loading direction results in high stiffness and strength. However, continuous fibers limit the design freedom and result in high production costs. Fabricating components from DiCoFRP is easier, as this material has better formability (i.e., the natural ability to conform to curved surfaces) and flow ability than CoFRP, thus making it easier to form complex geometries, such as ribs. The mechanical properties of DiCoFRP, such as strength and stiffness, are lower, but DiCoFRP provides increased design freedom and economical production costs. Figure 1.1 schematically shows the advantages and disadvan-