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An Introduction to Composite Materials

Third Edition

This fully expanded and updated edition provides both scientists and engineers with all the information they need to understand composite materials, covering their underlying science and technological usage. It includes four completely new chapters on surface coatings, highly porous materials, bio-composites and nano-composites, as well as thoroughly revised chapters on fibres and matrices, the design, fabrication and production of composites, mechanical and thermal properties and industry applications. Extensively expanded referencing engages readers with the latest research and industrial developments in the field, and increased coverage of essential background science makes this a valuable self-contained text. A comprehensive set of homework questions, with model answers available online, explains how calculations associated with the properties of composite materials should be tackled, and educational software accompanying the book is available at doitpoms.ac.uk.

This is an invaluable text for final-year undergraduates in materials science and engineering, and graduate students and researchers in academia and industry.

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An Introduction to Composite Materials

Third Edition

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Preface to the Third Edition

The topic of composite materials continues to evolve in terms of range, research activity and technological importance. This was the case between publication of the first edition in 1981 and the second in 1996. The coverage of the book was expanded and broadened to reflect this. In fact, the rate of development of composites has accelerated in the period since then and hence a further substantial enlargement and evolution in coverage has been implemented. Composites certainly now constitute one of the most important and diverse classes of material. All materials scientists and engineers need to be familiar with at least the main principles and issues involved in their usage.

While this edition retains much of the structure and conceptual framework of the previous two editions, it now includes four completely new chapters. Moreover, all of the other chapters, which progressively cover the various types of fibre and matrix, the structure of composites, their elastic deformation, strength and toughness, the role of the interface and the thermal characteristics of composite systems, have all been rewritten, to a greater or lesser extent. There has, of course, been extensive updating to reflect the prodigious levels of research and industrial development in the area over the past couple of decades. The citation of references has been expanded and restructured. While previously there was a short list of sources for further information at the end of each chapter (with limited specific citation in the text), this edition provides much more comprehensive referencing, both in quantity and in terms of detail. This change is designed to improve the potential value to researchers, as well as undergraduates.

Nevertheless, much of the material remains pitched at around the level of a final-year undergraduate or a Masters course. In fact, another innovation in this edition is the provision of a large number of questions (with model answers available on the website). Many of these are derived from a third-year undergraduate course on composite materials that has been running (and evolving!) for over 30 years in the Materials Science Department at Cambridge University. A further pedagogical development concerns educational software packages that can be used in conjunction with the book. These form part of a major initiative called DoITPoMS (Dissemination of IT for the Promotion of Materials Science), hosted on the Cambridge University site (www.doitpoms.ac.uk), which comprises a large number of interactive modules covering a wide range of topics. Many are relevant to the general area of composite materials, but several are specific to topics in the book and reference to them is included in the enhanced coverage.

In addition to this expansion in terms of the range of teaching resources, attempts have been made to encompass more of the necessary background science, so as to reduce the need to consult other texts. Examples of this include more comprehensive coverage of the manipulation of stresses and strains as (second-rank) tensors, which is particularly important when treating highly anisotropic materials such as composites, and a considerably expanded chapter on fracture mechanics. These are both areas in which the background knowledge needed for a full understanding of the behaviour of composites is relatively demanding. Bringing this material within the remit of the book is aimed at creating a more coherent overall picture, within a consistent framework of nomenclature and symbolism.

In addition, the new chapters are aimed at expansion of the range of situations that can usefully be treated using the approaches of composite theory. The first of these (Chapter 11) concerns the mechanics of substrate/coating systems, a topic of considerable scientific and technological interest. It is shown how tools developed within the framework of the book can be used to obtain insights into the development of curvature in such systems, and also into the driving forces for spallation (debonding) of such coatings. The following chapter, on highly porous materials, is based on a similar philosophy – in this case showing how such materials, which are also of technological importance, can usefully be treated as special types of composite material.

Chapter 13 is also a new addition. This concerns bio-composites, such as wood and bone. Of course, these are widely recognised as (complex) composite materials, and the treatment presented here is fairly superficial. Nevertheless, information is presented on how they relate to manufactured composites, and there is some coverage of the important topics of recycling, degradation and sustainability. The final new chapter relates to scale effects in composites and to the class of materials sometimes referred to as nanocomposites. Despite the enormous levels of interest and research in such materials over recent decades, levels of industrial exploitation have remained minimal – at least as far as load-bearing components are concerned. The reasons for this are outlined.

The final two chapters, as in the previous edition, concern fabrication of composites and their application. These are largely in the form of case histories of various types. There has again been considerable expansion and updating of these, reflecting the huge range of current industrial usage and the ways in which composites have penetrated numerous markets – and in many cases facilitated their expansion and raised their significance. There is extensive cross-reference in these chapters to locations in the book where details are provided about characteristics of the composites concerned that have favoured their usage.

Finally, we would again like to thank our wives, Gail and Pauline, for their invaluable support during the preparation of this book.

T. W. Clyne and D. Hull
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More Information

Nomenclature

Parameters

A	(m^2)	cross-sectional area
A	(s^{-1} Pa^{-n})	constant in creep equation (10.17)
a	(–)	direction cosine
a	(m)	radius of sphere
a	(m^2 s^{-1})	thermal diffusivity
b	(m)	width
Bi	(–)	Biot number
C	(Pa)	stiffness (tensor of fourth rank)
C	(Pa^{-n} s^{-m-1})	constant in creep equation (10.18)
c	(J K^{-1} m^{-3})	volume specific heat
c	(m)	crack length or flaw size
c	(–)	cos(ϕ)
D	(m)	fibre diameter
d	(m)	fibre/particle diameter
E	(Pa)	Young's modulus
E'	(Pa)	biaxial modulus
e	(–)	relative displacement
f	(–)	reinforcement (fibre) volume fraction
F	(N)	force
G	(J m^{-2})	strain energy release rate
G	(Pa)	shear modulus
g	(–)	fraction (undergoing pull-out)
H	(m)	thickness (of substrate)
h	(m)	thickness (of coating)
h	(m)	spacing between fibres
h	(m)	height
h	(W m^{-2} K^{-1})	heat transfer coefficient
I	(–)	unit tensor (identity matrix)
I	(–)	invariant (in the secular equation)
I	(m^4)	second moment of area
K	(Pa)	bulk modulus
K	(Pa $m^{1/2}$)	stress intensity

K	(W m^{-1} K^{-1})	thermal conductivity
k	(J K^{-1})	Boltzmann's constant
L	(m)	sample length
L	(m)	fibre half-length
M	(m N)	bending moment
m	(–)	Weibull modulus
N	(mole^{-1})	Avogadro's number
N	(–)	number of loading cycles
N	(m^{-2})	number of fibres per unit area
n	(–)	dimensionless constant
n	(–)	stress exponent
P	(N)	force
P	(Pa)	pressure
P	(–)	probability
P	(–)	porosity
Q	(m^3 m^{-2} s^{-1})	fluid flux
q	(W m^{-2})	heat flux
R	(J K^{-1} mole^{-1})	universal gas constant
R	(m)	far-field radial distance from fibre axis
r	(m)	radius of fibre, tube or crack tip
S	(Pa^{-1})	compliance tensor
S	(–)	Eshelby tensor
S	(Pa)	stress amplitude during fatigue
S	(m^2 m^{-3})	specific surface area
s	(–)	fibre aspect ratio ($2L/d = L/r$)
s	(–)	$\sin(\phi)$
T	(K)	absolute temperature
T	(N m)	torque
T'	(K m^{-1})	thermal gradient
t	(m)	ply or wall thickness
t	(s)	time
U	(J)	work done during fracture
u	(m)	displacement in x direction (fibre axis)
V	(m^3)	volume
v	(m s^{-1})	velocity
W	(J m^{-3})	work of fracture
x	(m)	distance (Cartesian coordinate)
y	(m)	distance (Cartesian coordinate)
z	(m)	distance (Cartesian coordinate)
α	(K^{-1})	thermal expansion coefficient
β	(–)	reinforcement/matrix ratio conductivity ratio
β	(–)	dimensionless constant
Δ	(–)	relative change in volume

δ	(m)	crack opening displacement
δ	(m)	pull-out length
δ	(m)	distance from neutral axis to interface
ε	(–)	strain
ϕ	(°)	loading angle (between fibre axis and loading direction)
Φ	(°)	global loading angle (between laminate reference axis and loading direction)
γ	(–)	shear strain
γ	(J m^{-2})	surface energy
η	(–)	interaction ratio
η	(–)	dimensionless constant
η	(Pa s)	viscosity
κ	(m^{-1})	curvature
κ	(m^{2})	(specific) permeability
λ	(m)	mean free path
λ	(–)	dimensionless constant
θ	(û)	wetting angle
ν	(–)	Poisson ratio
ρ	(kg m^{-3})	density
ρ	(m)	distance from fibre axis
Σ	(N m^{2})	beam stiffness
σ	(Pa)	stress
τ	(Pa)	shear stress
ψ	(°)	phase angle (mode mix)
ξ	(–)	dimensionless constant

Subscripts

0	initial
1	x direction (along fibre axis)
2	y direction
3	z direction
A	applied
a	air
b	background
b	buckling
c	coated
c	composite
c	critical
d	debonding
e	fibre end
f	failure
f	fibre (reinforcement)

fr	frictional sliding
g	global
H	hoop
H	hydrostatic
i	interfacial
k	kink band
L	liquid
m	matrix
n	network
p	pull-out
p	particle
r	radial
s	survival
RoM	rule of mixtures
t	stress transfer
th	threshold
trans	transverse
u	failure (ultimate tensile)
u	uncoated
v	volume
Y	yield (0.2% proof stress often taken)
θ	hoop
*	critical (e.g. debonding or fracture)

Superscripts

ax	axial
C	constrained
T	transformation
T*	misfit
tr	transverse