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Preface

This book examines strategies for experimental approaches to stiffness, strength and toughness testing. There are numerous options in these activities and one of the aims of the book is to critically consider beneficial approaches in the context of multiple objectives. How test results are interpreted may be more important than the physical validity of the test procedure in some instances. A good test strategy can compensate for imperfections or insufficiencies in a particular procedure and integrate the results from individual test components into an entity that is more informative than the simple sum of the individual parts. Thus, whilst various classes of test have to be segregated for the convenience of a reader, they cannot be so segregated in testing practice because one class of test may support another via correlations that might surprise or offend the purist, but that are invaluable at the sharp end of commercial competitiveness.

The book divides mechanical evaluation into two areas: modulus measurement and strength/ductility measurement. Each area is then considered in terms of the type of input function, namely constant deformation rate, sinusoidal excitation, step-function tests and impulse excitation. Consequently, all of the usual procedures in mechanical property evaluations are accommodated; universal test machine tests, creep modulus, dynamical mechanical modulus, stiffness anisotropy, general fracture toughness, long-term strength, strength in aggressive environments, fatigue and impact toughness.

The presentational style of the book is novel. The 11 chapters dealing with modulus and strength/ductility are quite short. They provide a condensed opinion of what is beneficial and what is mythical, but largely without formal review since much of that is covered in other texts. Consequently, there is no attempt at citing detailed references nor is there a formal account of the many test methods. However, there is a copious section on other recommended reading.

Each chapter contains small but numbered sections. Throughout these sections there are opportunities to provide illustration of a point. These illustrations appear as referenced supplements at the end of each chapter, e.g. Supplement 1.4 discusses samples, specimens and tests. By placing them as appendices, each chapter can be read without deviation in order to obtain an overall view on what is a vast topic. On the other hand, the supplements (which exceed 50 in number) can be a source of specific study in using the book, each one standing essentially self-contained.

The book is aimed at a broad audience of material scientists and engineers. For those in industry, whether involved as material suppliers, processors or end-users, there is an account of the approaches that they can use in characterizing mechanical properties as well as utilizing mechanical properties in end-product application or in contemplating the influence of processing on properties. Students in engineering, materials science or polymer science departments will benefit from the short, yet broad-ranging, chapter content, but also be guided by the many illustrations of application of a principle or an approach.

Both authors have worked in the Mechanical Property Group in ICI's Research Department. They overlapped for 10 years but covered a total span of 50 years from which much of their knowledge and experience has developed. During this long period they had the benefit of working with a large number of colleagues. This was a rich experience, and both authors acknowledge the pleasure, benefits and learning that emerged from the constructive interactions.

Abbreviations

ABS	acrylonitrile butadiene styrene
APC	aromatic polymer composite
ASTM	American Society for Testing and Materials
BPDA	3, 4, 3′, 4′ biphenyl tetracarboxylic dianhydride
BSI	British Standards Institute
BTL	Bell Telephone Laboratory
CLS	cracked lap shear
COD	crack opening displacement
CT	compact tension
c.v.	coefficient of variation
DCB	double cantilever beam
DDE	diamino diphenyl ether
DIN	Deutsches Institut für Normung
DMA	dynamical mechanical analyser
ENF	end-notched flexure
ESC	environmental stress cracking
ESIS	European Structural Integrity Society
HD	high density as in high density polyethylene
HDT	heat distortion temperature
HDPE	high density polyethylene
ISO	International Organization for Standardization
LEFM	linear elastic fracture mechanics
MEK	methyl ethyl ketone
MFI	melt flow index
NDT	non-destructive testing
NPL	National Physical Laboratory
PEEK	poly(ether ether ketone)
PES	poly(ethersulphone)
PMDA	pyromellitic dianhydride
PMMA	poly(methyl methacrylate)
PP	polypropylene

PTFE	poly(tetrafluoroethylene)
PTMT	poly(tetramethylene terephthalate)
PVC	poly(vinyl chloride)
R-curve	plot of fracture toughness vs. crack length
SEN	single edge notched
tan δ	tangent of the loss angle δ
TC4	Technical Committee 4
3D	three dimensional
w/w	weight/weight concentration

Symbols

a	crack length
a	half-length of intrinsic defect
a	radius of a support ring (re impact equipment)
a	lateral dimension
a_1, a_2	side dimension of a rectangular plate
$a_{0...n}$	coefficients
a_f	effective crack length
A	shape factor
A	cross-sectional area
A	constant
A	coefficient
A_i	a series of coefficients $A_1, A_2, \ldots$
α	highest temperature transition (with respect to loss processes)
b	specimen width
$b_{0...m}$	coefficients
$b_{\min}$	minimum value of specimen width for plane strain conditions
B	coefficient
$B(\sigma, t)$	bulk compliance which is stress and time dependent
β	next to highest temperature transition (re loss processes)
$\beta(b, h)$	shape factor for torsion of a beam
c	$\cos\theta$
c^*	complex compliance for a Voigt element
c', c''	real and imaginary components of compliance associated with a Voigt element
C	stiffness $[E/(1-\nu^2)]$
$\overline{C}$	transform compliance
$\overline{C}_c(p)$	Laplace creep function
$C^*(\omega)$	complex compliance (dependent on angular frequency)

$C(t)$	time dependent compliance also creep compliance function
$C_c(t)$	creep function
C^*	complex compliance
C', C''	real and imaginary components of complex compliance
$C(\sigma, t)$	uniaxial compliance dependent on stress and time
C_{ijkl}	stiffness coefficients where i, j, k, l can have values of 1, 2 or 3
Cij	stiffness coefficients for an applied stress with the direction of the normal to the surface being i and a strain axis j (where i, j can be 1, 2 or 3)
cv	coefficient of variation
d	tank wall thickness
d	diameter of a cylinder
d	displacement
$\mathrm{d}a/\mathrm{d}n$	crack growth per cycle
D	flexural rigidity (EI)
D	ductility factor
δ	deflection of a beam
δ	phase angle associated with complex modulus
δ	crack opening displacement
δ_l	increase in length
$\delta(t)$	time dependent deflection
δ_b	deflection due to bending
δs	deflection due to shear
δcrit	critical value of crack opening displacement
Δ	crack length correction
ΔV	change in volume
ΔH	activation energy
ΔT	temperature increment
ΔP	force difference (re fatigue testing)
ΔK	difference in stress field intensity factor (re fatigue testing)
$\Delta\sigma_R$	change in remote stress (re fatigue testing)
e	exponential function
E	axial modulus also known as Young's modulus and as modulus of elasticity
(EI)	flexural rigidity
$E(t)$	time dependent modulus
$E_c(t)$	tensile creep modulus
E_t	modulus at time t
E_c	composite modulus
E_f	fibre modulus
E_m	matrix modulus

E_{ij}	engineering axial modulus where i, j can be 1, 2 or 3
E_r	relaxation modulus in tension
E_θ	in plane modulus where typically $\theta = 0°, 45°, 90°$
$E(100)$	100 sec axial modulus
E^*	complex modulus
ε_{ij}	strain in the plane i, j where i, j relate to the rectangular co-ordinates x, y, z
ε	strain (engineering)
ε_H	Henky or logarithmic strain
$\varepsilon_{\text{equiv}}$	equivalent strain
$\varepsilon_{l,w,h}$	axial, width and thickness strains
ε_{kl}	strain tensor where k, l can be 1, 2 or 3
ε_{ij}	strain tensor where i, j can be 1, 2 or 3
f	frequency
$f(\theta)$	angular distribution of stress
$f(h)$	function of specimen thickness
$f(\nu)$	function of Poisson's ratio
$f(a)$	function of crack length
$f(\theta)$	function dependent on the angle θ
f_0	constant
f_1, f_2	specific frequencies
$f(\sigma)$	function of stress
$F(\sigma, t)$	function of stress and time
FR	fractional recovery
F	large displacement correction
ϕ	fibre volume fracture
ϕ	geometry function
$\phi(\varepsilon)$	function of strain
ϕ	phase angle associated with complex modulus but used in fixed vibration systems ($\phi \neq \delta$)
g	acceleration due to gravity
$g(t)$	function of time
G	shear modulus
G	strain energy release rate
G	surface energy
G^*	complex shear modulus
$G(t)$	time-dependent shear modulus
G', G''	real and imaginary components of a complex shear modulus
G_{ij}	engineering shear modulus where i, j can be 1, 2 or 3
$G(100)$	100 s shear modulus
G_c	critical value for strain energy release rate but more usually known as fracture toughness
G_{Ic}	opening mode fracture toughness

γ	fracture surface energy
γ	third from highest temperature transition (re loss processes)
γ_{ij}	shear strain where i, j can be 1, 2 or 3
H	height of liquid in a cylindrical tank
h	specimen depth, thickness
h	specimen diameter
$h_{1,2}$	outer and inner specimen diameters, respectively, of a tube
η	viscosity associated with a dashpot
η_α	inefficiency factor for imperfectly aligned continuous fibres
η_c	inefficiency factor for imperfectly discontinuous fibres
η_d	inefficiency factor for debonded fibres
I	area moment of inertia
J_{2D}	second invariant of the deviatoric part of the stress tensor
J_1	first invariant of the stress tensor
J_c	crack resistance
k	stress concentration
k	spring constant
k^*	complex stiffness
k', k''	real and imaginary components of stiffness for a Voigt element
K	bulk modulus
K_a	apparent bulk modulus
K^*	complex bulk modulus
K', K''	real and imaginary components of a complex bulk modulus
K^l	Larsen–Miller creep rupture parameter for equating time and temperature
$K_{I,II,III}$	opening mode, shear mode and antishear mode (tearing mode) for stress field intensity factor, respectively
K_c	critical value of stress field intensity factor but better known as fracture toughness
K_{Ic}	opening mode fracture toughness
K_{c1}	plane strain fracture toughness
K_{c2}	plane stress fracture toughness
l	gauge length
l	length of a cylinder
l	decay length (in St Venat's principle)
l	specimen height
l_o	original gauge length

L	effective beam length or span
L	length of a diagonal
λ	a specific decay length (in St Venat's principle)
λ	extension ratio
m	Paris law integer
m	mass of impactor
m	an integer in the range $0 \ldots m$
$\overline{M}_r(p)$	Laplace creep modulus function
$M_r(t)$	relaxation creep modulus function
M^*	complex modulus
M', M''	real and imaginary components of complex modulus
M_o	instantaneous modulus
M_t	applied torque
μ	coefficient of friction
n	an integer in the range $0 \ldots n$
n	$\sin\theta$
n	power law coefficient
N or n	number of fatigue cycles
N	loading block correction
ν	lateral contraction ratio also known as Poisson's ratio
$\nu(t)$	time-dependent lateral contraction ratio
ν', ν''	real and imaginary components of a complex lateral contraction ratio
ν^*	complex lateral contraction ratio
$\nu(\sigma, t)$	stress and time-dependent lateral contraction ratio
ν_{ij}	engineering lateral contraction ratio where i, j can be 1, 2 or 3
p	a variable
P	applied force
P	peak force
$P_{\max}$	maximum force
$P_{\min}$	minimum force
Q	transverse shear stiffness
θ	an angle
θ	angle measured anticlockwise from the line of a crack
r	a radius
r	an integer from 0 to r

r	distance from crack tip
r_P	plastics zone radius also length of the line zone in a Dugdale model
r_o'	effective area of contact between impactor nose and specimen
r_0	actual area of contact between impactor nose and specimen
R	gas constant (8.314 J/mol K)
R	ratio of minimum to maximum force in fatigue
ρ	density
ρ	notch-tip radius
s	$\sin\theta$
S	span
S	stress
S_{ijkl}	are compliance coefficients where i, j, k, l can be 1, 2 or 3
S_{ij}	are compliance coefficients for an applied strain with the direction of the normal to the surface being i and the line of action of the stress being j (where i, j can be 1, 2 or 3)
σ	stress (including true stress)
σ_o	a step function of stress
$\sigma(t)$	time-dependent stress
σ_a	applied stress
σ_{ij}	stress tensor where i, j can be 1, 2 or 3 (also for σ_{kl}) or x, y or z
$\sigma_{11}, \sigma_{22}, \sigma_{33}$	normal stresses
$\sigma_{12}, \sigma_{23}, \sigma_{31}$	shear stresses
$\sigma_L(r, \theta)$	local stress at the tip of a crack
σ_R	applied stress at a point remote from the crack (notch)
σ_y	yield stress
σi	principal stress where i can be 1, 2 or 3
σ_n or σ_{net}	net stress
σ_{max}	maximum stress
σ_f	stress at fracture
σ_m	stress in the tensile skin layer at mid-span (re bending of a beam)
σ_t, σ_c	tensile and compressive stress, respectively
σ_D	design stress
t	time
t_R	reduced time (re creep recovery)
t_{min}	minimum creep rupture lifetime
t_{max}	maximum creep rupture lifetime
t_{ON}	time on load

T	temperature
T_b	embrittlement temperature
T_1, T_2	specific temperatures
T_g	glass–rubber transition temperature
τ	a relaxation time; for a spring-dashpot array, it is the ratio of viscosity to spring constant i.e η/κ
τ_{ij}	shear stress where i, j can be 1, 2 or 3 or alternatively x, y or z
τ_{max}	maximum shear stress
u	a variable
U	stored energy
Ut	energy stored by a specimen at any time t
v	velocity
v_c	velocity of crack propagation in glass
v_t	velocity of crack propagation in an infinite medium
v_t	velocity of an impactor (re instrumented impact equipment)
vo	initial velocity of an impactor
V	volume
$\Delta V/V$	volume strain
w	width
w_P	energy per unit volume
W	specimen width
ω	angular frequency
x	a variable
x_t	displacement of specimen at any time t
Y	geometry factor in fracture mechanics
z	distance from the neutral axis (for a beam specimen)

Contents