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978-1-108-83789-7 — Testing of the Plastic Deformation of Metals
T. W. Clyne, J. E. Campbell
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Testing of the Plastic Deformation of Metals

Discover a novel, self-contained approach to an important technical area, providing both theoretical background and practical details. Coverage includes mechanics and physical metallurgy, as well as study of both established and novel procedures such as indentation plastometry. Numerical simulation (FEM modeling) is explored thoroughly, and issues of scale are discussed in depth. Discusses procedures designed to explore plasticity under various conditions, and relates sample responses to deformation mechanisms, including microstructural effects. Features references throughout to industrial processing and component usage conditions, to a wide range of metallic alloys, and to effects of residual stresses, anisotropy and inhomogeneity within samples. A perfect tool for materials scientists, engineers and researchers involved in mechanical testing (of metals), and those involved in the development of novel materials and components.

T. W. Clyne is an Emeritus Professor in the Department of Materials Science and Metallurgy at the University of Cambridge and also the Chief Scientific Officer at Plastometrex Ltd. In addition, he is the Director of DoITPoMS, an educational materials science website, a Fellow of the Royal Academy of Engineering, a Helmholtz International Fellow and a Leverhulme Emeritus Fellow.

J. E. Campbell (PhD University of Cambridge) is Chief Engineer at Plastometrex Ltd. with expertise in mechanical testing of metals with a focus on indentation and finite element modeling.

“This beautifully written and illustrated book elucidates both the mechanics and mechanisms of plastic deformation of metals and describes the testing methods used to reveal those properties.

While their treatment is comprehensive, Clyne and Campbell have kept the focus on essential topics and have produced a highly readable book that promises to be an instant classic.

The book is both authoritative and tutorial and will be welcomed by students and practicing engineers alike.”

William D. Nix
Stanford University

“This is the best book on metal plasticity I have ever seen. It is the most authoritative text available, and yet the most understandable. There is sufficient detail for the serious practitioner, but it is also accessible enough for the novice. The coverage of stresses, strains and continuum plasticity through to every conceivable test technique is the most comprehensive available.”

Mark Rainforth
The University of Sheffield

“Clyne and Campbell have produced a wonderful book which I recommend thoroughly. It is well-written, easy to read and beautifully produced.

The subject matter is very important, but deceptively challenging. Existing textbooks do not cover it carefully enough. The authors have done a tremendous job to explain the salient points with much-needed rigor and a great deal of style.”

Roger C. Reed
University of Oxford

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Preface

The plasticity of metals is central, not only to materials science as a subject, but also to the whole history of technological development. Broadly speaking, the only metal found naturally in elemental form is gold, which has been prized throughout human history – partly due to its lustre, but also because it can readily be formed into various shapes (including very thin foil). Development of the skills and knowledge needed to extract other metals has been transformational for human society and their most important feature is arguably their capacity for permanent shape change, without fracturing. While an understanding of the mechanisms involved is relatively recent, it still extends back several decades. Many thousands of books and papers, published over the past 100 years, cover the topic in detail. This coverage includes both the micro-mechanisms, with the discovery of the dislocation being pivotal, and engineering aspects, usually with the plasticity being treated on a continuum basis.

Several books contain a mixture of physical metallurgy and associated mechanical properties, with mechanical testing procedures often covered in some way. However, relatively few books have been dedicated to testing of metal plasticity. The importance of detailed characterization, and of measurements being made with an understanding of what is taking place inside a sample during a test, has therefore prompted us to produce this book. Its content is based both on several decades of teaching and research experience in Cambridge University and also on extensive interaction with a range of industrial partners and collaborators over that period. This has included, over the past few years, our close involvement with the founding and development of Plastometrex, a company that is oriented towards the development of novel procedures for testing of metal plasticity.

The book has 10 chapters, broadly divided into three sections. The first of these provides background concerning mechanics and microstructural aspects (related to plasticity). The second covers the traditional testing techniques of tensile, compressive and hardness testing, while the third is devoted to various other test configurations and conditions, many involving recent developments. Such testing arrangements include those for study of creep behavior, high strain rates, superelastic deformation, cyclic loading etc., in addition to conventional plasticity characterization. Finite element method (FEM) modeling, which is a powerful tool for investigation of mechanical deformation, figures strongly throughout. The coverage includes “nanoindentation,” but is mainly oriented towards obtaining bulk mechanical properties, for which it is not well suited (due to the deformed volume being too small for its response to be representative of the bulk). The important recent advances concerning indentation relate less to it being carried out on a very fine scale, but more to it being instrumented so as to obtain detailed information about the (bulk) mechanical characteristics. This represents a fundamental advance, relative to its origins in hardness testing, and it is explored here in some detail. There is reference throughout to industrial processing and component usage conditions, to a wide range of metallic alloys and to effects of residual stresses, anisotropy and inhomogeneity within samples.

A couple of points may be noted concerning timing. As mentioned above, we were involved in the founding of Plastometrex, which took place in 2018. At around that time, we were starting to feel that a book providing detailed background to conventional test procedures, as well as the potential for novel developments, could have value – nothing substantial of that type was then available. Some exploratory steps were taken during 2019, with serious production of material starting towards the end of that year. Of course, the lockdown associated with the Covid-19 pandemic, which started in the UK in late March of 2020, did affect this procedure, although in fact most of the manuscript preparation had been completed by that time. It did have a dramatic effect on the functioning of the University, although as it happens our involvement there was starting to reduce sharply in any event. Lockdown probably gave a boost to a lot of book-writing, but in our case its main effect was rather one of impeding progress (including the creation of some challenges for Plastometrex). The manuscript was in fact delivered to CUP in June 2020. We would like to thank the production and editing staff at CUP for working closely and helpfully with us during the second half of 2020 – a period during which the lockdown in the UK, while easing in a rather staccato manner, was still causing a range of problems. Of course, none of us know quite how things will pan out during the coming years, concerning the pandemic and other potential sources of disruption. Perhaps one of the few certainties is that metals, and particularly the way that they undergo plastic deformation, will continue to be of prime importance.

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

Nomenclature

Parameters

A	(m^2)	area
A	(K)	temperature (of austenite formation)
a	(–)	direction cosine
a	(m)	distance between inner and outer loading points (Fig. 10.6)
a	(m)	lattice parameter (cubic system)
a	(Pa)	constant in Basquin law (Eqn. (10.21))
b	(–)	exponent in Basquin law (Eqn. (10.21))
b	(m)	chord length (Fig. 8.6)
b	(m)	Burgers vector
C	(Pa)	stiffness (4th rank tensor)
C	(–)	strain rate sensitivity parameter (Eqn. (3.15))
C	(–)	dimensionless constant in Knoop hardness expression (Eqn. (7.8))
C	($\mathrm{Pa}^{-n}\ \mathrm{s}^{-(m+1)}$)	parameter in Miller–Norton creep law (Eqn. (3.17))
c	(m)	crack length or flaw size
D	(m)	sample thickness or diameter
d	(m)	grain size
E	(Pa)	Young's modulus
e	(–)	relative displacement (2nd rank tensor)
F	(N)	force (load)
G	($\mathrm{J\ m}^{-2}$)	strain energy release rate
G	(Pa)	shear modulus
g	(–)	goodness of fit parameter (Fig. 10.25))
H	($\mathrm{kgf\ m}^{-2}$)	hardness number
h	(m)	indenter depth
h	(m)	thickness
h	(–)	parameter relating to Miller indices for crystallographic planes
I	(Pa)	invariants in the secular equation for stress (Eqn. (2.13))
I	(m^4)	second moment of area
K	(Pa)	bulk modulus
K	(Pa)	work hardening coefficient
K	($\mathrm{Pa\ m}^{-1}$)	constant in Eqn. (10.36)

K	(Pa m$^{1/2}$)	stress intensity factor
k	(–)	parameter relating to Miller indices for crystallographic planes
k	(–)	dimensionless factor (Eqn. (10.7))
l	(–)	parameter relating to Miller indices for crystallographic planes
L	(m)	length
L	(m)	distance between obstacles (Eqn. (4.14))
L	(m)	spacing between dislocations (Eqn. (4.12))
M	(m N)	bending moment
M	(K)	temperature (of martensite formation)
m	(–)	parameter in Miller–Norton creep law (Eqn. (3.17))
N	(–)	dimensionless number
n	(–)	stress exponent (in creep law – Eqns. (3.17) and (9.3))
n	(–)	work hardening exponent
P	(Pa)	pressure
Q	(J mole^{-1})	activation energy
R	(J K^{-1} mole^{-1})	universal gas constant
R	(m)	indenter radius
R	(m)	radius of curvature
R	(m)	surface roughness
r	(m)	radial distance
S	(Pa^{-1})	compliance (4th rank tensor)
S	(N m^{-1})	machine compliance (gradient of load–displacement curve – Eqn. (9.2))
S	(– or m^{2})	sum of the squares of the residuals (for indenter depth – Eqns. (8.2) and (8.3))
S	(Pa)	stress amplitude during fatigue
s	(–)	slenderness ratio (Eqn. (10.8))
T	(–)	transform matrix
T	(K or ˚C)	temperature
T	(N m)	torque
t	(m)	wall thickness
t	(s)	time
U	(J m^{3})	stored elastic strain energy
u	(–)	parameter relating to Miller indices for crystallographic directions
u	(m s^{-1})	velocity
v	(–)	parameter relating to Miller indices for crystallographic directions
W	(J)	energy of a dislocation (Eqn. (4.6))
W	(J)	energy released during crack advance (Eqn. (10.12))
w	(–)	parameter relating to Miller indices for crystallographic directions
w	(m)	width

x	(m)	distance (Cartesian coordinate)
y	(m)	distance (Cartesian coordinate)
z	(m)	distance (Cartesian coordinate)

β	(m (Pa$\sqrt{\text{m}}$)$^{-n}$)	parameter in Paris–Erdogan fatigue law (Eqn. (10.20))
β	(° or radians)	angle subtended at the coil axis by a segment of coil (Fig. 10.3a)
Δ	(–)	relative change in volume (dilation – Eqn. (2.21))
δ	(m)	penetration, displacement or deflection
δ	(m)	crack opening displacement (Eqn. (10.19))
ε	(–)	strain (2nd rank tensor)
ε	(–)	dimensionless constant (Eqn. (9.2))
ϕ	(° or radians)	angle
γ	(–)	shear strain
γ	(J m^{-2})	surface energy
μ	(–)	coefficient of friction
κ	(m^{-1})	curvature
λ	(Pa)	variable in secular equation for stress (Eqn. (2.13))
λ	(° or radians)	angle (between slip direction and tensile axis)
Λ	(N or J m^{-1})	line tension or energy per unit length of a dislocation (Eqn. (4.7))
θ	(° or radians)	angle
ν	(–)	Poisson ratio
ρ	(m^{-2})	dislocation density
Σ	(N m^{2})	beam stiffness
σ	(Pa)	stress (2nd rank tensor)
τ	(Pa)	shear stress (2nd rank tensor)
ξ	(–)	fraction of material transformed to martensite (Fig. 8.23)
ω	(–)	rotation (2nd rank tensor)
Ω	(–)	dimensionless length (Eqn. (10.10))

Subscripts

0	initial or reference
1	x direction
2	y direction
3	z direction
A	austenite
age	ageing
amb	ambient
B	Brinell
Braz	Brazier
c	critical

c	contact
cr	creep
f	finish
H	hydrostatic
i	indenter
i	suffix indicating direction
j	suffix indicating direction
K	Knoop
k	suffix indicating direction
L	Leeb
L	limit
M	martensite
max	maximum
N	nominal (engineering)
p	(equivalent) plastic
p	projected
p	polar
RA	Rockwell (category A)
RB	Rockwell (category B)
RC	Rockwell (category C)
ST	solution treatment
r	reduced
r	radial
s	start
T	true
V	Vickers
VC	Vickers cone
vM	von Mises
Y	yield
*	critical (e.g. fracture or ultimate tensile strength)

Acronyms

AFM	atomic force microscope
ASTM	American Society for Testing and Materials
bcc	body-centered cubic (crystal structure)
BSI	British Standards Institute
DIC	digital image correlation
DSC	differential scanning calorimetry
DoITPoMS	dissemination of IT for the promotion of materials science
EDM	electro-discharge machining
fcc	face-centered cubic (crystal structure)
FEM	finite element method
FIB	focussed ion beam (milling)
GP	Guinier–Preston (zones)

HCF	high cycle fatigue
hcp	hexagonal close-packed (crystal structure)
LCF	low cycle fatigue
LVDT	linear variable displacement transducer
MMC	metal matrix composites
OFHC	oxygen-free high conductivity (copper)
RA	reduction in area
SE	superelasticity
SEM	scanning electron microscope
SHPB	split Hopkinson pressure bar
SMA	shape memory alloys
SME	shape memory effect
TEM	transmission electron microscope
TSHB	torsional split Hopkinson bar
TLP	teaching and learning package
UTS	ultimate tensile strength (or stress)
UV	ultra-violet