

## Testing of the Plastic Deformation of Metals

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**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.

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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

# Testing of the Plastic Deformation of Metals

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## Contents

	<i>Preface</i>	page xi
	<i>Nomenclature</i>	xiii
<b>1</b>	<b>General Introduction</b>	1
	1.1 Rationale and Scope of the Book	1
	1.2 Structure and Readership of the Book	2
	1.3 Basic Elastic and Plastic Property Ranges	3
<b>2</b>	<b>Stresses, Strains and Elasticity</b>	7
	2.1 Stress and Strain as Second Rank Tensors	7
	2.2 Transformation of Axes	9
	2.2.1 Transforming First Rank Tensors (Vectors)	9
	2.2.2 Transforming Second Rank Tensors and Principal Stresses	11
	2.2.3 Use of Mohr's Circle	12
	2.3 Representation of Strain	14
	2.4 Stress–Strain Relationships and Engineering Constants	16
	2.4.1 Stiffness and Compliance Tensors	16
	2.4.2 Relationship to Elastic Constants	17
	2.4.3 Engineering Shear Strains, Shear Modulus and Bulk Modulus	18
	2.4.4 Relationships between Elastic Constants	19
<b>3</b>	<b>Continuum Plasticity</b>	21
	3.1 The Onset of Plasticity and Yielding Criteria	21
	3.1.1 Deviatoric (von Mises) and Hydrostatic Stresses and Strains	22
	3.1.2 Yield Envelopes in Stress Space – von Mises and Tresca Criteria	23
	3.1.3 True and Nominal (Engineering) Stresses and Strains	27
	3.2 Constitutive Laws for Progressive Plastic Deformation	28
	3.2.1 Quasi-Static Plasticity – the Ludwik–Hollomon and Voce Laws	28
	3.2.2 The Strain Rate Dependence of Plasticity and the Johnson–Cook Formulation	31

	3.2.3 Constitutive Laws for Superelasticity	32
	3.2.4 Progressive Creep Deformation and the Miller–Norton Law	34
3.3	Residual Stresses	36
	3.3.1 Origins of Residual Stress	37
	3.3.2 Effects of Residual Stress on Plasticity	40
	References	40
<b>4</b>	<b>Mechanisms of Plastic Deformation in Metals</b>	<b>43</b>
4.1	Basic Dislocation Structures and Motions	43
	4.1.1 The Atomic Scale Structure of Metals	43
	4.1.2 Concept of a Dislocation	44
	4.1.3 The Dislocation Line Vector and the Burgers Vector	46
	4.1.4 Screw Dislocations	47
	4.1.5 Force on a Dislocation and Energies Involved	48
4.2	Further Dislocation Characteristics	50
	4.2.1 Tensile Testing of Single Crystals and Schmid’s Law	50
	4.2.2 Dislocation Interactions and Work Hardening Effects	51
	4.2.3 Creation of Dislocations and Types of Dislocation Mobility	53
	4.2.4 Rearrangement of Dislocations and Recrystallization	56
4.3	Dislocations in Real Materials and Effects of Microstructure	58
	4.3.1 Plastic Deformation of Polycrystals	58
	4.3.2 Solution Strengthening (Substitutional Atoms)	59
	4.3.3 Effects of Interstitial Solute	60
	4.3.4 Precipitation Hardening and Dispersion Strengthening	63
4.4	Deformation Twinning and Martensitic Phase Transformations	66
	4.4.1 Deformation Twinning	67
	4.4.2 Martensitic Transformations	71
4.5	Time-Dependent Deformation (Creep)	73
	4.5.1 Background	73
	4.5.2 Coble Creep	75
	4.5.3 Nabarro–Herring Creep	76
	4.5.4 Dislocation Creep	76
	4.5.5 Effects of Microstructure on Creep	77
	References	78
<b>5</b>	<b>Tensile Testing</b>	<b>81</b>
5.1	Specimen Shape and Gripping	81
	5.1.1 Testing Standards	81
	5.1.2 Geometrical Issues and Stress Fields during Loading	82
	5.1.3 Issues of Sample Size	85
5.2	Measurement of Load and Displacement	87
	5.2.1 Creation and Measurement of Load	87
	5.2.2 Displacement Measurement Devices	87

	5.3 Tensile Stress–Strain Curves	88
	5.3.1 Nominal and True Plots	88
	5.3.2 The Onset of Necking and Considère’s Construction	89
	5.3.3 Neck Development, UTS, Ductility and Reduction in Area	92
	5.3.4 Load Drops and Formation of Lüders Bands	98
	5.4 Variants of the Tensile Test	100
	5.4.1 Testing of Single Crystals	100
	5.4.2 Biaxial Tensile Testing	100
	5.4.3 High Strain Rate Tensile Testing	101
	5.4.4 Tensile Creep Testing	102
	References	103
<b>6</b>	<b>Compressive Testing</b>	<b>107</b>
	6.1 Test Configuration	107
	6.1.1 Sample Geometry, Strain Measurement and Lubrication Issues	107
	6.1.2 Buckling Instabilities	108
	6.1.3 Sample Size and Micropillar Compression	109
	6.2 Compressive Stress–Strain Curves	110
	6.2.1 Nominal and True Stress–Strain Plots	110
	6.2.2 FEM Modeling, Sample/Platen Friction and Barreling Effects	112
	6.3 Tension/Compression Asymmetry and the Bauschinger Effect	115
	6.3.1 Tension/Compression Asymmetry	115
	6.3.2 The Bauschinger Effect	117
	6.4 The Ring Compression Test	119
	References	120
<b>7</b>	<b>Hardness Testing</b>	<b>123</b>
	7.1 Concept of a Hardness Number (Obtained by Indentation)	123
	7.2 Indentation Hardness Tests	125
	7.2.1 The Brinell Test	125
	7.2.2 The Rockwell Test	129
	7.2.3 The Vickers Test and Berkovich Indenters	131
	7.2.4 The Knoop Test	137
	7.3 Effects of Sample Condition	138
	7.3.1 Microstructure, Anisotropy and Indentation of Single Crystals	138
	7.3.2 Residual Stresses	140
	7.4 Other Types of Hardness Testing	142
	7.4.1 Rebound Hardness Testing	142
	7.4.2 Scratch Testing and the Mohs Scale	144
	References	145

<b>8</b>	<b>Indentation Plastometry</b>	148
	8.1 Introduction to Indentation Plastometry	148
	8.2 Experimental Issues	149
	8.2.1 Indenter Shape and Size	149
	8.2.2 Penetration Depth, Plastic Strain Range and Load Requirements	151
	8.2.3 Sample Preparation	154
	8.2.4 Experimentally Measured Outcomes	157
	8.3 FEM Simulation Issues	158
	8.3.1 Representation of Plasticity Characteristics	158
	8.3.2 Meshing, Boundary Conditions and Input Data	159
	8.3.3 Characterization of Misfit (“Goodness-of-Fit”)	164
	8.3.4 Convergence Algorithms	164
	8.4 Range of Indentation Plastometry Usage	166
	8.4.1 Presentation of Results	166
	8.4.2 Effects of Material Anisotropy and Inhomogeneity	167
	8.4.3 Measurement of Residual Stresses	169
	8.4.4 Indentation Creep Plastometry	173
	8.4.5 Indentation Superelastic Plastometry	178
	8.4.6 Commercial Products	179
	Appendix 8.1 Nelder–Mead Convergence Algorithm	183
	Appendix 8.2 Distribution of Plastic Work in terms of Strain Range	185
	References	186
<b>9</b>	<b>Nanoindentation and Micropillar Compression</b>	192
	9.1 General Background	192
	9.2 Nanoindentation Equipment	193
	9.2.1 Equipment Design	193
	9.2.2 Nanoindenter Tips	195
	9.2.3 High Temperature Testing and Controlled Atmosphere Operation	198
	9.3 Nanoindentation Testing Outcomes	200
	9.3.1 Background	200
	9.3.2 Measurement of Stiffness and Hardness	201
	9.3.3 Characterization of Creep	203
	9.4 The Nanoindentation Size Effect	204
	9.4.1 Experimental Observations	204
	9.4.2 Size Effect Mechanisms and “Pop-in” Phenomena	205
	9.5 Micropillar Compression Testing	208
	9.5.1 Creation of Micropillar Samples	208
	9.5.2 Test Issues	210
	9.5.3 Test Outcomes and Size Effects	211
	References	214



<b>10</b>	<b>Other Testing Geometries and Conditions</b>	219
	10.1 Bend and Torsion Testing	219
	10.1.1 Mechanics of Beam Bending	219
	10.1.2 Mechanics of Torsion	221
	10.1.3 Three-point and Four-point Bend Testing	224
	10.1.4 FEM of Four-point Bend Testing	226
	10.1.5 Torsion Tests	228
	10.1.6 Combined Tension–Torsion Tests	230
	10.2 Buckling Failure	231
	10.2.1 Elastic (Euler) Buckling	231
	10.2.2 Plastic Buckling	232
	10.2.3 Brazier Buckling of Thin-Walled Structures during Bending	234
	10.3 Cyclic Loading Tests	235
	10.3.1 Background to Cyclic Loading and Fatigue Failure	235
	10.3.2 Fracture Mechanics and Fast Fracture	236
	10.3.3 Sub-Critical Crack Growth	239
	10.3.4 Stress–Life ( $S$ – $N$ ) Fatigue Testing	241
	10.4 Testing of the Strain Rate Dependence of Plasticity	243
	10.4.1 High Strain Rate Tensile Testing	245
	10.4.2 Hopkinson Bar and Taylor Tests	247
	10.4.3 Ballistic Indentation Testing	249
	Appendix 10.1 Calculating the Second Moment of Area, $I$	254
	Appendix 10.2 Beam Deflections from Applied Bending Moments	256
	Appendix 10.3 Mechanics of Springs	261
	Appendix 10.4 Interpretation of Data from Strain Gauge Rosettes	264
	References	265
	<i>Index</i>	270

## 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

$A$	( $\text{m}^2$ )	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))
$C$	( $\text{Pa}^{-n} \text{s}^{-(m+1)}$ )	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)
$G$	( $\text{J m}^{-2}$ )	strain energy release rate
$G$	(Pa)	shear modulus
$g$	(–)	goodness of fit parameter (Fig. 10.25))
$H$	( $\text{kgf m}^{-2}$ )	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))
$I$	( $\text{m}^4$ )	second moment of area
$K$	(Pa)	bulk modulus
$K$	(Pa)	work hardening coefficient
$K$	( $\text{Pa m}^{-1}$ )	constant in Eqn. (10.36)

$K$	(Pa m <sup>1/2</sup> )	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 <sup>–1</sup> )	activation energy
$R$	(J K <sup>–1</sup> mole <sup>–1</sup> )	universal gas constant
$R$	(m)	indenter radius
$R$	(m)	radius of curvature
$R$	(m)	surface roughness
$r$	(m)	radial distance
$S$	(Pa <sup>–1</sup> )	compliance (4th rank tensor)
$S$	(N m <sup>–1</sup> )	machine compliance (gradient of load–displacement curve – Eqn. (9.2))
$S$	(– or m <sup>2</sup> )	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 <sup>3</sup> )	stored elastic strain energy
$u$	(–)	parameter relating to Miller indices for crystallographic directions
$u$	(m s <sup>–1</sup> )	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)
$\beta$	(m (Pa $\sqrt{m}$ ) <sup>-n</sup> )	parameter in Paris–Erdogan fatigue law (Eqn. (10.20))
$\beta$	(° or radians)	angle subtended at the coil axis by a segment of coil (Fig. 10.3a)
$\Delta$	(–)	relative change in volume (dilation – Eqn. (2.21))
$\delta$	(m)	penetration, displacement or deflection
$\delta$	(m)	crack opening displacement (Eqn. (10.19))
$\varepsilon$	(–)	strain (2nd rank tensor)
$\varepsilon$	(–)	dimensionless constant (Eqn. (9.2))
$\phi$	(° or radians)	angle
$\gamma$	(–)	shear strain
$\gamma$	(J m <sup>-2</sup> )	surface energy
$\mu$	(–)	coefficient of friction
$\kappa$	(m <sup>-1</sup> )	curvature
$\lambda$	(Pa)	variable in secular equation for stress (Eqn. (2.13))
$\lambda$	(° or radians)	angle (between slip direction and tensile axis)
$A$	(N or J m <sup>-1</sup> )	line tension or energy per unit length of a dislocation (Eqn. (4.7))
$\theta$	(° or radians)	angle
$\nu$	(–)	Poisson ratio
$\rho$	(m <sup>-2</sup> )	dislocation density
$\Sigma$	(N m <sup>2</sup> )	beam stiffness
$\sigma$	(Pa)	stress (2nd rank tensor)
$\tau$	(Pa)	shear stress (2nd rank tensor)
$\xi$	(–)	fraction of material transformed to martensite (Fig. 8.23)
$\omega$	(–)	rotation (2nd rank tensor)
$\Omega$	(–)	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

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c	contact
cr	creep
f	finish
H	hydrostatic
i	indenter
<i>i</i>	suffix indicating direction
<i>j</i>	suffix indicating direction
K	Knoop
<i>k</i>	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)

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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