

# MECHANICAL BEHAVIOUR OF MATERIALS UNDER PRESSURE

H. Ll. D. Pugh, National Engineering Laboratory, East Kilbride, Scotland

Elsevier Materials Science Series, Elsevier Publishing Company Ltd., 1970

## CONTENTS

*List of Contributors* v

*Preface* xv

### *Chapter 1*

HISTORICAL INTRODUCTION - *BORIS VODAR and JEAN KIEFFER*

Historical Background 1

Monographs, Research Centres and Conferences 5

More Recent Developments in Static High Pressure Research 10

    Production of high static pressures 10

    Survey of high pressure apparatus 12

    The measurement of high pressures 18

    Mechanical behaviour of materials under pressure and related developments  
    20

    Physical and physico-chemical properties of matter. Synthesis of materials 24

High Dynamic Pressures 34

Conclusion 43

References 45

### *Chapter 2*

THE DESIGN OF HIGH PRESSURE CONTAINERS AND ASSOCIATED EQUIPMENT - *T. E. DAVIDSON and D. P. KENDALL*

Introduction 54

Theory of Pressure Vessel Design 55

    Monobloc cylinders without residual stresses 55

    Residual stresses 59

        Multi-layer cylinders 59

Two element cylinders-same material 60

Two element cylinders-different materials 62

Multi-layer cylinders having more than two elements 63

Autofrettage 64

Analysis of assumptions 65

Available solutions 67

Residual stresses in autofrettaged cylinders 75

Maximum elastic operating pressure of autofrettaged cylinders 76

Selection of degree of overstrain 77

Methods of autofrettage 78

Effect of deviations from ideal material behaviour on autofrettage theory and practice 81

Autofrettage and multi-layer cylinders combined 85

Segmented cylinders 87

Variable external support 87

Direct external pressure 89

Tapered external cylinder 89

Segmented cylinder 91

Summary of pressure vessel design 97

Materials for Pressure Vessels 103

Yield strength 103

Ductility and toughness 103

Available materials 105

Environmental factors 106

Seals, Pistons and Closures 107

Support of End Closures 114

List of Symbols 115

References 116

*Chapter 3*

THE MEASUREMENT OF HYDROSTATIC PRESSURE - *STANLEY E. BABB, Jr.*

Introduction 119

Primary Gauges 119

Secondary Gauges 127

    Resistance gauges 127

        Coil preparation and seasoning 130

        Calibration 132

        Other resistance gauge materials 143

        Temperature response of resistance gauges 144

    Other pressure gauges 147

Differential Pressure Measurement 149

Summary 150

Acknowledgements 150

List of Symbols 151

References 151

*Chapter 4*

ELASTIC CONSTANTS UNDER PRESSURE - *J. R. DRABBLE*

Introduction 153

Thermodynamics of Solids 154

    Internal configuration and strain 154

    Infinitesimal strain 156

    Volume changes 157

    Change of reference state 158

Stress-strain relationships and elastic coefficients 158

Relationships between the elastic coefficients of the initial state and elastic coefficients of the natural state 162

The example of cubic or isotropic materials subjected to an initial hydrostatic pressure 164

Measurements of Elastic Coefficients under Pressure 169

The variation of compressibility with pressure 169

The propagation of acoustic waves in stressed media 171

Wave propagation referred to the initial state 172

Wave propagation referred to the natural state 175

Experimental Techniques for Investigating the Propagation of Sound in Stressed Materials 177

Introduction 177

General requirements 178

Measurement techniques 179

The sing-around system 179

The pulse superposition method 181

Interpretation of Resultron Measurements of Sound Propagation 182

List of Symbols 188

References 190

### *Chapter 5*

## EXPERIMENTAL DEFORMATION OF MINERALS AND ROCKS UNDER PRESSURE - *M. S. PATERSON*

Introduction 191

Apparatus 192

Brittle fracture in rocks 199

The brittle-ductile transition 201

Plasticity of Single Crystals of Minerals 202

Calcite 204

Other non-silicates 206

Quartz 207

Other common silicates 210

Permanent Deformation of Rocks 210

Sand 212

Marble 214

Other rocks 219

Influence of pore pressure 222

Influence of strain rate 224

Yield criteria 226

Some other experiments of geological interest 228

Acknowledgements 230

References 231

*Chapter 6*

CONTENTS

MECHANICAL PROPERTIES OF MATERIALS UNDER HYDROSTATIC PRESSURE - *MAREK  
BRANDES*

Introduction 236

Methods and Apparatus for the Study of Mechanical Properties of Materials under Hydrostatic Pressure 237

Apparatus for tension and compression tests 237

Torsion apparatus 250

Effects of Hydrostatic Pressure on Plastic Flow and Fracture 253

Stress distribution in the neck of a tensile specimen 253

Ductility 256

Yield stress 262

Tensile strength 264

True stress-strain relationships 267

The fracture of ductile materials	269
Behaviour of Brittle Materials under Hydrostatic Pressure	272
The Use of Hydrostatic Pressure for the Determination of the Brittle Fracture Strength of Ductile Materials and of the Yield Stress of Brittle Materials at Room Temperature	277
Brittle fracture strength (technical cohesive strength) of ductile materials	277
Yield stress in tension of brittle materials	278
Effect of Hydrostatic Pressure on the Brittle-Ductile Transition Temperature	280
Shearing Strength under Ultra High Pressures	283
Apparatus and method used for the production and measurement of shearing stresses	283
Shearing strength of some materials	285
Conclusions and Needs for Future Research	292
Acknowledgements	293
List of Symbols	294
References	295
<i>Chapter 7</i>	
THE EFFECT OF PRESSURE ON THE FATIGUE OF METALS - <i>B. CROSSLAND</i>	
Introduction	299
Thick-walled Cylinder Theory	304
Fatigue of Thick-walled Cylinders Subjected to Repeated Pressure	310
Experimental work	312
Results of repeated pressure tests on thick-walled cylinders	321
Discussion	324
The Effect of Pressure on Torsional Fatigue Strength	337
The Effect of Pressure on the Direct-Stress Fatigue Strength	342
The Effect of Pressure on Rotating Bending Fatigue Strength	347
General Discussion	349
List of Symbols	352

References 353

*Chapter 8*

CREEP UNDER HIGH PRESSURES - *PAUL G. McCORMICK and ARTHUR L. RUOFF*

Introduction 355

    Nabarro-Herring creep 356

    Intermediate temperature and stress creep 358

    Low temperature creep 366

Experimental Techniques 366

Hydrostaticity 374

Experimental Results 375

Discussion 383

Discussion of Further Research Possibilities 386

Acknowledgements 387

List of Symbols 387

References 388

*Chapter 9*

HYDROSTATIC EXTRUSION - *H. LI. D. PUGH*

Introduction 391

    Features of Hydrostatic Extrusion 394

    Reduction in friction 394

    Die design 397

    Versatility of the process 398

    Disadvantages of the process 398

Mechanics of Hydrostatic Extrusion 398

Equipment for Hydrostatic Extrusion 408

    High pressure equipment 409

    High pressure seals 410

High pressure fluids	412
Extrusion tooling	412
The Extrusion Pressure-Displacement Characteristic	416
Lubrication	419
Liquids and lubricants	419
Speed of extrusion	424
Process Variables	429
Billet geometry	429
Die angle	431
Extrusion ratio	434
Billet material	439
Properties of Product	442
Distribution of hardness	442
Mechanical properties	446
Comparison with other cold worked products	452
Dimensions	455
Extrusion of Complex Sections	459
Extrusion of tubes	459
Die design	463
Complex sections	463
Hydrostatic Extrusion at Elevated Temperatures	469
Controlled Hydrostatic Extrusion	472
Unassisted hydrostatic extrusion	473
Damped hydrostatic extrusion	477
Billet-assisted hydrostatic extrusion. Augmented extrusion	479
Product-assisted hydrostatic extrusion. Hydrostatic extrusion-drawing	482
Theory of hydrostatic extrusion-drawing	489

Hydrostatic Extrusion-Drawing of Wire 492

The process 492

Equipments for controlled wire extrusion 495

Effect of process variables on the extrusion of wire 498

Hydrostatic Extrusion of Billets of Unlimited Length 502

General considerations 502

Intermittent (or semi-continuous) hydrostatic extrusion 505

Continuous hydrostatic extrusion 510

Acknowledgements 515

List of Symbols 515

References 517

*Chapter 10*

THE APPLICATION OF HYDROSTATIC PRESSURE TO THE FORMING OF METALS - *H. LI. D. PUGH*

Introduction 522

Extrusion 523

Conventional extrusion against a back pressure 523

Differential pressure (or fluid-to-fluid) extrusion 532

Extrusion pressure 541

The effect of back pressure on the properties of extruded metals 541

Other methods of applying back pressure 546

Forging and Related Processes 548

Compression 549

Forging 550

Upsetting or flanging 552

Bending 560

Shearing, blanking and cropping 563

Drawing and Related Processes 569

Wire and rod drawing 570

Sheet drawing 574

Deep drawing 579

Tube expansion 583

Conclusions 584

Principle 1 585

Principle 2 586

Principle 3 587

Acknowledgements 588

List of Symbols 588

References 588

*Chapter 11*

THE COMPACTION OF POWDERS BY ISOSTATIC PRESSURE - *S. J. PAPROCKI and E. S. HODGE*

Introduction 591

Hydrostatic Pressing 592

Relationship between powder properties and densification behaviour 592

Effect of particle geometry on behaviour during pressing 592

Relationship of powder surface condition to compacting behaviour 593

Effect of powder apparent density on uniformity of pressing behaviour 595

Factors governing green density 596

Factors governing green strength 597

Hydrostatic compaction apparatus 598

Assembly of components for hydrostatic compaction 605

Characteristics of hydrostatically pressed compacts 607

Size distribution 607

Green density 609

Strain hardening 611

Hot Isostatic Pressing 612

Pre-compaction of powders 612

Tap density 612

Vibratory packing 613

Die pressing 616

Hydrostatic pressing 617

High energy densification 618

Assembly of components 619

Direct consolidation 620

Use of mandrels 620

Pressure transmitting media 620

Hot isostatic pressing apparatus 622

Preparation of porous structures 626

Preparation of dense structures 629

Preparation of unique structures 631

Future prospects 634

Acknowledgements 635

References 636

*Chapter 12*

PRESSURE-INDUCED EFFECTS ON DEFECT STRUCTURE AND PROPERTIES - S. V. RADCLIFFE

Introduction 638

Changes in Crystal Properties Under Pressure 639

Elastic moduli and dislocation energy 639

Dislocation mobility 643

Pressure-induced Defect Structures 651

Crystal anisotropy effects 651

Second phase effects 660

Face-centred cubic metals 664

Body-centred cubic metals 665

Hexagonal metals 674

Non-metals 674

Summary and Conclusions 677

References 677

*Chapter 13*

THE EFFECT OF HIGH-PRESSURE SHOCK WAVES ON METALS: MECHANICAL AND METALLURGICAL BEHAVIOUR - *A. H. JONES, C. J. MAIDEN and W. M. ISBELL*

Introduction 680

Characteristics of High Intensity Waves 680

Rankine-Hugoniot relationships 681

Attenuation waves 683

Stability of shock waves 685

Constitutive Equations 690

High pressure region: Mie-Gruneisen equation of state 690

Elastic-plastic flow in uniaxial strain 698

Time dependent effects 703

Strain rate 703

Spallation 705

Experimental Techniques 709

Shock waves from high explosives 709

Shock waves from flat plate impact 713

Measurement of shock wave parameters 718

Measurement of shock and free surface velocity 719

Measurement of particle motion 723

Measurement of pressure 723

Measurement of density behind the shock front 725

Shock Hardening Effects 725

Physical state at the shock front 725

Face-centred cubic metals 728

Copper 728

Nickel 732

Aluminium 732

Solid solution alloys 732

Austenitic steels 733

Body-centred cubic metals 736

B.c.c. metals other than iron 736

Iron 736

Plain carbon steels 740

Other binary alloys of iron 741

Hexagonal close-packed metals 742

List of Symbols 742

References 743

*Appendix - Pressure Units* 748

*Index* 751