

A black and white micrograph of a metal surface, likely a metallographic specimen, showing a prominent grid-like pattern of plastic deformation. The pattern consists of intersecting lines forming a series of small, irregular squares or diamonds, characteristic of a plastic deformation texture. The background is a lighter, mottled gray.

# **The Plastic Deformation of Metals**

Second Edition

R. W. K. Honeycombe

# The Plastic Deformation of Metals

R. W. K. Honeycombe

*Goldsmiths' Professor of Metallurgy  
University of Cambridge*



Edward Arnold



American Society for Metals

© R. W. K. Honeycombe 1984

First published 1968  
by Edward Arnold (Publishers) Ltd.,  
41 Bedford Square  
London WC1B 3DQ

Edward Arnold (Australia) Pty Ltd.,  
80 Waverley Road  
Caulfield East,  
Victoria 3145,  
Australia

Reprinted 1971, 1974  
First published as a Paperback 1975  
Reprinted 1977  
Second Edition 1984

**British Library Cataloguing in publication Data**

Honeycombe, R. W. K.

The plastic deformation of metals. -2nd ed.

1. Metals—Plastic properties

I. Title

620.1'6'33      TA490

ISBN 0-87170-186-3 (American Society for Metals)

To June, Juliet and Celia

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photo-copying, recording or otherwise, without the prior permission of Edward Arnold (Publishers) Ltd.

Printed in Great Britain

# **The Plastic Deformation of Metals**

## Preface

In the last twenty years, the fundamental basis of metallurgy has become much more firmly established. One of the most impressive developments has undoubtedly been the theory of dislocations which accounts for many of the characteristics of crystalline solids, in particular the behaviour during plastic deformation. Several comprehensive books have been written on this subject, but there seems to be a definite need for a text which describes systematically the actual behaviour of metals and alloys during various types of deformation, and attempts to explain this as far as possible in terms of dislocation theory.

The approach I have adopted echoes that of the classical *Kristallplastizität* by E. Schmid and W. Boas, in so far as the behaviour of single crystals is taken as a logical starting point, but the emphasis is on the large volume of post-war work which has been done in this field. The results of such investigations are then used to examine more complex deformation phenomena in polycrystalline aggregates, for example, textures, creep, fatigue and fracture.

The book is aimed at graduate and undergraduate students of metallurgy and materials science in Universities and Colleges of Technology who need an overall picture of the plastic deformation of metals, in which both the theory and behaviour of metals receive attention. It should also be useful in explaining to engineers the basic principles which determine the properties of the materials they use. The references included are not comprehensive, but are selected to provide a broad basis for further reading in the subject. An elementary working knowledge of metallography and crystallography has been assumed.

The book was mostly written while I was at the University of Sheffield, and I am very grateful to Professor A. G. Quarrell and colleagues in the Department of Metallurgy there for helpful discussions and encouragement. Mrs. Wendy Morton deserves special thanks for patiently deciphering my manuscript and for doing much of the final typing. I owe a particular debt to Professor E. O. Hall for reading the manuscript and for making many helpful comments. I must also thank Dr. Brian Ralph very much for raising numerous useful points at the proof stage and Mrs. Evelyn

Martin for her help in the preparation of the index. The sources of all figures have been acknowledged, and I would like to add my thanks to the various authors who have helped me in this way.

Finally, I would like to take this opportunity of expressing my deep gratitude to my old friend Dr. Walter Boas, who first introduced me to the study of the deformation of crystals.

R. W. K. Honeycombe

Cambridge,  
1968

## Preface to Second Edition

In this new edition I have taken the opportunity to switch to SI units. I have also included at the end of each chapter, additional general references to relevant books which have been published since 1968. The text is unchanged because I feel that the elements of the subject remain broadly the same today. However it is inevitable that, over the fifteen years since the book was first published, there have been many important developments in the subject, for example in the fields of creep, fatigue and fracture. To do justice to this work a new book would have to be written, but in the meantime I trust that this book, by emphasizing well established principles, will provide a springboard to later developments in the field.

Finally I would like to pay tribute to the late Dr Walter Boas who died earlier this year, and who will be remembered for his outstanding contributions to our understanding of the plastic deformation of metals.

R. W. K. Honeycombe

Cambridge  
1982

### Conversion of Units

$\text{M Nm}^{-2}$ to $\text{lb. in.}^{-2}$	$\times 145.038$
$\text{M Nm}^{-2}$ to $\text{kg. mm.}^{-2}$	$\times 0.10197$
$\text{lb in}^{-2}$ to $\text{M Nm}^{-2}$	$\times 0.006895$
$\text{kg mm}^{-2}$ to $\text{M Nm}^{-2}$	$\times 9.80665$
1 Angström unit ( $\text{\AA}$ )	$= 10^{-10} \text{ m}$
1 Angström unit	$= 10^{-1} \text{ nanometre (nm)}$
1 micron ( $\mu\text{m}$ )	$= 10^4 \text{ Angström units}$
1 micron	$= 10^{-6} \text{ m}$
1 Joule (J)	$= 10^7 \text{ erg}$
1 eV	$= 1.602 \times 10^{-19} \text{ J}$

# Contents

Preface	v
Chapter	
1 INTRODUCTION	1
2 THE DEFORMATION OF METAL CRYSTALS—GENERAL ASPECTS	5
2.1 Introduction	5
2.2 Preparation of metal single crystals	6
2.2.1 Solidification from the melt.   2.2.2 Grain growth in the solid state	
2.3 Crystallographic nature of plastic deformation	10
2.4 Anisotropy of plastic properties of crystals—geometry of slip	14
2.5 Critical resolved shear stress for slip—Schmid's Law	17
2.6 Effect of variables on the critical shear stress	20
2.7 Determination of shear strain	21
2.8 Stress-strain curves of metal crystals	23
2.9 Hexagonal metals—geometrical considerations	24
2.10 Face-centred cubic crystals—geometrical considerations	27
2.11 Stress-strain curves of face-centred cubic crystals	29
3 ELEMENTARY DISLOCATION THEORY	33
3.1 The theoretical strength of a crystal	33
3.2 Properties of simple dislocations	35
3.2.1 The edge dislocation.   3.2.2 The screw dislocation	
3.3 Dislocation loops	39
3.4 Force on a dislocation	41
3.5 Stress to move a dislocation	41
3.6 Multiplication of dislocations—dislocation sources	42
3.7 Dislocation pile-ups	45



3.8	The experimental detection of dislocations	47
3.8.1	The bubble model.	
3.8.2	Growth of crystals.	
3.8.3	Etch pits.	
3.8.4	Precipitation.	
3.8.5	Thin-foil electron microscopy.	
3.8.6	Field ion microscopy.	
3.8.7	X-Ray diffraction	
3.9	Stress fields around dislocations	53
3.9.1	Stress field of an edge dislocation.	
3.9.2	Stress field of a screw dislocation	
3.10	The stored energy associated with a dislocation	55
3.11	Line tensions of dislocations	57
3.12	Networks of dislocations	58
3.13	Non-conservative movement of dislocations	60
3.14	Dislocation jogs	61
3.15	Dipoles	63
3.16	Forces between dislocations	64
3.16.1	Parallel edge dislocations on parallel planes.	
3.16.2	Parallel screw dislocations	
3.17	Dissociation of dislocations in close-packed structures	67
3.18	Dislocations and stacking faults	70
3.19	Evidence for the dissociation of dislocations	72
3.20	Sessile dislocations	75
3.20.1	Frank dislocations.	
3.20.2	Formation of Lomer-Cottrell dislocations	
<b>4</b>	<b>DEFORMATION OF METAL CRYSTALS</b>	<b>81</b>
4.1	Deformation of face-centred cubic metal crystals	81
4.1.1	Stage 1 hardening.	
4.1.2	Microstructure during Stage 1.	
4.1.3	Dislocation densities.	
4.1.4	Stage 2 hardening.	
4.1.5	Role of secondary slip in Stages 1 and 2.	
4.1.6	Stage 3 hardening.	
4.1.7	Microstructure during Stage 3.	
4.1.8	The temperature dependence of the flow stress	
4.2	The deformation of body-centred cubic metal crystals	106
4.2.1	Crystallographic observations.	
4.2.2	Geometrical aspects of glide in body-centred cubic metals.	
4.2.3	The flow stress.	
4.2.4	Stress-strain curves of body-centred cubic crystals.	
4.2.5	Dislocations in the body-centred cubic lattice	
4.3	The deformation of hexagonal metal crystals	112
4.3.1	Axial ratios in the hexagonal lattice.	
4.3.2	Crystallography of slip in hexagonal metals.	
4.3.3	Dislocations in hexagonal crystals.	
4.3.4	Stress-strain curves of hexagonal metals—work hardening.	
4.3.5	Observations on dislocations in hexagonal metals	

<b>5 THEORIES OF WORK HARDENING OF METALS</b>	<b>129</b>
5.1 Introduction	129
5.2 Earlier theories	129
5.3 More recent theories of work hardening	132
5.4 Theory of the flow stress	133
5.5 Stage 1 hardening	134
5.6 Stage 2 hardening	136
5.7 Stage 3 hardening	141
5.8 Hexagonal metals	142
<b>6 SOLID SOLUTIONS</b>	<b>145</b>
6.1 Interactions of solute atoms with dislocations	145
6.1.1 Elastic interactions. 6.1.2 Modulus interactions.	
6.1.3 Electrical interactions. 6.1.4 Chemical interactions	
6.2 Experimental evidence for solute-dislocation interactions: yield phenomena	149
6.3 Theories of the yield point	151
6.4 Deformation of solid solution crystals	157
6.4.1 Critical shear stress of solid solutions. 6.4.2 Temperature dependence of $\tau_0$ of solid solutions. 6.4.3 Stress-strain curves of solid solution crystals. 6.4.4 Dislocations in solid solutions	
6.5 Deformation of ordered solid solutions	172
6.6 Theories of solid solution strengthening	173
6.6.1 Cottrell locking theory. 6.6.2 Chemical interaction theory. 6.6.3 Mott and Nabarro theory. 6.6.4 Theory combining size and modulus effects (Fleischer)	
<b>7 THE DEFORMATION OF CRYSTALS CONTAINING A SECOND PHASE</b>	<b>180</b>
7.1 Introduction	180
7.2 The interaction of dislocations with precipitates	180
7.3 Mott and Nabarro theory for aged alloys	181
7.4 The cutting of zones and precipitates by dislocations	185
7.5 The interaction of dislocations with incoherent precipitates	186
7.6 Stress-strain curves of aged alloys	187
7.7 Stress-strain curves of crystals with incoherent precipitates	189
7.8 Effect of dispersion on the yield stress	191
7.9 The effect of temperature on the deformation of aged alloy crystals	193
7.10 Microstructure of precipitate-dislocation interactions	195

<b>8</b>	<b>OTHER DEFORMATION PROCESSES IN CRYSTALS</b>	<b>199</b>
8.1	Introduction	199
8.2	Evidence for inhomogeneous deformation in crystals	199
8.3	Kinking in hexagonal crystals	200
8.4	Deformation bands in face-centred cubic crystals	202
	8.4.1 Kink bands. 8.4.2 Bands of secondary slip	
8.5	Deformation by twinning	204
8.6	Crystallography of twinning	205
8.7	Twinning of hexagonal metals	209
8.8	Twinning of body-centred cubic metals	211
8.9	Twinning of face-centred cubic metals	213
8.10	Dislocation movements in twinning	216
	8.10.1 Body-centred cubic structure. 8.10.2 Dislocation mechanisms for the face-centred cubic structure.	
	8.10.3 Hexagonal structures	
<b>9</b>	<b>THE DEFORMATION OF AGGREGATES</b>	<b>221</b>
9.1	The role of grain boundaries in plastic deformation	221
9.2	The nature of grain boundaries	221
9.3	Effects of boundaries on the strength of crystals	223
	9.3.1 Bicrystals. 9.3.2 Deformation of coarse-grained aggregates—variations in strain. 9.3.3 Deformation of coarse-grained aggregates—microstructure	
9.4	Theories of the deformation of aggregates	227
9.5	Grain boundary sliding at elevated temperatures	230
9.6	Deformation of polycrystalline face-centred cubic metals	231
	9.6.1 Stress-strain curves. 9.6.2 Role of stacking fault energy. 9.6.3 Effect of grain size	
9.7	Deformation of body-centred cubic polycrystalline metals	238
	9.7.1 Stress-strain curves of pure body-centred cubic metals. 9.7.2 Yield phenomena in polycrystalline iron. 9.7.3 Effect of grain size. 9.7.4 Effect of temperature. 9.7.5 Stress-strain curves of other body-centred cubic metals. 9.7.6 Effect of interstitial impurities on mechanical properties. 9.7.7 Theories of the yield point in polycrystalline body-centred cubic metals	
9.8	Deformation of polycrystalline solid solutions	248
9.9	Dislocations in deformed polycrystalline aggregates	251
9.10	Deformation of alloys containing two phases	252
	9.10.1 Two ductile phases. 9.10.2 Ductile-brittle phases	
9.11	Whiskers, fibres and fibre reinforcement	255
	9.11.1 Growth of metal whiskers. 9.11.2 Properties of metal whiskers. 9.11.3 Fibre reinforcement	

<b>10</b>	<b>FORMATION OF POINT DEFECTS IN METALS</b>	<b>266</b>
10.1	Introduction	266
10.2	The retention of vacancies by quenching	266
10.3	Effect of quenching-in of vacancies on mechanical properties	268
10.4	Electron microscopy of quenched metals	269
10.5	Formation of point defects during deformation	275
10.6	Structural evidence for point defects in deformed metals	277
10.7	Formation of point defects by irradiation	278
10.8	Structural studies on irradiated metals	279
10.9	Effect of irradiation on mechanical properties	281
	10.9.1 Single crystals. 10.9.2 Polycrystalline aggregates	
<b>11</b>	<b>ANNEALING OF DEFORMED METALS</b>	<b>287</b>
11.1	Introduction	287
11.2	Recovery in single crystals	288
11.3	Polygonization	290
11.4	Changes in physical properties during recovery	293
	11.4.1 Stored energy. 11.4.2 Electrical resistivity.	
	11.4.3 Density	
11.5	Recrystallization	299
11.6	Variables in recrystallization	301
	11.6.1 Strain. 11.6.2 Temperature. 11.6.3 Purity.	
	11.6.4 Grain size	
11.7	Recrystallization kinetics	304
	11.7.1 Formal theory. 11.7.2 Experimental determination of $N$ and $G$	
11.8	The origin of recrystallization nuclei	308
11.9	Recent theoretical developments	311
11.10	Relationship between recovery and recrystallization	312
11.11	Grain boundary movement during recrystallization	314
	11.11.1 Effect of orientation. 11.11.2 Impurities	
11.12	Normal grain growth	319
11.13	Kinetics of grain growth	322
<b>12</b>	<b>ANISOTROPY IN POLYCRYSTALLINE METALS</b>	<b>326</b>
12.1	Introduction	326
12.2	Development of preferred orientations (textures)	326
	12.2.1 Fibre textures. 12.2.2 Rolling textures. 12.2.3 Role of stacking fault energy	
12.3	Theories of face-centred cubic rolling textures	333
12.4	Recrystallization textures	335
	12.4.1 Introduction. 12.4.2 Origin of annealing textures	

12.5	Secondary recrystallization (exaggerated grain growth)	339
12.6	Anisotropy of mechanical properties	341
12.7	Texture strengthening	345
12.8	Anisotropy of magnetic properties	347
12.9	Anisotropy of thermal expansion	349
<b>13</b>	<b>CREEP IN PURE METALS AND ALLOYS</b>	<b>356</b>
13.1	Introduction	356
13.2	Analysis of creep curves	357
13.3	Structural changes during creep	361
	13.3.1 Deformation of single crystals under creep conditions. 13.3.2 Deformation of polycrystalline aggregates	
13.4	Contributions of slip and grain-boundary sliding to creep strain	367
13.5	Activation energy for steady-state creep	369
13.6	Significance of the activation energy for creep	372
13.7	Theories of steady-state creep	373
	13.7.1 Nabarro-Herring mechanism. 13.7.2 Recovery theory. 13.7.3 Weertman climb theory. 13.7.4 Other possible dislocation mechanisms in high temperature creep. 13.7.5 Creep at intermediate temperatures. 13.7.6 Mechanism of creep at low temperatures	
13.8	Tertiary creep—the onset of creep failure	380
	13.8.1 Effect of temperature. 13.8.2 Effect of stress. 13.8.3 Mechanisms of intergranular creep fracture	
13.9	Creep in alloys	386
	13.9.1 Solid solutions—effect of solute atoms on secondary creep. 13.9.2 Creep curves of solid solutions. 13.9.3 Effect of order-disorder reactions on creep. 13.9.4 Precipitation and dispersion hardened alloys	
13.10	Rules for development of creep resistance	393
13.11	Deformation at high temperatures and high strain rates	394
13.12	Superplasticity	398
<b>14</b>	<b>FATIGUE</b>	<b>402</b>
14.1	General characteristics	402
14.2	Behaviour of single crystals	404
14.3	Basic experiments on polycrystalline aggregates	410
14.4	Structural changes during fatigue	411
14.5	Theories of fatigue crack initiation	416
14.6	Metallurgical variables in fatigue	418
	14.6.1 Stress amplitude. 14.6.2 Stress system. 14.6.3 Stress concentrations. 14.6.4 Temperature. 14.6.5 Frequency. 14.6.6 Strain amplitude. 14.6.7 Chemical effects. 14.6.8 Grain size	

CONTENTS	xiii
14.7 The propagation of fatigue cracks	425
14.8 Fatigue at elevated temperatures	427
14.9 Fatigue in practice	429
<b>15 FRACTURE</b>	<b>433</b>
15.1 Introduction	433
15.2 Brittle fracture in amorphous materials	433
15.3 Crack propagation criterion in crystalline solids	434
15.4 Crack nucleation in crystals	435
15.5 Brittle fracture of single crystals	438
15.6 General characteristics of brittle fracture—the transition temperature	441
15.7 Theory of the ductile brittle transition	444
15.8 Practical aspects of brittle fracture	448
15.9 Metallography of brittle fracture	451
15.10 Fracture toughness	452
15.11 Ductile fracture	453
15.12 Ductile failure in single crystals	454
15.13 Ductile fracture in polycrystalline aggregates	456
15.14 The initiation and propagation of ductile cracks	458
15.15 Metallographic examination of ductile fractures	459
Author Index	465
Subject Index	473

## Chapter 1

# Introduction

Perhaps the most characteristic property of a metal is ductility or the ability to suffer much deformation without breaking. This property was extremely useful even to our remote ancestors when they discovered deposits of native gold and copper as well as occasional iron meteorites. Indeed, gold is the most ductile of metals, which for many centuries has been beaten into the thinnest of leaf. While practical knowledge of the forming of metals extends backwards for thousands of years, our understanding of the physical phenomena associated with deformation has only developed within the last forty years. Some of the basic principles have been elucidated, but many associated phenomena will require much further research before they are thoroughly understood. It is the aim in this book to provide a framework to the subject involving known facts and principles, but occasionally the temptation to indulge in some speculation will not be resisted.

If an increasing load is applied to a metal wire suspended from a fixed point, extension will occur which is completely recoverable when the load is removed. The metal is then said to be deformed elastically, and there is a linear relationship between stress  $\sigma$  and strain  $\epsilon$  which Hooke's law defines thus,  $E = \sigma/\epsilon$ . At any given load the ratio of the stress  $\sigma$  to the elastic strain  $\epsilon$  is a constant  $E$ , known as Young's modulus in the case of a uniaxial tensile stress. However, beyond a certain load, complete recovery of the strain does not occur on unloading because the metal has deformed plastically or permanently. We define the transition as the yield stress or the initial flow stress. The total elastic strain is extremely small, so the plastic strain accounts for the overwhelming proportion of the deformation. The engineer when designing machines tries to avoid stressing a part anywhere near the yield stress but, to form and fabricate metals, a metallurgist must work in the plastic range. In this book we shall explore the behaviour of metals from the yield stress to the point at which they break apart; we shall examine the basic mechanisms which allow such operations as rolling, forging, drawing and pressing to be successfully carried out.

In the early part of this century, Rosenhain and Ewing showed that

plastic deformation of metals produced on the surface many parallel microscopic steps called slip bands, which suggested to them that the metal had sheared along the bands rather like cards in a shuffled pack. These early observations showed clearly that the shear occurred along well-defined crystallographic planes in the metal, the markings changing direction at the grain boundaries. However, detailed study was difficult in normal metal specimens because one grain might exhibit several different sets of markings, and the need for investigation of the behaviour of individual grains or crystals became apparent. Only in this way could the problem of plastic deformation be simplified.

A little later, in 1910, Andrade developed a technique of growing large individual crystals from the melt by a method later to be elaborated by Bridgman, who used it to prepare single crystals of many metals of uniform dimensions, covering a wide range of possible orientations relative to the specimen axis. The way thus lay open for the detailed study of plastic deformation of metal crystals, with the result that the period 1920–34 was rich in experimental investigations of crystal plasticity. Fundamental studies of the deformation of most of the common metals led to important generalizations, such as the critical resolved shear stress criterion, and allowed the principles of crystal geometry to be precisely stated. Behaviour of metals in the three main crystallographic groups, face-centred cubic, body-centred cubic and close-packed hexagonal, was compared and contrasted. Results of this period of extensive activity were summarized in the classical monograph on crystal plasticity by E. Schmid and W. Boas published in 1936. Chapter 2 of the present book will present the classical experimental results on the deformation of single crystals while in Chapter 4 the subject will be discussed in the light of more recent developments. Since 1945 much new work has been done, in some cases with metals of much higher purity which has led to the modification of earlier ideas.

In 1934 Orowan, Polanyi and Taylor independently introduced the concept of a dislocation, a crystal line defect which was necessary to account for the fact that the observed strength of metals generally was about a thousand times less than the theoretical estimates. It is no exaggeration to say that the dislocation has proved to be the most important discovery of metal physics in the last thirty years. What was at first an elegant theoretical concept has, in the post-war years, proved to be a triumphant reality, significant not only in the process of plastic deformation itself but also in crystal growth, recovery and other diverse phenomena. Development of the theory was interrupted by the war, but was resumed in 1945 to blossom in the following decade. The manifestations of the theory are now many, but the principles can be summarized so that they are of use to students of metallurgy. This has been the aim in Chapter 3, where simple types of dislocation are described and some of their properties outlined; this chapter also contains some of the direct evidence obtained for the existence of dislocations. It is interesting to reflect that after a decade of



fruitful theory, the well-tried metallographic approach in the guise of thin-foil electron metallography has provided the final proof of many theoretical pronouncements.

Perhaps the most impressive of the plastic properties is work hardening or the ability of a metal to become stronger as it deforms. Work hardening has proved to be a very difficult problem to solve, so much so that it is impossible to present a concise and convincing quantitative theory. However, the dislocation theory has provided many useful ideas, some of which are considered in Chapter 5, and used in an attempt to explain the experimental results.

While work hardening contributes greatly to the strength of a metal, the addition of alloying elements is a much more effective way of increasing its resistance to deformation. The effect of even very small concentrations of solute atoms on the strength of a metal crystal can be very substantial, as shown in Chapter 6. The effect of alloying elements both in solid solution and present as a separate phase on the process of plastic deformation must be examined in an attempt to understand the behaviour of complex alloys (Chapter 7). While deformation by slip is widespread, it is not the only mechanism by which plastic strain is achieved. In Chapter 8 the important process of deformation twinning is introduced.

Many theories concerned with mechanical properties of metals are best tested on single crystals. However, there comes a stage when an attempt must be made to use single crystal behaviour to understand the deformation of polycrystalline aggregates. Clearly the properties of the individual crystals provide the key, but the deduction of polycrystalline behaviour from them is difficult and only limited progress has been made. In Chapter 9 the role of the grain boundaries is first outlined, followed by a discussion of the stress-strain curves of polycrystalline aggregates.

Atomic holes or vacant lattice sites are an important by-product of plastic deformation, which are often accompanied by the formation of interstitial atoms. Such point defects are of considerable significance not only in deformation processes, but in recovery and solid state diffusion. They are also a direct consequence of irradiation in crystalline solids, and are dominant factors in determining their mechanical properties (Chapter 10).

It has been known for thousands of years that a metal hardened by working can be restored to its original ductility by heating. There is a series of interesting processes by which this end is reached, which commences with the rearrangement of defects within the deformed crystals (recovery) and concludes with the replacement of the deformed grains by a new set of strain-free crystals (recrystallization). These phenomena are discussed in Chapter 11. While such processes may not at first glance appear to be relevant to a study of deformation, it should be appreciated that if the temperature is raised, these phenomena can occur during deformation.