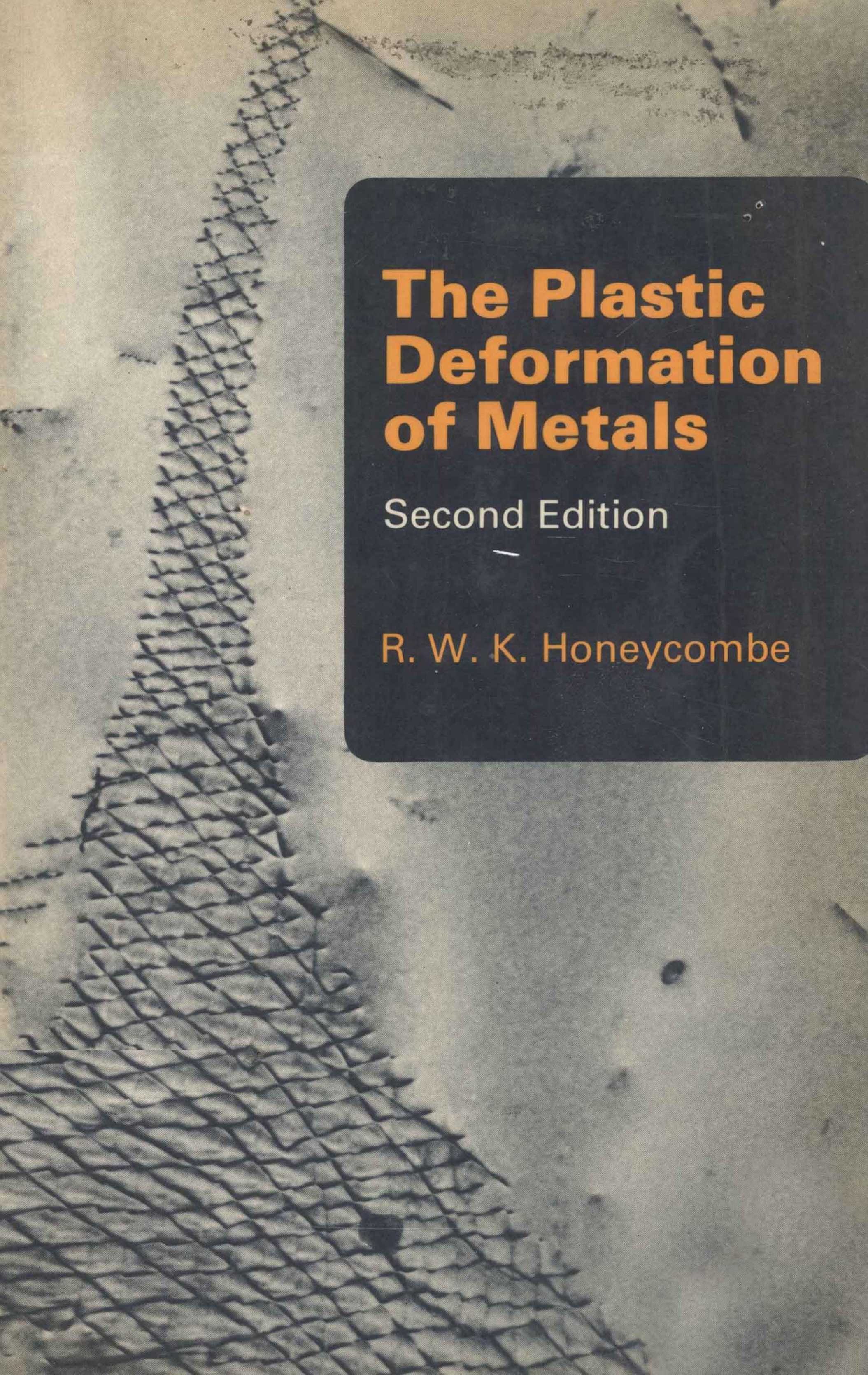

The Plastic Deformation of Metals

Second Edition

R. W. K. Honeycombe

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Edward Arnold   American Society for Metals

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

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 *Kristallplastizitaet* 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

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

Contents

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 σ and strain ϵ which Hooke's law defines thus, $E = \sigma/\epsilon$. At any given load the ratio of the stress σ to the elastic strain ϵ 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.