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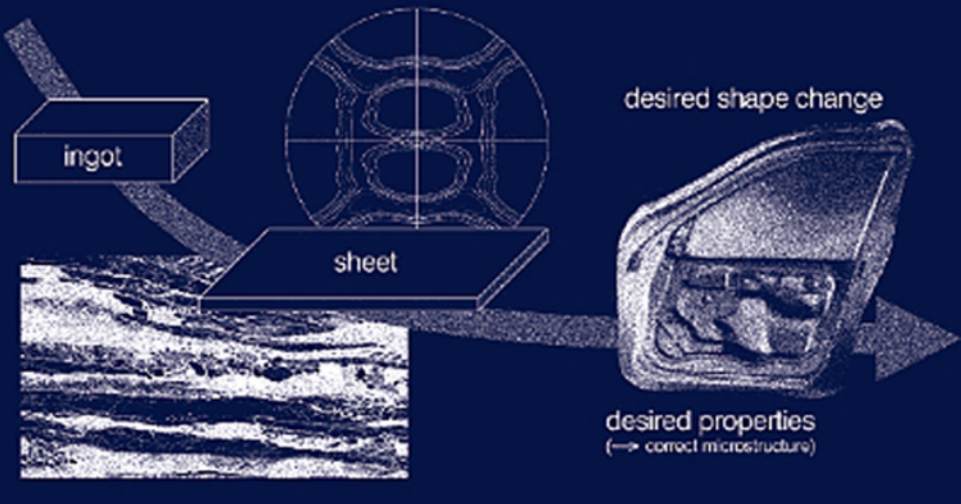
Thermo-Mechanical Processing of Metallic Materials



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PERGAMON MATERIALS SERIES

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Thermo-Mechanical Processing of Metallic Materials

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Dedication

This book is dedicated to the late Robert W. Cahn (1924–2007), who encouraged the writing of this volume and edited it with his usual clear insights into both Materials Science and good writing. One of the co-authors (RDD) was mentored by Robert over many years, offering him invaluable help, insights and lively discussion on many topics.

Robert W. Cahn made many important contributions to Materials Science, including the successful hypothesis, made while he was still a graduate student, that recrystallization nuclei grew from, what were then called, polygonized cells, and so had orientations produced by the prior deformation. That idea has been at the heart of recrystallization research for the last 60 years.

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Contents

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Preface

The present volume is the eleventh in the Pergamon Materials Series, but only the first with avowedly technological subject matter. The thermo-mechanical processing of metals and alloys is right at the heart of materials engineering, and at the same time it is firmly linked with the underlying science of plastic deformation, recrystallization and texture formation.

Accordingly, the book includes a broad spectrum of subject matter from basic science to production engineering . . . in fact, Materials Science and Engineering (MSE).

It is barely more than a century since Walter Rosenhain uncovered the basic mechanism of plastic deformation of crystalline metals; another 20 years had to elapse before X-ray diffraction had become available to study the formation of textures, and another 30 years after that before electron microscopy was mature enough to reveal fine detail of the microstructural processes involved in recrystallization. All these came together, together with modern developments in mechanical engineering, to create the methods used in the shaping of containers and other components made of aluminium alloys, steels, titanium and zirconium, the description of which represents the culmination of this intriguing book.

I have pleasure in commending to our readership this exemplification of MSE at its best.

Robert W. Cahn (Series Editor)
Cambridge

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List of Symbols

This list contains the most important symbols used in the text.
Occasionally some letters or symbols are used for other purposes; this is specifically stated in the text.

b	Burgers vector
B	Magnetic induction
C	Concentration
d	Subgrain diameter
D	Diameter (grain, roll, . . .)
D_{gb}, D_b	Grain boundary and bulk diffusion coefficients
E	Young's modulus
E'	Plane strain Young's modulus
f	Frequency
F	Load
G	Shear modulus
H	Magnetic field
J	Energy
k	Boltzmann constant
$K, K_1, K_2, \ldots, K_n$	Constants defined in the text
l	Length
m	Strain rate sensitivity coefficient
M	Mass (also mobility)
n	Strain hardening coefficient
P	Driving pressure
p	Pressure, hydrostatic pressure
Q	Activation energy
R	Gas constant
R_{ext}	Extrusion ratio
$R(\alpha)$	Resistance against thinning in direction α
$\bar{R}$	Normal anisotropy
RA	Reduction in area
r	Radius of precipitate
s	Thickness
t	Time
v	Velocity
V	Volume
w	Width

W	Work
Z	Zener–Hollomon parameter
α	Drawing angle in wire drawing, angle to tensile direction
δ	Boundary thickness
ΔR	Planar anisotropy
γ_{gb}	Grain boundary energy
γ_{SFE}	Stacking fault energy
ε	Strain in general
$\overline{\varepsilon}$	Von Mises equivalent strain
ε_c	Critical strain
ε_{fr}	Fracture strain
ε_u	Uniform deformation
ε_t	Thickness strain
ε_{total}	Total deformation
ε^o or $\dot{\varepsilon}$	Strain rate
μ	Friction coefficient
v	Poisson's ratio
θ	Misorientation across a boundary
$\overline{\theta}$	Work hardening
ρ	Dislocation density
$\overline{\sigma}$	Von Mises equivalent stress
σ	Stress in general
σ_f	Flow stress during forming
σ_y	Initial flow stress (also YS)
σ_F	Drawing stress in wire drawing
σ_{fr}	Fracture stress
σ_s	Saturation stress
τ	Shear stress
τ_c	Critical shear stress
Ω	Atomic volume

Abbreviations

bcc	Body-centred cube
CDRX	Continuous dynamic recrystallization
CSL	Coincidence site lattice
DRV	Dynamic recovery
DSC	Differential scanning calorimetry
DRX	Dynamic recrystallization
EBSD	Electron backscatter diffraction
fcc	Face-centred cube
FLD	Forming limit diagram
HAGB	High-angle grain boundary
hcp	Hexagonal closed packed
HIP	Hot isostatic pressing
JMAK	Johnson–Mehl–Avrami–Kolmogorov kinetic model
LDR	Limiting drawing ratio
ND, RD, TD	Normal, rolling, transverse direction
ODF	Orientation distribution function
PSN	Particle-stimulated nucleation
SEM	Scanning electron microscope
SFE	Stacking fault energy
SRX	Static recrystallization
TEM	Transmission electron microscope
UTS	Ultimate tensile strength
YS	Yield strength

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PART I: SCIENCE

Chapter 1
General Introduction

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Chapter 1

General Introduction

Most metal-forming operations have two direct consequences. On a 'macroscopic scale' the desired shape change is obtained and on a 'micro scale' the microstructure of the material is changed. This microstructure is related to the mechanical and physical properties of the metal and is heavily dependent on external parameters such as temperature, strain, strain rate, deformation mode, lubricants, etc.

The blacksmith in ancient times was mainly concerned with the macroscopic shape change, but modern metal industry requires thermo-mechanical processes that lead to a product with optimal properties, not only for dimensional precision and appearance, but also with respect to the mechanical and physical properties (Figure 1.1).

Thermo-mechanical processing (TMP) describes the set of heating and shaping operations by which relatively simple, basic materials are converted into high-quality components. The term is principally applied to the processing of metallic alloys but extensions to ceramics, polymers and many of their combinations are increasingly being developed. It is as old as mankind and as new as the latest microelectronic device. One of the earliest examples is of course the forging of bronze (copper–tin alloys) for both tools and personal decoration in the Bronze Age (~3000 BC); as-cast alloys were subjected to a sequence of heating and plastic deformation operations to shape the component and simultaneously improve the material properties, usually strength and tenacity. The basic idea has changed

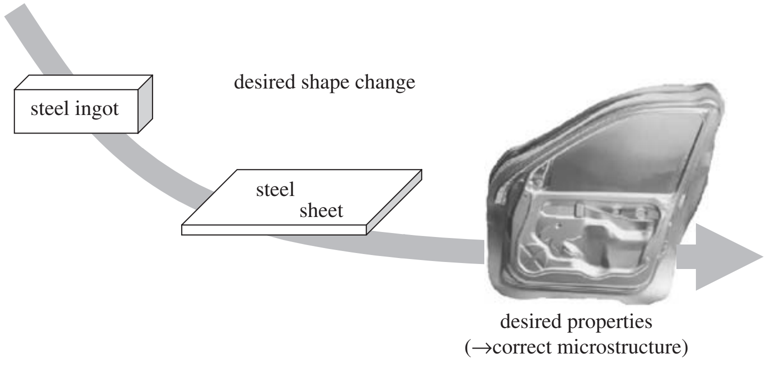

Figure 1.1. Metal forming: a combination of a desired shape change with a controlled microstructure.

little over the centuries but the industrial machines and levels of scientific understanding have undergone a dramatic transformation, essentially in the last 50 years. In particular, the role of microstructure evolution during shaping is now widely accepted as critical for understanding and relating the process/material/property combinations.

The subject is usually treated in two separate parts: mechanical processing (as a branch of mechanics) and physical metallurgy (as part of materials science). One of the aims of the present book is to bring the two disciplines closer together to develop a more unified approach that could facilitate new advances in the field. Although TMP is a dynamic subject of modern research, books on the subject are rare, if non-existent. The aim of the present text is to give an overview of the main manufacturing processes, but also to provide some understanding of the complicated relations between a forming process and the microstructure of a metal on one hand, and between this microstructure and the mechanical properties on the other.

In Part I, *Science*, the microstructural science of the subject is treated. It is assumed that most readers have already acquired some typical undergraduate-level knowledge of material science. Those readers can probably skip Chapters 2 and 3, which provide an elementary survey and suggestions, for further reading about microstructures and properties of materials and about plasticity. The other chapters of Part I treat, at a more advanced level, important issues such as work hardening, softening mechanisms (recrystallization), texture and residual stresses. Deformation mechanisms like creep and superplasticity are introduced and the influence of phase transformations on TMP is highlighted. Since more and more predictive models concerning TMP operations are being developed, the last chapter will focus on this rapidly expanding field.

In Part II, *Technology*, the most important metal-forming operations are described. The paragraphs on primary forming processes such as rolling, extrusion, forging and wire drawing are mainly focussed on the 'macro scale' (shaping a metallic part) although here also some connections with microstructural control will be made. In the chapter about 'sheet metal forming', some forming operations like deep drawing, bending, stretching and incremental forming will be explained. A key point in this chapter is the relation between plastic anisotropy and formability. Some advanced forming operations like hydroforming, hipping and superplastic forming will end this extensive chapter on forming operations. An overview of the major macroscopic problems that may arise during metal forming, is provided in Chapter 12 and as far as possible, the microstructural origins of those macroscopic problems are discussed. Finally, Chapter 13 will illustrate the possibilities of measuring material properties and studying material behaviour during TMP-type deformation on a labscale.

The third part of this book, *Case studies*, is mainly devoted to the ‘micro scale’. In a number of examples the TMP of some products is analysed and discussed. These case studies show how properties can be successfully optimized by a careful control of the microstructure during processing. Examples from the aluminium industry include the processing of beverage cans, capacitor foil, extrusion of metal matrix composites and rolling of thick plates for aerospace applications. The TMP of steel products is illustrated with a case study on steel for car bodies, a short description of the development of dual phase and TRIP steels, the concept of controlled rolling of HSLA steel, a discussion on the production of electrical steel and the patenting of steel wires. Two examples of successful processing of hexagonal metals are provided with a discussion about Zr for the nuclear industry and Ti for aero-space applications. Finally, some new developments are discussed: the production of sub-micron materials by severe plastic deformation and an example of ‘grain boundary engineering’ to improve the local corrosion resistance of stainless steel.

This textbook is written at the level of an advanced Master course. It is our hope that it can serve as a course textbook for students taking a course on TMP. On the other hand, this book is also intended for engineers in industry. It will offer them a coherent overview of the field and provide them references to the most important literature.