MATERIALS AT HIGH STRAIN RATES

Edited by

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ELSEVIER APPLIED SCIENCE
LONDON and NEW YORK

ELSEVIER APPLIED SCIENCE PUBLISHERS LTD
Crown House, Linton Road, Barking, Essex IG11 8JU, England

Sole Distributor in the USA and Canada
ELSEVIER SCIENCE PUBLISHING CO., INC.
52 Vanderbilt Avenue, New York, NY 10017, USA

WITH 13 TABLES AND 173 ILLUSTRATIONS

British Library Cataloguing in Publication Data

Materials at high strain rates.
1. Strains and stresses—Measurement
I. Blazynski, T. Z.
620.1'123'0287 TA417.6

Library of Congress Cataloging in Publication Data

Materials at high strain rates.

Includes bibliographies and index
1. Materials—Dynamic testing. 2. Fracture mechanics.
I. Blazynski, T. Z.
TA418.32.M38 1987 620.1'123 87-598

ISBN 1-85166-067-4

Filmset and printed in Great Britain by The Universities Press (Belfast) Ltd.

PREFACE

Although high energy-rate processes and operations have been in existence for over two decades, the full exploitation of the opportunities which they offer has often been made difficult, if not impossible, by the relative scarcity of easily available information about the response of materials to the imposed conditions.

The importance attached to the properties of both metallic and non-metallic materials, subjected to the effects of high-rate loading, is reflected in the growing number of international conferences and in the volume of the associated proceedings and individual papers published. However, for the researcher, the practising production engineer and the designer, the task of collecting and then assimilating this literature is an arduous one.

The present book is intended to ease this situation by providing a concise review of the state of this knowledge in a way which ensures, on the one hand, considerable depth of treatment and, on the other, a fair but critical exposition of developments in this field.

The book is divided into seven chapters, written by well-established 'practitioners' in their respective areas of activity, and provides information about both the general material response and the more specific loading situations. Consequently, Chapters 1 to 3 are concerned with the effects of high-rate dynamic loading in metallic alloys, including the incidence of adiabatic shear, and in ceramics and polymers. Chapters 5 to 7 deal with the initiation, type and effect of fracture, including computational modelling of these phenomena, and with the limited surface response to impact. Chapter 4, forming a link between the two groups, is devoted entirely to the methods of testing the mechanical properties of materials subjected to the treatment described. All chapters contain extensive lists of references which in themselves become sources of additional and more detailed information.

The book is thus an exercise in the summation of the present state of practical and theoretical knowledge, being of interest not only to the practising engineer and/or material scientist already working in this field, but also to the beginner in need of reliable information.

My thanks are due to the authors of individual chapters who, by pooling their expertise, have produced a comprehensive and authoritative review.

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CONTENTS

Chapter 1

METALLURGICAL EFFECTS OF SHOCK AND HIGH-STRAIN-RATE LOADING

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1.1 INTRODUCTION

Deformation induced metallurgical effects are now generally well documented to be the result of stress or strain-induced microstructures, or microstructural changes in crystalline (polycrystalline) metals and alloys. In many cases, strain hardening, work hardening, or other controlling deformation mechanisms can be described by the generation, movement and interactions of dislocations (which can produce drag or a range of impedances, including obstacles to further motion). While dislocations may be involved in a range of metallurgical effects which are manifest in the mechanical response of metals and alloys, there are of course the mitigating and controlling effects of temperature, strain, strain rate and the strain (or stress) state. At very high strains and strain rates there can be abrupt changes in deformation mode leading to noticeably different microstructures; these give rise to noticeable metallurgical effects: microstructurally related flow stress, ductility, hardness and other related mechanical property changes.

Metallurgical effects, characterized mainly by the relationships between deformation-induced microstructures and residual mechanical properties, are therefore the result of the complex interrelationships between stress, stress state, strain, strain rate and temperature. Changes in plastic stress in a uniaxial stress state (uniaxial tension) can be expressed by a mechanical modeling expression as:

$$d\sigma = \left(\frac{\partial\sigma}{\partial\varepsilon}\right)_{\dot{\varepsilon},T} d\varepsilon + \left(\frac{\partial\sigma}{\partial\dot{\varepsilon}}\right)_{\varepsilon,T} d\dot{\varepsilon} + \left(\frac{\partial\sigma}{\partial T}\right)_{\varepsilon,\dot{\varepsilon}} dT \quad (1.1)$$

where σ, ε, $\dot{\varepsilon}$ and T have their usual meaning of stress, strain, strain rate and absolute temperature respectively. In effect, this expression is an indication that even if the loading or deformation parameters are controlled externally to the deforming material, there can be functional relationships which could override that control. For example, temperature in a deforming material can be raised by increasing the strain, and by adiabatic heating at high strain rates. In addition, very high pressures in the shock loading regime can create both transient and residual heating.

As a simple starting point in developing a reasonably coherent overview of some of the metallurgical effects of shock-wave and high-strain-rate phenomena, one might consider the stress–strain relationship at room temperature (and constant, low strain rate, implicit in eqn (1.1)) shown in Fig. 1.1. Figure 1.1 illustrates a range of microstructures which include planar dislocation arrays at lower strains which evolve into more dense and microstructurally different arrays at higher strains. These different arrays (microstructures) are composed of twin-faults and α'-martensite which forms at the intersections of twin-fault bundles.

The dislocation density changes are simply related to changes in stress (or strain) through expressions of the form

$$\sigma = \sigma_0 + K\sqrt{\rho} \quad (1.2)$$

$$\rho = \rho_0 + A\varepsilon \quad (1.2a)$$

where σ_0, K and A are constants and ρ is the dislocation density (ρ_0 is the initial dislocation density). In the context of flow stress or residual yield stress (at constant strain), eqn (1.2) also expresses the fact that the residual yield or flow stress will be increased by the creation of dislocations, and indeed the yield stress at each of the strain conditions noted in Fig. 1.1 would be expected to increase from the previous conditions so long as ρ increases, or other microstructural changes occur which lead to strengthening of the material.[1] Since hardness and yield stress are related, the hardness at each of the strain conditions illustrated in Fig. 1.1 would also be expected to change (increase).

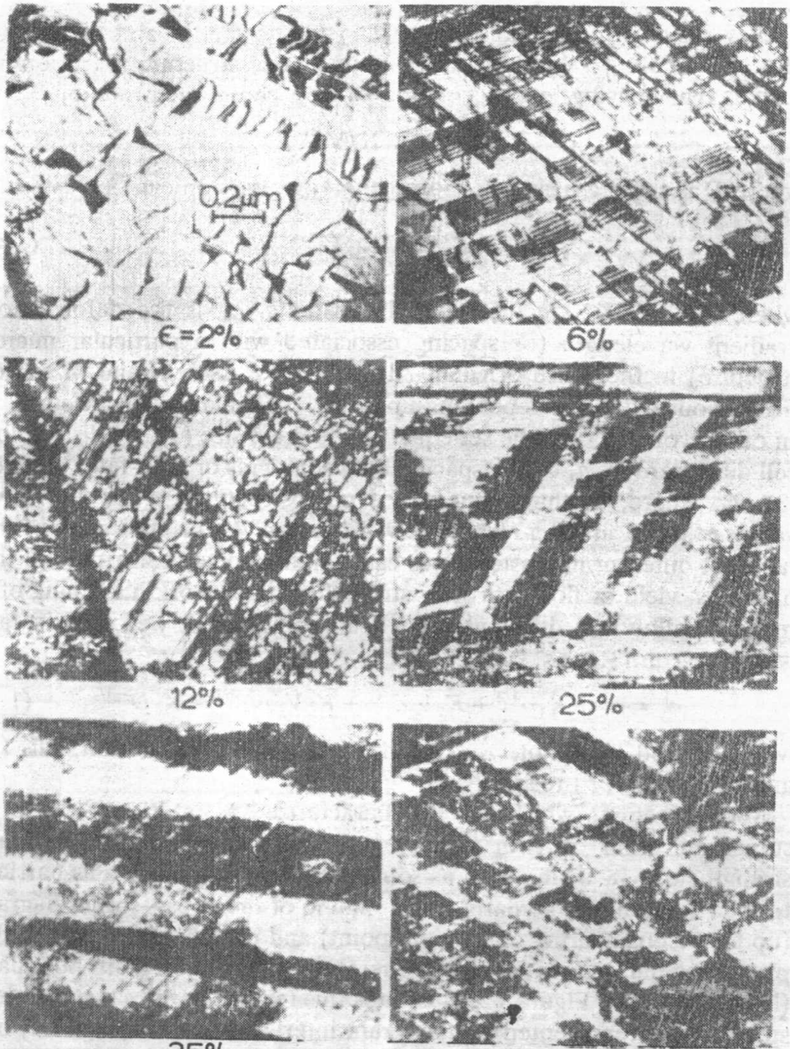

FIG. 1.1 Examples of residual microstructures in type 304 stainless steel after deformation in uniaxial tension to average total strains (ε) indicated (room temperature; $\dot{\varepsilon} = 10^{-3}\,s^{-1}$). The microstructures are characterized by increasing densities of dislocation arrays, stacking faults and twin-faults, with α'-martensite forming at twin-fault intersections and constituting a prominent volume fraction nearly equivalent, as a volume fraction percent, to the total strain value from about 25% strain.

Flow stress or yield stress in polycrystalline metals and alloys can often be related to the grain size or other microstructural partitioning such as twin spacing, etc., as expressed by a Hall–Petch relation

$$\sigma = \sigma_0 + K/\sqrt{D} \qquad (1.3)$$

where D is the grain size. A more general expression can be written:[2]

$$\sigma_y = K' + K'' \sum_j (\lambda^G)^{-m_j} \qquad (1.4)$$

where K' and K'' are interrelated constants, λ^G is the deformation gradient wavelength (or spacing associated with a particular microstructure) in the sense originally described by Ashby,[3] and m_j varies from about 0·25 to 1 depending upon the particular microstructure, j. In other words, λ^G can be set equal to the grain size (1), D, dislocation cell diameter (2), d, or the spacing between twins or twin-fault bundles (3), Δ, where, in that sequence of microstructures, m_j would have values of 0·5, 1 and 0·5 respectively. Equation (1.4) is indicative of the fact that different microstructures can simultaneously contribute to the hardness, yield or flow stress, or strengthening or work hardening of a metal or alloy in a different way. If all contributed, we could in fact write out eqn (1.4) as[4]

$$\sigma_y = \sigma_0 + K_1\rho^{1/2} + K_2V_cd^{-1} + K_3V_T\Delta^{-1/2} + K_4D^{-1/2} \qquad (1.5)$$

where V_c and V_T denote the volume fractions of dislocation cells (c) and twin-faults (T) respectively.

Microstructures which can be characterized as interfaces[5] (such as sub-grain, grain or twin boundaries) contribute to hardening and strengthening by acting both as sources for dislocations and as barriers to their motion. In the early strain regime of the stress–strain diagram (up to the engineering offset yield point) and into the early part of the plastic regime, dislocations are generated primarily by grain boundary (ledge) sources.[4] Figure 1.2 illustrates this feature in the same stainless steel sample represented by the strain intervals shown in Fig. 1.1, but at a lower strain level. Figure 1.2 also demonstrates that dislocations emitted from a source in one grain boundary can pile up against an opposing or neighboring grain boundary. Consequently, since the area of grain boundary or the number of dislocation sources would be expected to increase with decreasing grain size, and since a smaller grain size would develop effective barriers to dislocations sooner, the effects implicit in eqn (1.3) would occur. In general, therefore, as the

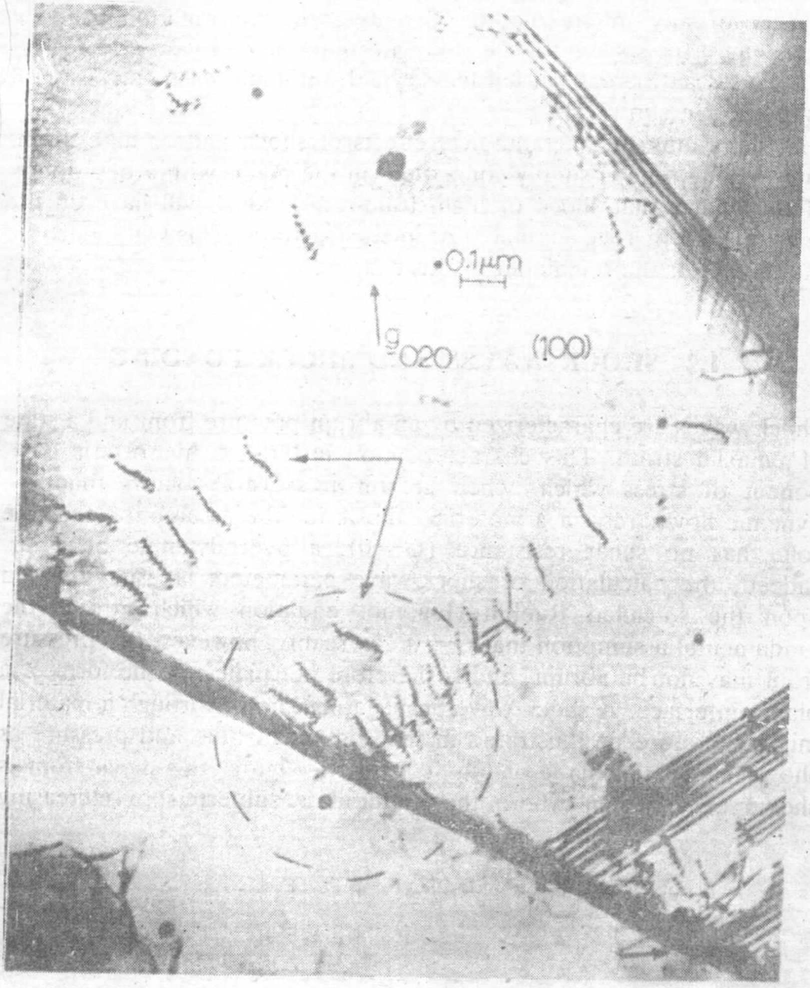

FIG. 1.2 Dislocations are generated predominantly from grain boundary ledge sources (arrows), especially during the onset of deformation, in most metals and alloys. The number of grain boundary ledges as well as the number of dislocations emitted from individual sources increases with increasing strain.[1] Dislocations emitted from a source in one grain boundary can pile up against an opposite grain boundary. The piled-up dislocations can shear the grain boundary and create a new ledge source, allowing the emission process to continue by that mechanism. This illustration is from a 304 stainless steel sample strained 1·3% in tension at $10^{-3}\ s^{-1}$ (room temperature).

density of any microstructure increases, the deformation gradient wavelength (or spacing) associated with that microstructure decreases; this causes an increase in hardness, yield, ultimate tensile stress, etc., as implicit in eqn (1.5).

In describing the metallurgical effects of shock and/or high-strain-rate loading, one is simply concerned, in the main, with a description of the effects that shock or high-strain-rate loading will have on the development or redevelopment of microstructures. This will indeed be the theme for the remainder of this chapter.

1.2 SHOCK WAVES AND SHOCK LOADING

Shock waves are characterized by an abrupt pressure front and a state of uniaxial strain. This characterization includes a hydrostatic component of stress which, when greater by several factors than the dynamic flow stress in a material, allows for the assumption that the solid has no shear resistance ($G = 0$); a hydrodynamic behavior. Indeed, the calculation of shock-wave parameters is usually based upon the so-called Rankin–Hugoniot equation which utilizes the fundamental assumption that $G = 0$.[6] In reality, however, this pressure front may not be abrupt, and is therefore not planar in the form of a planar interface. A shock wave propagating into or through a material might therefore be illustrated in the context of time and pressure as shown in the schematic of Fig. 1.3. In this figure, the shock front is shown as a region where the material is subjected to increasing

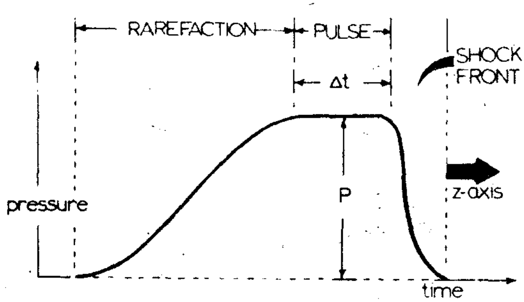

FIG. 1.3 Idealized (schematic) view of a shock pulse traveling through a solid material. The z-direction is assumed to be normal to the plane shock wave front and to the specimen surface.