VISCOPLASTIC FLOW IN SOLIDS PRODUCED BY SHEAR BANDING

RYSZARD B. PĘCHERSKI

WILEY

A complete overview of the topic of viscoplastic flow in solids produced by shear banding

This book presents novel ideas about inelastic deformation and failure of solids in a clear, concise manner. It exposes readers to information that will allow them to acquire the competence and ability to deal with up-to-date manufacturing and failure processes. It also portrays a new understanding of deformation processes. Finally, shear banding's typical mechanism becomes the active cause of viscoplastic flow and not the passive effect.

Viscoplastic Flow in Solids Produced by Shear Banding begins by discussing the new physical model of multilevel hierarchy and the evolution of micro-shear bands. In conclusion, it examines the difficulties of applying a direct multiscale integration scheme and extends the representative volume element (RVE) concept using the general theory of the singular surfaces of the microscopic velocity field sweeping out the RVE. This book reveals a new formulation of the shear strain rate generated by the consecutive systems of shear bands in the workflow integration approach. This book:

- Presents fresh ideas about inelastic deformation and failure of materials
- Provides readers with the ability to deal with up-to-date manufacturing and failure processes
- Sheds light on the interdisciplinary view of deformation processes in solids

Viscoplastic Flow in Solids Produced by Shear Banding will appeal to researchers studying physical foundations of inelastic behaviour and failure of solid materials, dealing with analysis and numerical simulations of manufacturing forming processes. It is also an excellent resource for graduate and postgraduate students of material science and mechanical engineering faculties.

Ryszard B. Pęcherski, PhD, DSc, is researching in the Department of Theory of Continuous Media and Nanostructures at the Institute of Fundamental Technological Research, Polish Academy of Sciences in Warsaw. He received his MEng from the Gdańsk Polytechnic Department of Shipbuilding in Gdańsk, Poland, in 1973, his PhD in 1979 and his DSc in 1998 from the Institute of Fundamental Technological Research, Warsaw, Poland. He has been a member of the research staff since 1977. He was a Fellow of the Japan Society for Promotion of Sciences, Tohoku University, Sendai (Takeo Yokobori), Japan, from 1979–1980 and a Fellow of the Aleksander von Humboldt Foundation, University of Hanover, Hanover, Germany, from 1983–1987 (Erwin Stein). He was a member of the faculty of Civil Engineering at Cracow University of Technology, Kraków, Poland, from 2000–2007, and he received the title of Professor in October 2007. Finally, from July 2007–February 2022, as a member of the Mechanical Engineering and Robotics faculty at AGH University of Science and Technology in Kraków, he taught English courses on mechanics of materials. He also invited lecture courses delivered in the International Centre for Mechanical Sciences, CISM, Udine, 2012, and the Summer School of Mechanics in Agadir, Maroc, 2013, related to modelling inelastic behaviour of solids accounting for micro-shear banding. His lectures on the mechanics of modern materials in École Nationale d'Ingeniéurs de Metz, 2014 (Alexis Rusinek – host professor) contained the earlier threads and ideas woven into the concept of the work.

Cover Design: Wiley
Cover Image: © Sergey Ryzhov/Shutterstock

www.wiley.com

WILEY

Also available as an e-book

ISBN 978-1-119-61858-4
90000
9 781119 618584

VISCOPLASTIC FLOW IN SOLIDS PRODUCED BY SHEAR BANDING

RYSZARD B. PĘCHERSKI

WILEY

Viscoplastic Flow in Solids Produced by Shear Banding

Viscoplastic Flow in Solids Produced by Shear Banding

Ryszard B. Pęcherski
Institute of Fundamental Technological Research
Polish Academy of Sciences, Warsaw, Poland

WILEY

This edition first published 2022

Registered Office(s)
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data

Names: Pęcherski, Ryszard B., author. | John Wiley & Sons, publisher.
Title: Viscoplastic flow in solids produced by shear banding / Ryszard B. Pęcherski.
Description: Hoboken, NJ : Wiley, 2022. | Includes bibliographical references and index.
Identifiers: LCCN 2022010729 (print) | LCCN 2022010730 (ebook) | ISBN 9781119618584 (cloth) | ISBN 9781119618607 (adobe pdf) | ISBN 9781119618638 (epub)
Subjects: LCSH: Shear (Mechanics). | Deformations (Mechanics). | Viscoplasticity.
Classification: LCC TA417.7.S5 P44 2022 (print) | LCC TA417.7.S5 (ebook) | DDC 620.1/1245–dc23/eng/20220408
LC record available at https://lccn.loc.gov/2022010729
LC ebook record available at https://lccn.loc.gov/2022010730

Cover Design: Wiley
Cover Image: © Sergey Ryzhov/Shutterstock

Set in 9.5/12.5pt STIXTwoText by Straive, Pondicherry, India

I am devoting this work to the memory of my late parents, both teachers. My mother, Kazimiera Natalia de domo Rogala. My father, Bolesław lycée mathematician, enjoyed sharing knowledge and an extensive math library with me.

I also want to express my extraordinary feelings directed to my late grandpa Antoni Rogala. He was 'guiding my pen' with his wit and imagination. The stories of his life in the turbulent times of the last century become enlightening examples of a positive attitude towards difficult situations.

Contents

Preface

The thorough Investigations of the new types of materials – nano- and ultrafine-grained metallic solids, amorphous metal alloys called glassy metals, and high-performance alloys – lead to an essential general conclusion. Observing their failure processes, one may notice that a paradigm shift transpires before our eyes regarding the widely known and accepted ductile failure micromechanisms as *initiation, growth, and coalescence of voids*. The recent nonstandard experiments confirm the novel observations about the vital importance of accompanying shear modes, e.g. stereo digital image correlation, the tomograms of X-ray, or synchrotron techniques related to 3D imaging methods. Dunand and Mohr (2010), using two- and three-dimensional digital image correlation technique, measured the surface strain fields on tensile specimens, including the one with a central hole and circular notches. The samples came from TRIP780 steel sheets. The authors concluded that the non-porous plasticity model's numerical predictions agree well with all macroscopic measurements for various loading conditions. Dunand and Mohr (2011) studied for TRIP780 steel the shear-modified Gurson model's predictive capabilities (Nielsen and Tvergaard 2010) and the modified Mohr–Coulomb fracture model (Bai and Wierzbicki 2008). The result is that significant differences between the two models appear with the less accurate prediction for the shear-modified Gurson model. Gorij and Mohr (2017) present a new micro-tension and micro-shear testing technique applying aluminium alloy 6016-T4 flat dogbone-shaped, as well as notched and central hole samples and smiley-shear micro-specimens to identify the parameters of hardening law and fracture initiation model. The Hosford–Coulomb damage indicator model predicts the ductile fracture initiation that appears imminent with the onset of shear localisation.

It became then evident that the known porous material models, e.g. by Shima et al. (1973), Shima and Oyane (1976), or Gurson (1977) extended by Tvergaard and Needleman (1984), reveal limited applications besides the cases when high triaxiality states are prevalent. Therefore, the studies of inelastic deformation and failure of materials should require, in my view, a fresh and novel approach. It aims towards a better understanding and description of the multilevel character of shear deformation modes. It is also worth stressing that Pardoen (2006) emphasizes the role of shear localisation in low-stress triaxiality ductile fracture.

The known experimental data reveal that metallic solids' inelastic deformation appears in the effect of competing mechanisms of slips, twinning, and micro-shear banding. Shear banding is a form of instability that localises large shear strains in relatively thin bands. The micro-shear bands transpire as concentrated shear zones in the form of transcrystalline layers of the order 0.1 μm thickness. The observations show that a particular micro-shear band operates only once and develops rapidly to its full extent. The micro-shear bands, once formed, do not contribute further to the increase of inelastic shear strain. Thus, it appears that successive generations of active micro-shear bands, competing with the mechanisms of multiple crystallographic slips or twinning, are responsible for the inelastic deformation of metals. Therefore, identifying the physical origins of the initiation, growth, and evolution of micro-shear bands is fundamental for understanding polycrystalline metallic solids' macroscopic behaviour.

A new physical model of multilevel hierarchy and evolution of micro-shear bands is at the centre of this work. An original idea of extending the representative volume element (RVE) concept using the general theory of propagation of the singular surfaces of microscopic velocity field sweeping the RVE appears useful for the macroscopic description of shear-banding mechanism in viscoplastic flow, cf. Pęcherski (1997, 1998). The essential novelty of the presented approach comes from numerous observations revealing that the process of shear banding is **the driving factor – a cause and not a result.** So it turns out, in my view, that the successive generations of micro-shearing processes induced mostly by changing deformation path produces and controls viscoplastic flow. On the other hand, one may recall many valuable papers containing the results of in-depth analysis, modelling of dislocation-mediated multi-slip plastic deformation, and numerical simulations of the laminate microstructure, bands, or shear strain localisation in crystalline solids cf. Dequiedt (2018), Anand and Kothari (1996), Havner (1992), as well as Petryk and Kursa (2013) and the wealth of papers cited herein.

Recent studies reveal that two types of shear banding, generating the inelastic deformation in materials, can play a pivotal role.

- The first type corresponds to *the rapid formation of the multiscale shear-banding systems*. It contains micro-shear bands of the thickness of the order of the 0.1 μm, which form clusters. The clusters propagate and produce the discontinuity of microscopic velocity field v_m. They spread over the RVE of a traditional polycrystalline metallic solid. A detailed discussion of such a case is presented in Pęcherski (1997, 1998). A new concept of the RVE with a strong singularity appears, and the *instantaneous shear-banding contribution function* f_{SB} originates.
- The second type is *a gradual, cumulative shear banding* that collects micro-shear bands' particular contributions and clusters. Finally, they accumulate in the localisation zone spreading across the macroscopic volume of considered material. Such a deformation mechanism appears in amorphous solids as glassy metals or polymers. It seems that there are the local shear transformation zones (STZs) behind the cumulative kind of shear banding, cf. Argon (1979, 1999), Scudino et al. (2011), and Greer et al. (2013). The volumetric contribution function f_{SB}^{v} of shear banding appears in such a case.

Often both types of the above-mentioned shearing phenomena appear with variable contribution during the deformation processes. During shaping operations, this situation can arise in polycrystalline metallic solids, typically accompanied by a distinct change of deformation or loading paths or a loading scheme. Also, materials revealing the composed, hybrid structure characterizing with amorphous, ultra-fine grained (ufg), and nanostructural phases are prone to the mixed type of shear banding responsible for inelastic deformation, cf. the recent results of Orava et al. (2021) and Ziabicki et al. (2016).

The commonly used averaging procedures over the RVE need deeper analysis to account for the multilevel shear-banding phenomena. The RVE of crystalline material is the configuration of a body element idealized as a particle. The particle becomes a carrier of the inter-scale shearing effect producing the visco-plastic flow. It leads to an original and novel concept of the particle endowed with the transfer of information on a multilevel hierarchy of micro-shear bands developing in the body element of crystalline material. The discussion about the difficulties and shortcomings of applying a traditional direct multiscale integration scheme appears in Chapter 4. The remarks mentioned above motivate the core subject of the work and underline the new way of thinking.

Ryszard B. Pęcherski
2022
Kraków and Warszawa, Poland

Acknowledgements

I want to express my gratitude for the helpful and friendly guidance offered during my writing efforts shown by Wiley's competent and patient staff led by Ms Juliet Booker, Managing Editor. Thank you very much for accompanying me on my long journey to navigate the bumpy roads of British syntax and phraseology. In such a case, the role of my cicerone – Ms Nandhini Tamilvanan, Content Refinement Specialist – appeared invaluable. Last but not least, acknowledgement belongs to the Creative Services Team coordinated by Ms Becky Cowan, Editorial Assistant, in preparing the book's cover. Their professionalism led me to choose the motif that sheds new light in Chapter 1 on the relevant issues related to industrial applications.

References

Anand, L. and Kothari, M. (1996). A computational procedure for rate-independent crystal plasticity. *J. Mech. Phys.* Solids. 44: 525–558.

Argon, A.S. (1979). Plastic deformation in metallic glasses. *Acta Metall.* 27: 47–58.

Argon, A.S. (1999). Rate processes in plastic deformation of crystalline and noncrystalline solids. In: *Mechanics and Materials: Fundamentals and* (ed. M.A. Linkages, R.W.A. Meyers and H. Kirchner), 175–230. New York: Wiley.

Bai, Y. and Wierzbicki, T. (2008). A new model of metal plasticity and fracture with pressure and Lode dependence. *Int. J. Plast.* 24: 1071–1096.

Dequiedt, J.L. (2018). The incidence of slip system interactions on the deformation of FCC single crystals: system selection and segregation for local and non-local constitutive behavior. *Int. J. Solids Struct.* 141–142: 1–14.

Dunand, M. and Mohr, D. (2010). Hybrid experimental–numerical analysis of basic ductile fracture experiments for sheet metals. *Int. J. Solids Struct.* 47: 1130–1143.

Dunand, M. and Mohr, D. (2011). On the predictive capabilities of the shear modified Gurson and the modified Mohr–Coulomb fracture models over a wide range of stress triaxialities and Lode angles. *J. Mech. Phys.* Solids. 59: 1374–1394.

Gorij, M.B. and Mohr, D. (2017). Micro-tension and micro-shear experiments to characterize stress-state dependent ductile fracture. *Acta Mater.* 131: 65–76.

Greer, A.L., Cheng, Y.Q., and Ma, E. (2013). Shear bands in metallic glasses. *Mater. Sci. Eng.,* **R. 74**: 71–132.

Gurson, A.L. (1977). Continuum theory of ductile rupture by void nucleation and growth. I. Yield criteria and flow rules for porous ductile media. *J. Eng. Mater. Technol.* 99: 2–15.

Havner, K.S. (1992). *Finite Plastic Deformation of Crystalline Solids*. Cambridge University Press.

Nielsen, K.L. and Tvergaard, V. (2010). Ductile shear failure of plug failure of spot welds modeled by modified Gurson model. *Eng. Fract. Mech.* 77: 1031–1047.

Orava, J., Balachandran, S., Han, X. et al. (2021). In situ correlation between metastable phase-transformation mechanism and kinetics in a metallic glass. *Nat. Commun.* 12: 2839. https://doi.org/10.1038/s41467=021-23028-9.

Pardoen, T. (2006). Numerical simulation of low stress triaxiality of ductile fracture. *Comput. Struct.* 84: 1641–1650.

Pęcherski, R.B. (1997). Macroscopic measure of the rate of deformation produced by micro-shear banding. *Arch. Mech.* 49: 385–401.

Pęcherski, R.B. (1998). Macroscopic effects of micro-shear banding in plasticity of metals. *Acta Mech.* 131: 203–224.

Petryk, H. and Kursa, M. (2013). The energy criterion for deformation banding in ductile single crystals. *J. Mech. Phys.* Solids. 61: 1854–1875.

Scudino, S., Jerliu, B., Pauly, S. et al. (2011). Ductile bulk metallic glasses produced through designed heterogeneities. *Scr. Mater.* 65: 815–818.

Shima, S. and Oyane, M. (1976). Plasticity for porous solids. *Int. J. Mech. Sci.* 18: 285–291.

Shima, S., Oyane, M., and Kono, Y. (1973). Theory of plasticity for porous metals. *Bull. JSME.* 16: 1254–1262.

Tvergaard, V. and Needleman, A. (1984). Analysis of the cup-cone fracture in a round tensile bar. *Acta Metall.* 32: 157–169.

Ziabicki, A., Misztal-Faraj, B., and Jarecki, L. (2016). Kinetic model of non-isothermal crystal nucleation with transient and athermal effects. *J. Mater. Sci. 51*: 8935–8952.

1

Introduction

1.1 The Objective of the Work

The subject of the book evolved since the 1990s from the many years' studies, in several joint research projects conducted together with the investigation group of Andrzej Korbel and Włodzimierz Bochniak, professors at the Faculty of Non-Ferrous Metals of the AGH University of Science and Technology in Kraków, Poland (formerly Akademia Górniczo – Hutnicza, in English: Academy of Mining and Metallurgy), cf. Figure 1.1. It concerned physics and theoretical description of deformation processes in metals, particularly in hard deformable alloys. The long-time joint efforts to understand the physical mechanisms responsible for observed phenomena coined the subject of this work. Many years of investigations of metal-forming processes based on multilevel observations – on a macroscopic scale with the naked eye, microscopic ones using optical microscopy, high-resolution transmission electron microscopy, and scanning electron microscopy – led to the critical conclusion. The traditional approach of classical plasticity theory based solely on crystallographic slip and twinning in separate grains is inadequate for predicting and modelling observed deformation processes. Such an observation played a pivotal role in developing an innovative metal-forming method called KOBO, the acronym of inventors names 'Korbel' and 'Bochniak'. This book attempts to provide theoretical foundations and empirical evidence of viscoplastic flow produced by shear banding. In the future, the presented results should make the basis for the formulation of computer codes necessary for numerical simulations of deformation processes in industrial applications. It seems that this book might fill at least partly the mentioned gap.

Viscoplastic Flow in Solids Produced by Shear Banding, First Edition. Ryszard B. Pęcherski.

Figure 1.1 The historical AGH UST emblem. *Source:* AGH University of Science and Technology (https://www.agh.edu.pl/en/university/history-and-traditions/emblem-and-symbols/).

1.2 For Whom Is This Work Intended?

The book's readers may be graduate and postgraduate students in engineering, particularly material science and mechanical engineering. Researchers working on the physical foundations of inelastic deformation of metallic solids and numerical simulations of manufacturing processes could also benefit from this study. The content of the work is also directed at specialists in the field of rational mechanics of materials. The prerequisite knowledge of material science and continuum mechanics with related mathematical foundations, as vector and tensor algebra and tensor analysis, will appear helpful for the readers. The fundamental background may provide the recent work written by eminent scholars of great experience, Morton E. Gurtin, Eliot Fried, and Lallit Anand (Gurtin et al. 2009). Also, a modern and integrated study across the different observation scales of the foundation of solid mechanics applied to the mathematical description of material behaviour presented in the pivotal work (Asaro and Lubarda 2006) is recommendable for the readers. These works comprehensively cover the subject of rational thermomechanics, being the contemporary approach of classical treatises 'standing on the shoulders of giants' (https://en.wikipedia.org/wiki/Standing_on_the_shoulders_of_giants), cf. Chapter 4 for the discussion of a historical thread.

1.3 State of the Art

1.3.1 Motivation Resulting from Industrial Applications

Korbel and Szyndler (2010) presented an overview of the Polish engineering inventions' contribution to metal-forming technologies. Three industrial sectors can play an important role: electrical power plants, transportation, and natural environment protection. First of all, one should focus on high-quality and energy-saving extrusion and forging processes of the elements made of structural steel, non-ferrous metals, and light alloys used to produce parts of machines and other equipment manufactured by all industry sectors.

There is a need and necessity to implement innovative technical and technological solutions into metal-forming practice, making production more efficient, energy-saving, and less expensive. So, we face three challenges with new, non-conventional technologies, such as metal-processing technology in the cyclically variable plastic deformation – known as the KOBO method, cf. the US and European patents description Korbel and Bochniak (1998). The technological solution of metal forming, the KOBO method, satisfies both demands: low manufacturing costs and control of the metal substructure properties in a single operation. The premises, at the background of the method, result from the thorough experimental studies of plastic deformation mechanisms in the course of strain path change conditions (Korbel and Szyndler 2010). The change in the mode of plastic flow from the crystallographic slip of dislocations within separate grains into trans-granular localised shear (shear banding) and associated decrease of metal hardening play a controlling role in the KOBO method. Figure 1.2 illustrates the extrusion process controlled by strain path change due to the reversible twisting of the die in an oscillatory manner. The die oscillations' angle and frequency are the controlling factors of the extrusion process influencing the metal structure and mechanical properties.

Figure 1.3 shows that the load of the order of 1MN is sufficient to cold–extrusion of hardly deformable aluminium alloy 7075 into the billet form with 700 times cross-section reduction.

Due to simultaneous measurements of the extrusion force and the die-twisting torque, it was possible to evaluate the forming process's power consumption and the dependence upon the extrusion rate. The discussion on the power consumption presented in Korbel and Szyndler (2010) illustrates the method's high potential in diminishing the process's plastic work with simultaneous increase of its efficiency. To assess the global effect of

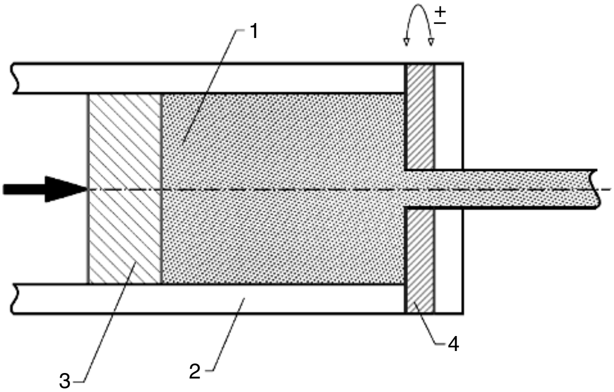

Figure 1.2 Scheme of metal extrusion throughout the oscillating die (KOBO method): 1 – billet, 2 – container, 3 – punch, 4 – oscillating die (Korbel and Szyndler 2010). *Source:* Copyright by Aleksandra Manecka – Padaż.

Figure 1.3 The pattern of the aluminium rest and extruded wire. The extrusion ratio equals 700. *Source:* Korbel and Szyndler 2010. Copyright of Włodzimierz Bochniak.

energy saving on the KOBO process, one should observe that there is no need to heat the billet higher than that in conventional metal extrusion processes. The studies of mechanical properties of extruded metals reveal additional essential features of KOBO products. Worthwhile mentioning is the unexpected thermal stability of the mechanical properties, e.g. plastic flow limit and ultimate tensile strength are not affected by heating in the temperature range where recovery processes are used to produce softening. Furthermore, hardly deformable aluminium alloys (e.g. Al 7075) and magnesium alloys (AZ31, AZ91) subjected to KOBO extrusion become superplastic at elevated temperature, cf. (Korbel and Szyndler 2010). The careful control of the KOBO-forming processes leads to the unique possibility of obtaining the extruded or forging products of the desired shape and properties. Experiments on extrusion of hardly deformable metallic materials reveal practically no limits in getting the desired shape of extrudates under ‘cold deformation’ conditions. Some chosen examples are displayed in Figures 1.4 and 1.5.

The paper (Bochniak et al. 2006) deals with the KOBO method of forming bevel gears from structural steel. The study’s subject is a single operation of complex forging on a press with the reversible rotating die displayed in Figure 1.6. Comparing the KOBO method’s forging process with the conventional ones reveals that the punch pressure and temperature are considerably lower. Despite such a reduction, the products represent the die shape correctly, the structure becomes homogeneous, and the material has desired mechanical properties (see Figure 1.4) containing an example of the regular bevel gear obtained by the KOBO method from structural steel at the studied temperature of 850 °C (Bochniak et al. 2006). Let us also recall a nice

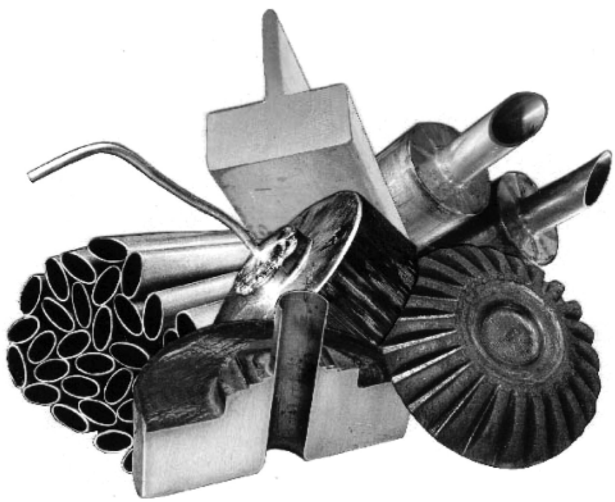

Figure 1.4 Examples of the KOBO extrusion and forging products received in semi-industrial conditions. *Source:* Korbel and Szyndler 2010. Copyright of Włodzimierz Bochniak.

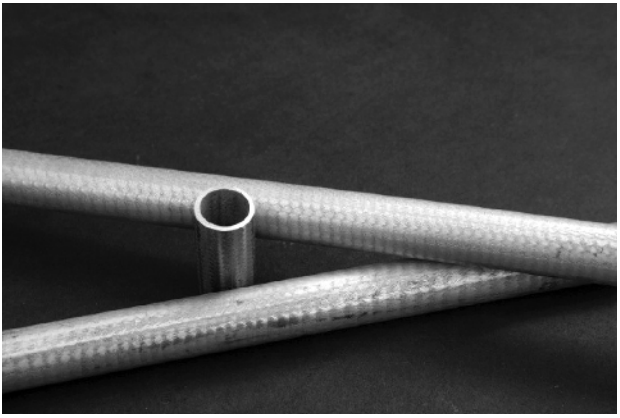

Figure 1.5 Fine tube of magnesium alloy AZ91 extruded at room temperature using 1MN load capacity press. *Source:* Korbel and Szyndler 2010. Copyright of Włodzimierz Bochniak.

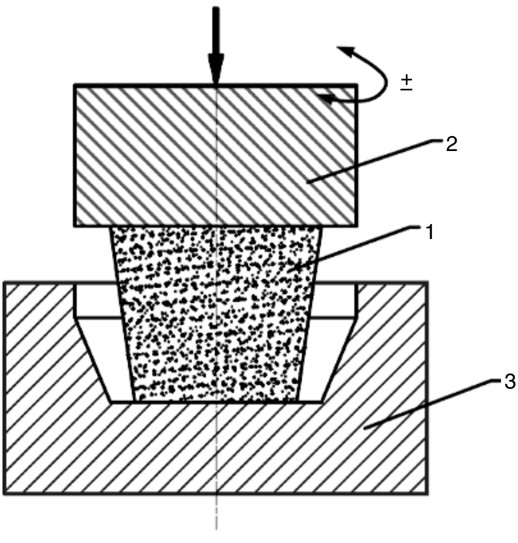

Figure 1.6 Schematic presentation of the forging process by the KOBO method: (1) forged material, (2) cyclically rotating punch, and (3) die (anvil). *Source:* (Bochniak et al. 2006). Copyright by Aleksandra Manecka – Padaż.

illustrative picture of the bevel gear displayed on the book's cover. The image provided kindly by the editorial staff comes from other sources, and the shown example of bevel gear is the traditional milling effect.

Summing up, the authors observe the KOBO method's extrusion or forging process from the structural point of view. The slips' organisation with increasing strain leads to transgranular, localised plastic strain. Such a localisation appears as growing clusters of micro-shear bands and is related to strain softening of metal. The rapid change of the loading scheme and corresponding change of the deformation path leads to instantaneous localisation of plastic flow in the shear bands irrespective of the deformation process's advancement. According to Korbel and Bochniak (2003), the mentioned procedure does not guarantee to keep this state for a long time, and the cyclic repetition of additional external agents in this process is required.

1.3.2 KOBO Processes Resulting in Viscous Effects

The experimental investigations and microscopic analysis of the substructure of metals and alloys carried out by Korbel and Bochniak investigation group led to the novel observation of viscous effects of deformation processes by the KOBO method. The results presented in the papers by Korbel et al. (2011), Bochniak et al. (2011, 2013) indicate that the point defects of supra-equilibrium concentration, generated in periodically variable conditions of plastic flow in the course of the KOBO process, play a decisive role. The massive production of point defects leads to the superplastic behaviour of metallic solid not observed in other plastic-forming methods. The authors state that: 'It seems reasonable, therefore, to conclude that die oscillation frequency (torsion of material) is the determinant of the amount of point defects and its increase should enhance the process. The occurrence of diffusing atoms or vacancies stream equalising the concentration leads to a significant decrease in viscosity of the material, generating an alternative to the dislocation slip mechanism of plastic deformation', cf. (Korbel et al. 2011), p. 2893. The analysis justifies the author's view that the mechanism of metal extrusion using the mentioned KOBO technology is induced by the intensive generation of point defects. Thus, the authors hypothesise that a viscous flow with 'Newtonian fluid' features is a dominant deformation mechanism in KOBO processes. Generally, they identify the description of deformation occurring, e.g. during extrusion by the KOBO method as viscoplastic flow. However, on the other hand, in deformable solids' mechanics, the early viscoplasticity model belongs to Bingham (1916). It shows the linear dependency of shear stress on shear strain rate:

$$\tau = \tau_0 + \mu\dot{\gamma},$$

where τ_0 is yield stress in shear and $\dot{\gamma}$ denotes the shear strain rate. Neglecting $\tau_0 = 0$, one arrives at the linear model of 'Newtonian fluid'. An analogy with magnetorheological materials appears here. From the papers of Frąś (2015), Frąś and Pęcherski (2018), it seems that the linear Bingham model does not conform to experimental data contrary to the original nonlinear viscoplasticity model of Perzyna (1963). The similar conclusion leads the above discussion on a viscous flow resulting from the massive production of point defects activated in KOBO processes. In my view, a more comprehensive theory of the viscoplastic flow produced by shear banding is in order. The observation about the importance of viscous effects accompanying rate-dependent plastic flow during KOBO processes is accounted for in the book.

1.4 Summary of the Work Content

The preface introduces novel concepts and the framework of the book. Chapter 1 presents the motivation and leading thread of the work related to a detailed discussion of the physical basis developed in Chapter 2. This chapter contains the synthetic approach to observations that appear helpful in formulating the viscoplastic flow description in metallic solids produced by shear banding. These views are underlined in the text as the set of statements denoted Observations 2.1, 2.2, . . . 6.1, including the results of own inquiries. The heuristic foundations of the theoretical description of large inelastic deformations create the rational formulation of a multiscale system of shear bands formation. Chapter 3, on the other hand, accounts for shear banding in the continuum model of inelastic deformations. This chapter contains the results of the earlier author's investigations related to micromechanical foundations of finite plastic deformations theory accounting for the shear-banding mechanism summarised in Observation 3.1 and Hypothesis 3.1, extending the generally accepted concept of representative volume element (RVE). The extension provides the possibility of the existence in RVE of the singular discontinuity surface of order one of the microscopic velocity field on which the tangential component of velocity experiences a jump travelling at the speed V_s. Further, Chapter 4 presents the basics of rational mechanics of materials. A small historical account of rational mechanics is given here. The continuum mechanics description of shear banding is the subject of Chapter 5. The theoretical foundations of the deformation of a body due to shear banding are presented in Chapter 6. In Chapter 7, the yield limit versus shear banding is considered, and, in particular, state of the art regarding the yield condition for modern materials is the subject of thorough study. Viscoplasticity models accounting for shear banding with related examples are under investigation in Chapter 8. The conclusions and remarks concerning further possible studies are provided in Chapter 9.

Acknowledgements

Many friends and coworkers supported and helped the author pursue this complex never-ending story on multiscale deformation mechanisms of different hard deformable metallic solids that I would like to recount, at least partly. As mentioned above, Andrzej Korbel, a Polish Academy of Arts and Sciences member, and Włodzimierz Bochniak became 'spiritus movens' of my long-time activity in this field. It happened due to the help of Mrs Romana Ewa Śliwa, a professor at the Rzeszów University of Technology. She was the first to see my preliminary presentations on localisation phenomena long ago, wisely suggesting contacts with already-knowledgeable and experienced material science researcher Andrzej Korbel. Then, during many years of my works on shear banding phenomena, it was Zdzisław Nowak, PhD, DSc, who showed me the possibilities of numerical analysis of plastic deformation processes accounting for the shear bands effects and identifying the shear banding contribution function. Also, Katarzyna Kowalczyk – Gajewska, PhD, DSc, gave me a helping hand in the numerical simulations of experimentally realised channel-die compression and shearing processes. The studies showed a valuable perspective with the significant experience and knowledge of professor Zenon Mróz, a Member of the Polish Academy of Sciences, and Katarzyna Kowalczyk – Gajewska on cyclically loaded tubes on the KOBO processes. I also received a big help from Mrs Aleksandra Manecka – Padaż, MSc, in elaborating the book's graphics. Together with discussions *in statu nascendi* of the work, her contribution became invaluable. The late professor Piotr Perzyna, my PhD advisor and scientific tutor, contributed to my studies with many valuable discussions about the shear banding model and its applications in the studies of viscoplastic processes.

References

Asaro, R.J. and Lubarda, V.A. (2006). *Mechanics of Solids and Materials*. Cambridge, New York: *Cambridge University Press*.

Bingham, E.C. (1916). An investigation of the laws of plastic flow. *US Bur. Stand. Bull.* 13: 309–353.

Bochniak, W., Korbel, A., Szyndler, R. et al. (2006). New forming method of bevel gears from structural steel. *J. Mater. Process. Technol.* 173: 75–83.

Bochniak, W., Korbel, A., Ostachowski, P., and Pieła, K. (2011). Superplastic flow of metal extruded by KoBo method. *Mater. Sci. Forum* 667–669: 1039–1044.

Bochniak, W., Korbel, A., Ostachowski, P. et al. (2013). Extrusion of metals and alloys by KOBO method, (Wyciskanie metali i stopów metodą KOBO). *Obróka Plastyczna Metali, (Metal Forming)* XXIV: 83–97, bilingual quarterly.

Frąś, L. (2015). The Perzyna viscoplastic model in dynamic behaviour of magnetorheological fluid under high strain rates. *Eng. Trans.* 63: 233–243.

Frąś, L. and Pęcherski, R.B. (2018). Modified split Hopkinson pressure bar for investigations of dynamic behaviour of magnetorheological materials. *JTAM* 56: 323–328.

Gurtin, M.E., Fried, E., and Anand, L. (2009). *The Mechanics and Thermodynamics of Continua*. Cambridge, New York: *Cambridge University Press*.

Korbel A. and Bochniak W, Method of plastic forming of materials, US Patent No. 5,737,959 (1998). European Patent No. 0711210 (2000).

Korbel, A. and Bochniak, W. (2003). KOBO type forming: forging of metals under complex conditions of the process. *J. Mater. Process. Technol.* 134: 120–134.

Korbel, A. and Szyndler, R. (2010). The new solution in the domain of metal forming – contribution of the Polish engineering idea, (Innowacyjne rozwiązania w obszarze obróbki plastycznej – udział polskiej myśli technicznej). *Obróbka Plastyczna Metali (Metal Forming)* XXI: 203–216, bilingual quarterly.

Korbel, A., Bochniak, W., Ostachowski, P., and Błaż, L. (2011). Visco-plastic flow of metal in dynamic conditions. *Metall. Mater. Trans. A* 42A: 2881–2897.

Perzyna, P. (1963). The constitutive equations for rate sensitive plastic materials. *Q. Appl. Math.* 20 (4): 321–332.