VISCOPLASTIC FLOW IN SOLIDS PRODUCED BY SHEAR BANDING

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Table of Contents

List of Illustrations

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

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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.

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 (s) 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 (), 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 viscoplastic 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.

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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.

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 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.

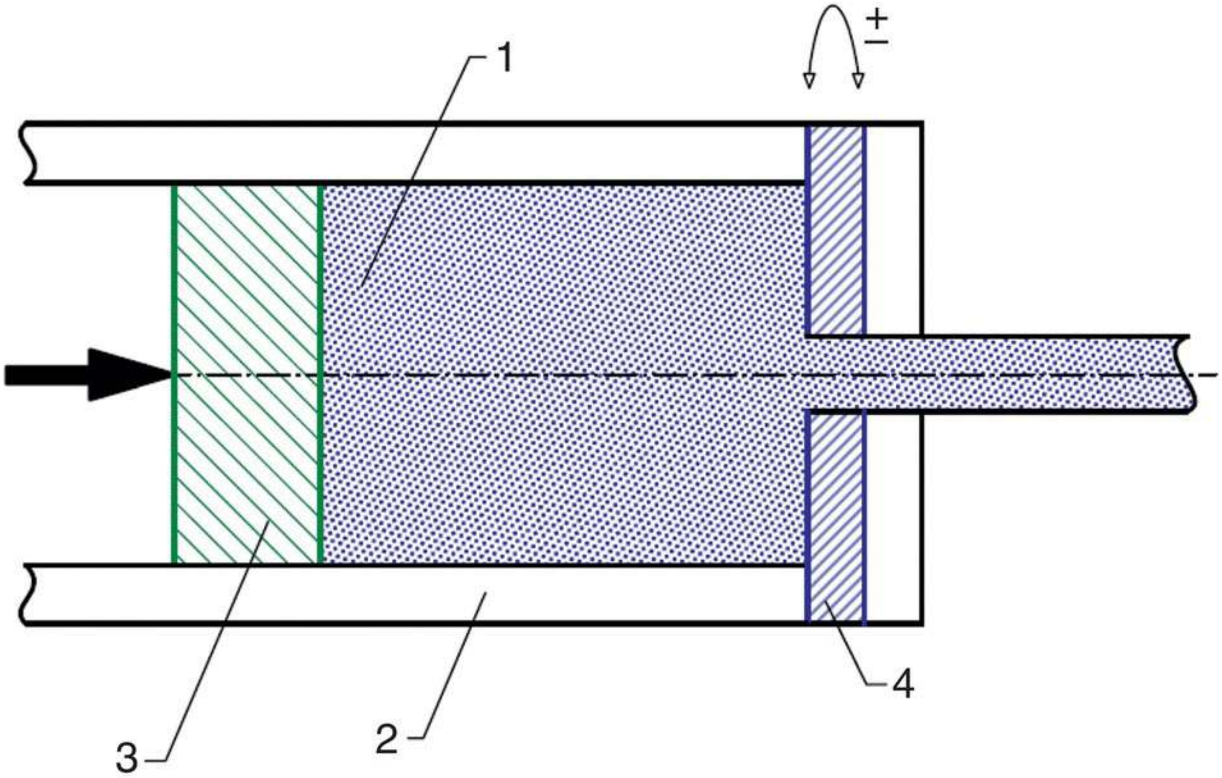

Figure 1.2 Scheme of metal extrusion throughout the oscillating die (KOBO method): 1 – billet, 2 – container, 3 – punch, 4 – oscillating die (Korbel and Szyndler 2010).

Source: Copyright by Aleksandra Manecka – Padaż.