Plastic Deformation of Nanostructured Materials

A. M. Glezer, E. V. Kozlov, N. A. Koneva
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Plastic Deformation of Nanostructured Materials

Plastic Deformation of Nanostructured Materials offers comprehensive analysis on the most important data and results in the field of materials strength and mechanics. This reference systematically examines the special features of the mechanical behavior and corresponding structural mechanisms of crystal structure defects with grain sizes that range from meso- to micro- levels.

The book is organized into six chapters. Each chapter gives special attention to various topics including a detailed analysis of the main components of the dislocation structure, the conditions of transition from dislocation slip to grain boundary sliding as well as present studies concerned with the nature of severe plastic deformation processes.

An indispensable reference for scientists, engineers, postgraduate students and others working in the physics of strength and development of highly efficient constructional multifunctional materials, **Plastic Deformation of Nanostructured Materials** highlights current interests on the structural mechanisms of plastic deformation of ultrafine-grained and nanostructured materials.

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Plastic Deformation of Nanostructured Materials

Introduction

The mechanical properties of materials are the basis of technical progress in various areas of engineering, instrument making, aerospace technology, nuclear technologies and many other aspects of human activity. Recently, the effort of materials scientists and other experts has resulted in the development of new approaches to increasing the strength and ductility of advanced structural materials. A special position is occupied by nanotechnologies capable of changing qualitative the mechanical behaviour of nanomaterials as a result of extensive dispersion of the structure. It has been shown that a large decrease of the grain size of the polycrystalline materials and the corresponding large increase of the bulk density of the grain boundaries greatly change the behaviour of dislocations – the main carriers of plastic flow and, consequently, the mechanisms of elastic deformation and the associated mechanical properties. A large number of scientific articles concerned with the effect of the small size of the crystals on the dislocation mechanisms of plastic deformation has been published in recent years. Undoubtedly, it is now time to publish the results and generalise the most important data.

The Russian literature contains a number of excellent monographs written by Russian and foreign scientists and devoted to the dislocation and disclination physics of plastic deformation of polycrystalline materials. Without pretending that this list is complete, one should mention first of all the monograph by R.W.K. Honeycombe 'Plastic deformation of materials' (1972), V.I. Trefilov, Yu.V. Mil'man and S.A. Firstov 'Physical fundamentals of the strength of refractory metals' (1975), V.E. Panin 'Structural levels of deformation of solids' (1985), V.V. Rybin 'High plastic strains and fracture or metals' (1986), O.A. Kaibyshev and R.Z. Valiev 'The grain boundaries and properties of metals' (1987), M.A. Shtremel' 'The strength of alloys' (in two parts, 1997) and a number of others.

Unfortunately, these monographs do not pay attention to the evolution of the mechanisms of dislocation flow at relatively small grain sizes (smaller than 1 μm). In the list of the monographs and reviews it is important to mention in particular books by K. Koch 'Constructional nanocrystalline materials' (2012) and M.Yu. Gitkin and I.A. Ovid'ko 'Physical mechanics of deformed nanostructures' (2003), and also a review by R.A. Andrievskii and A.M. Glezer 'The strength of nanostructures' in the journal Uspekhi fizicheskikh nauk (2009). The first of them is concerned mainly with the methods for producing constructional materials, their thermal stability and description of the mechanical and corrosion properties. As regards the plastic deformation mechanisms of nanomaterials, they are studied mostly from the viewpoint of computer simulation and do not describe the relationships observed in actual experiments. The latter also applies to a large extent to the second of the previously mentioned publications.

What is the subject of this book? The book examines in detail and systematically the special features of the mechanical behaviour and corresponding structural mechanisms of the behaviour of crystal structure defects with a decrease of the grain size in a polycrystalline ensemble in a stage preceding the nanolevel (from 1 μm to 100 nm) and in the nanosize range (less then 100 nm). Attention is given to the deformation behaviour of 'large' nanocrystals using the terminology proposed in [1] when the plastic deformation takes place by the nucleation, interaction and annihilation of the dislocations, up to 'middle sized' nanocrystals where the controlling role is played by the processes of grain boundary sliding.

This book is the result of 20 years of joint studies by researchers in Tomsk and Moscow, concerned with the strength of materials. The first chapter examines the stages of strain hardening of the polycrystals having different crystal lattices, and the effect of the dimensional factor on this process. The strain hardening pattern is examined on two structural levels (microscopic and the so-called mesoscopic level). The chapter also describes the condition of transition from dislocation sliding to twinning and martensitic transformation. The second chapter generalises the relationships governing the formation of dislocation structures in the deformed polycrystals and describes the mechanical properties under the effect of the change of the grain size (the Hall – Petch relation and its anomaly). Special attention is given to the conditions of transition from dislocation slip to grain boundary sliding with a decrease of the grain size. The third chapter contains the results of a detailed analysis of the main components of the dislocation structure from the viewpoint of the geometrically necessary and statistically stored dislocations. The concept of the critical grain size is introduced. The role of the inclusions of the second phase is evaluated. The fourth chapter examines the internal stress fields formed during the dislocation plastic flow. The methods for evaluating these fields and special features of the evolution in dependence on the grain size are outlined. The fifth chapter is concerned with the nature of high strain (severe) processes actively studied at present. The 'roadmap' of possible structure formation processes, observed at gigantic plastic strains, is described for the first time in the scientific literature. The important role of the cyclic processes of low-temperature dynamic recrystallisation and phase transformations, including amorphisation and crystallisation during deformation, is stressed. The sixth chapter uses titanium as an example to describe the structure and mechanical properties of modified surface layers of materials produced by ion implantation. It is shown that the target can be greatly strengthened by developing nanostructured phases of different nature formed during implantation with different ions.

We believe that this monograph can fill the existing gap in the publications concerned with the structural mechanisms of plastic deformation of ultrafine-grained and nanostructured materials which are of considerable scientific and applied interest at the moment. We hope that the book will be useful to scientists, engineers, post graduate students and others working in the problems of physics of strength and development of highly efficient constructional multifunctional materials.

We would be happy to receive any comments and wishes directed at improving the quality of the book and its importance for advanced materials science.

Reference

1. Glezer A.M., Structural classification of nanomaterials. Deformatsiya i razrushenie materialov. 2010. No. 2. 1-18.

Contents

1

Stages of plastic deformation of polycrystalline materials

1.1. Introduction. Description of the problem

Different plastic deformation processes (tensile loading, compression, rolling, extrusion, creep, fracture) are usually characterised by distinctive stages. Of these stages of active deformation, uniaxial tension and compression have been studied most extensively. These types of deformation have been investigated widely on single and polycrystals with different grain sizes and the type of crystal lattice. Many dependences of the stress (σ) on strain (ε), $\sigma = f(\varepsilon)$, in the true coordinates have been published. A system of views of the individual stages of deformation under tensile and compressive loading has been formed. Although the relationships of work hardening have been studied for a long time, these problems still remain in the centre of attention of the world society of metal physicists. This is indicated by the fact that in the 11th volume of Dislocation in Solids, published in 2002 (edited by F.R.N. Nabarro M.S. Duesbery), a large part of the reviews was concerned with work hardening. In 2003, the series Progress in Materials Science included a review by U.F. Kocks and H. Mecking of this problem.

In this chapter, we analyse the current views regarding the individual stages of plastic deformation and work hardening of the polycrystals. The stages of deformation of the polycrystalline metallic materials were generalised for the first time in the well-known monographs [1–4]. The eight-stage pattern of plastic flow of the metallic polycrystals has been experimentally determined and described. The stages differ both in the value of the work hardening coefficient

$$\theta = \frac{d\sigma}{d\varepsilon}, \tag{1.1}$$

and in the dependence of this coefficient on ε [5]. The studies carried out to determine the individual stages of the polycrystalline materials include the work of a large group of foreign and Russian investigators. Unfortunately, the materials presented in the currently available Russian textbooks for plastic deformation of the polycrystals is still very scarce and no attention is given to the actual problem of the plastic deformation stages. The textbooks and lecture course literature still describe the old-fashioned three-stage deformation pattern and, in most cases, only for single crystals. The stages of work hardening of the polycrystals have practically not been investigated. At the same time, these problems are in the centre of attention of the world society of experts in metal physics and strength of materials.

1.2. Main stages of plastic deformation of polycrystals at the mesolevel

In the generalised form, the characteristics of the individual stages of deformation of polycrystalline aggregates in tensile or compressive loading are shown in Figure 1.1. In particular, the Figure shows the

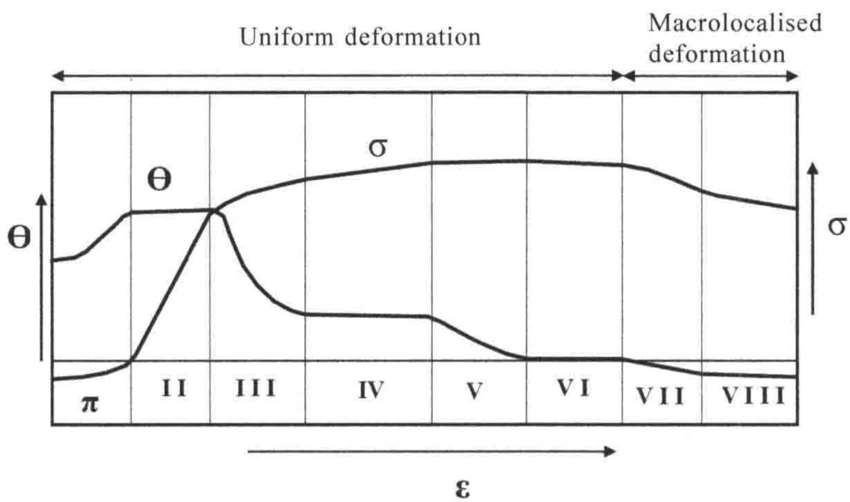

Fig. 1.1. Plastic deformation stages. The dependences $\sigma = f(\varepsilon)$ and $\theta = f(\varepsilon)$ are shown. The Roman numbers indicate the plastic deformation stages. The ranges of uniform and macrolocalised deformation are shown.