Available online at www.sciencedirect.com
ScienceDirect
Acta Materialia 57 (2009) 3431–3438
Acta MATERIALIA
www.elsevier.com/locate/actamat

Modelling the steady state deformation stress under various deformation conditions using a single irreversible thermodynamics based formulation

Mingxin Huang [a,*], Pedro E.J. Rivera-Díaz-del-Castillo [a], Olivier Bouaziz [b], Sybrand van der Zwaag [a]

[a] Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, The Netherlands
[b] ArcelorMittal Research, Voie Romaine-BP30320, 57283 Maizières-lès-Metz Cedex, France

Received 7 October 2008; received in revised form 17 March 2009; accepted 18 March 2009
Available online 7 May 2009

Abstract

A new unified description for the steady state deformation stress in single and polycrystalline metals and for various deformation conditions is presented. The new formulation for dislocation controlled deformation stems from the field of irreversible thermodynamics. The model applies to conditions of dynamic recovery as well as dynamic recrystallization and has been validated for constant strain rate and creep loading conditions. Unlike existing approaches, the new model captures transitions between deformation mechanisms within a single formulation. For conditions of dynamic recrystallization, the average dislocation density is found to be a function of the shear strain rate and a term combining the dislocation climb velocity and the grain boundary velocity.

Keywords: Dynamic recovery; Dynamic recrystallization; Flow stress; Dislocation; Thermodynamics

1. Introduction

Steady state deformation conditions, i.e. conditions for which the work hardening rate is zero, have traditionally attracted a lot of attention from metal physicists as well as experimentalists as steady state deformation conditions are relevant to high temperature forming and are more amenable to detailed microstructural analysis and mathematical modelling [1–11]. Such a steady state deformation condition can be obtained under three metallurgically different conditions: (1) constant strain rate deformation under conditions of dynamic recovery (DRV) only; (2) creep under DRV only; and (3) constant strain rate deformation under conditions of both DRV and dynamic recrystallization (DRX). The details of each metallurgical process and the corresponding steady state will be discussed shortly.

For the first case, the stress–strain curve can be generally divided into three stages (work hardening stages II, III and steady state; assuming multi-slip of dislocations takes place at all strain levels, work hardening stage I can be ignored [1]). At low temperatures, a fourth work hardening stage (IV) can appear between stage III and the steady state [5]. This deformation condition is not considered here.

The steady state is reached as the flow stress saturates. It is worth noting that the steady state is usually difficult to achieve under conventional tensile testing conditions since the sample will fail by cracking or necking before it reaches this stage, but it can generally be achieved under hot rolling or torsion conditions.

The second condition under which a steady state can be achieved is creep. As opposed to plastic deformation under a constant strain rate, creep is usually associated with

* Corresponding author. Present address: ArcelorMittal Research, Voie Romaine-BP30320, 57283 Maizières-lès-Metz Cedex, France.
E-mail addresses: mingxin.huang@arcelormittal.com, mingxinhuang@hotmail.com (M. Huang).

1359-6454/$36.00
doi:10.1016/j.actamat.2009.03.023

time-dependent plasticity under a fixed stress at an elevated temperature, often higher than $0.5T_m$ where T_m is the absolute melting temperature [6]. Creep of pure face-centred cubic (fcc) metals is in general divided into three stages: (1) primary creep, in which the strain rate (or creep rate) is changing with increasing strain or time; (2) secondary creep where strain rate is constant over a range of strain; and (3) tertiary creep, where the strain rate increases due to cavitation and/or cracking [6]. The secondary creep is the steady state (constant stress and strain rate) which is dealt with in the current model.

It is worth noting that, besides the dislocation controlled mechanism, steady state creep may also be induced by a diffusion controlled mechanism (e.g. Nabarro–Herring creep and Coble creep) [6]. Nabarro–Herring creep is caused by the mass transport of vacancies through the grains from one grain boundary to another [6,7]. The strain in Coble creep is controlled by the diffusion of vacancies along grain boundaries [8]. However, in the present model only dislocation controlled deformation processes are considered.

Finally, a third metallurgical process which can also induce the steady state is usually related to metals with low stacking fault energy. For such metals, dislocations extend into relatively large stacking faults, which hinders the climb and/or cross-slip of dislocations, so that a sufficient dislocation density can be accumulated to trigger DRX for such metals deformed at elevated temperatures [9]. When DRX occurs, both nucleation and growth (grain boundary migration) take place while the strain is being applied [9]. The stress–strain curves associated with DRX can be single or cyclic peak [9] followed by the steady state.

It is often observed that the average dislocation density and subgrain size are constant with straining at the steady state [12]. In order to understand the development of microstructures at the steady state introduced via various metallurgical processes, a number of physical models have been proposed in the literature.

The steady state achieved via the first two metallurgical processes (DRV only under constant strain rate and creep) are in general described by the same model. For instance, the model proposed by Mecking and Kocks [4] and the one developed by Gottstein and Argon [3] predict the average dislocation density and the flow stress at the steady state of constant strain rate test and creep test. More recently, a three parameter approach proposed by Nes [1] and Marthinsen and Nes [2] describes the steady state of constant strain rate test and creep test in terms of the subgrain size, the dislocation density inside the subgrains, and the subgrain boundary dislocation density or the subgrain boundary misorientation.

However, for the third metallurgical process (DRV + DRX), a different physical model is required as the material microstructure is no longer homogeneous but contains regions with a high dislocation density (unrecrystallized regions) and regions of a low dislocation density (recrystallized region). For instance, incorporating DRX, the average dislocation density and the flow stress at the steady state can be described by the models proposed by Sandstrom and Lagneborg [11] and Hodgson and coworkers [10]. These models employ the dislocation density as a key parameter which is assumed to progress following kinetic approaches.

An alternative approach to modelling plastic deformation other than via pre-assumed dislocation kinetics concepts, is via irreversible thermodynamics, as plastic deformation is indeed an irreversible process in the context of irreversible thermodynamics theory. Since irreversible thermodynamics models essentially consider differences in transient states, rather than the routes via which these states are obtained, they offer a great potential of capturing the plastic deformation characteristics in a single mathematical model although the underlying metallurgical processes are different. Extending a recent irreversible thermodynamics model for plastic deformation during room temperature deformation [13–15], the current paper aims to present a unified model for describing the steady state deformation conditions under dynamic recovery and dynamic recrystallization conditions for both single crystals and polycrystalline metals. A very good agreement between the experimental data and the model predictions, using reported values for the physical parameters such as activation energies and temperature dependent elastic constants, was obtained.

2. Model

2.1. Entropic analysis

There are three irreversible processes related to dislocations occurring at the steady state: (1) dislocation generation; (2) dislocation glide; and (3) dislocation annihilation. They are illustrated highly schematically in Fig. 1: during a shear strain interval $d\gamma$, $d\rho^+$ dislocations are generated at the subgrain/cell boundary in the form of Frank–Read sources; then, the generated dislocations

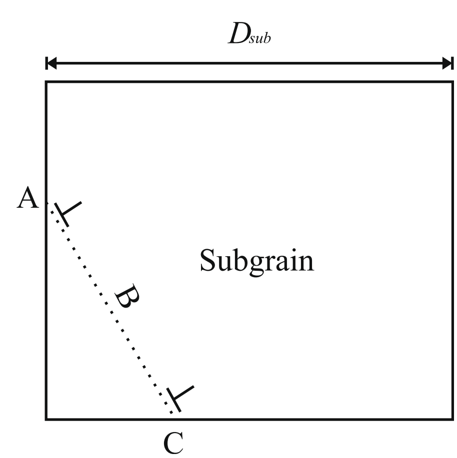

Fig. 1. Dislocations are generated at A, then glide through the subgrain/cell following path B and finally trapped at C.