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Review Article

Perceptive comparison of mean and full field dynamic recrystallization models

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ABSTRACT

Review of dynamic recrystallization models is the subject of the present work. Development of both mean field and full field approaches during last three decades is presented and discussed. Conventional mean field models based on closed form equations as well as differential equations are presented first. Then full field models are elaborated focusing on the cellular automata approach as an example. Capabilities as well as limitations and drawbacks of these approaches are highlighted based on the set of case studies. Experimental data for validation of models were obtained from uniaxial compression tests at Gleeble 3800 thermo-mechanical simulator.

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1. Introduction

Ongoing technological progress requires specific elevated properties of products what is most often related to detailed control and prediction of microstructure evolution during hot working and subsequent heat treatment. These operations are of considerable importance in the thermomechanical processing of steels and other metallic materials. By proper combination of strains and temperatures in subsequent deformations (passes), control of microstructure and properties of products is possible. The phenomena involving changes of the microstructure at elevated temperatures are divided into two major groups. Those occurring during deformation are referred to as dynamic and those occurring after deformation are referred to as static. The former are the subject of the present paper. The dynamic recrystallization (DRX) has major influence on microstructure evolution and

numerical modelling of this phenomenon is crucial for appropriate simulation of thermomechanical processing of steels.

Problem of dynamic recrystallization has been in the field of interest of researchers for more than half of the century and numerous papers on this topic have been published. Although it is difficult to select the most important papers among this large number of publications, those showing physical basis of DRX models should be mentioned. McQueen [1] discussed controversies in various theories of dynamic recrystallization, which have to be considered in development of models. Jonas [2] discussed practical aspects of accounting for DRX in modelling industrial processes. Modelling DRX started in mid 20th century and Jonas in Canada [2–4], Sellars in Europe [5], Sakai in Japan [4,6,7] and Hodgson in Australia [8,9] can be considered as the most important contributors to the development of models. Since these early developments, more advanced numerical models have been developed and used in both scientific

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research and practical industrial applications. Complex metallurgical phenomena can be now introduced in models framework and microstructure can be directly accounted for during simulation. However, the computing costs increase with the increase of models complexity, therefore, searching for a balance between these costs and the predictive capabilities of models is also an important task of the research.

The main purpose of the present paper is to review and analyze the current state of the physical and numerical approaches for treating dynamic recrystallization problems. The focus is on selection of the proper model for a particular application. New challenges that are emerging in the modelling of the DRX are also briefly discussed.

2. Physical basis for development models of dynamic recrystallization

Numerous theories exist in the literature for modelling dynamic recrystallization. These theories are discussed briefly with an emphasis on their capability to describe physical phenomena occurring during DRX.

2.1. An introduction to dynamic recrystallization

When deformation at sufficiently high temperature exceeds a certain critical strain, dynamic recrystallization (DRX) is initiated and progresses with further deformation until a steady state, where the microstructure is stable due to a dynamic equilibrium between softening by dynamic nucleation and work-hardening. Thus, DRX also known as discontinuous recrystallization is the phenomenon, which occurs during straining of metals at higher temperature and lower strain rates. To control DRX temperature compensated time parameter, now called Zener–Hollomon parameter (Z), was introduced. DRX is characterized by a nucleation rate of low dislocation density grains and by a posteriori growth rate. The latter produces a homogeneous grain size when the equilibrium is reached. When a critical strain is reached in low stacking fault energy (SFE) metals, strain hardening and dynamic recovery cease to be the principle mechanisms responsible for the microstructure behaviour. The DRX becomes the main phenomenon accompanying the process. Dynamic recrystallization is not restricted to FCC metals and it is frequently observed in other materials, as well.

If an equilibrium of a steady state is reached in a single cycle, the hot curve is said to have a monotonic stress behaviour. When the critical strain is exceeded, the hardening rate decreases and the maximum stress is reached. Following this the stress descends on a particular kinetic rate until reaching the steady state stress. Thus, the occurrence of DRX usually results in a single peak in the flow curve of deformed material. Fig. 1 shows schematically typical responses of metals subjected to hot deformation.

A transition from single peak to multiple peak behaviour has been reported under certain deformation conditions (very low strain rate and high temperature) and/or initial microstructures (small grain sizes). If stress oscillation appears before reaching the steady state, then several recrystallization and grain growth cycles occur and the stress behaviour is said

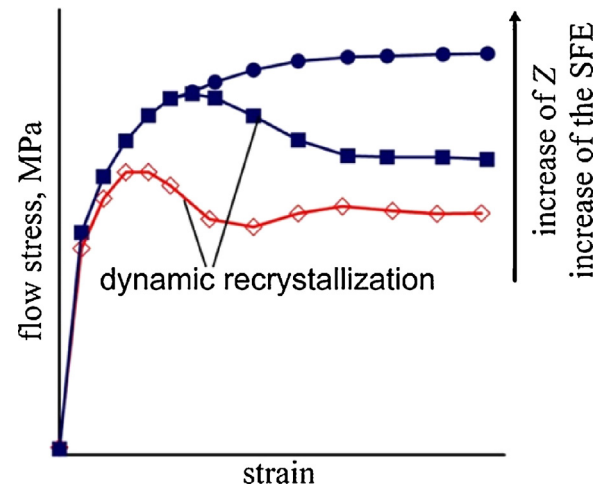


Fig. 1 – Typical material responses to plastic deformation.

to be a multi peak type. Recapitulating, the particular stress behaviour before reaching the steady state depends on the temperature and strain rate, however initial grain size also plays an important role.

2.2. Main mechanisms of the DRX

Two DRX mechanisms operate in metals and alloys with low-to-medium stacking fault energy during hot-to-warm working. Under conditions of low flow stresses, which corresponds to hot working, new grains evolve by conventional (discontinuous) nucleation and growth mechanisms, respectively. On the other hand, new grains may develop as a result of continuous increase of misorientations between deformed subgrains during warm working, when larger flow stresses are observed. The former mechanism only is discussed in the present work.

2.2.1. Onset of DRX

The discontinuous DRX is initiated in the microstructure when strain hardening and dynamic recovery are unable to accommodate immobile dislocations. The onset can be controlled by critical strain or by critical dislocation density. When the critical value is reached the DRX initiates at the pre-existing grain boundaries [10]. Grains become saturated with dislocation barriers that form typical cell structures leading eventually to high-angle boundaries occurrence. The grain boundaries are bulged until a new grain is formed. Schematic diagram of bulge mechanism is shown in Fig. 2a. Thus, the criterion for the onset of the DRX should be based on the net energy change due to the simple nucleation. Equation describing total energy is presented in Fig. 2. In this equation τ is the dislocation line energy and γ_b is the grain boundary energy per unit area.

As shown in Fig. 2b, the high angle boundary is moving from right to left into unrecrystallized material which has a high dislocation density of ρ_{def} with velocity of dx/dt . The dislocation density of the potential nucleus behind the moving boundary drops to a low value of ρ_0 , however, concurrent deformation of the material raises the dislocation density

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