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A mean field model of dynamic and post-dynamic recrystallization predicting kinetics, grain size and flow stress

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ABSTRACT

A physically-based two-site mean field model has been developed to describe the microstructural evolution due to recrystallization *during* and *after* deformation. The model has been applied to predict the recrystallized fraction, recrystallized grain size, and flow stress of 304L austenitic stainless steel during discontinuous dynamic recrystallization (DDRX), post-dynamic recrystallization (PDRX) and grain growth (GG). The model parameters vary with temperature and strain rate but do not depend on grain size. In PDRX and GG regime, the parameters only depend on temperature. The model responds well to conditions with different temperatures, strain rates, strains and/or annealing times. Particular attention is paid to the occurrence of two-stage growth in the recrystallized grain size plots when PDRX occurs. There is a good quantitative agreement between model predictions and experimental results obtained in the different recrystallization regimes, opening the possibility of modeling multi-pass operations compatible with industrial applications.

1. Introduction

Recrystallization is an important phenomenon that causes microstructural changes in deformed materials, thereby affecting its properties. Many metallic components are produced from large castings, which are then further deformed by forging, extrusion, rolling, etc., into an intermediate or final product. Three different recrystallization behaviors are usually observed during these processes, namely, dynamic, post-dynamic and static recrystallization. The recrystallization regime depends on whether it occurs during hot deformation or between deformation intervals.

In static recrystallization (SRX), the deformation is interrupted before reaching the critical strain for dynamic recrystallization (DRX), ε_{cr}^{DRX}. During this recrystallization regime, both nucleation and growth of new grains take place during annealing periods between intervals of hot deformation. On the other hand, these processes can also be observed during deformation once ε_{cr}^{DRX} is reached, leading to dynamic recrystallization. Post-dynamic recrystallization (PDRX) refers to the growth of dynamically formed nuclei once deformation (greater than ε_{cr}^{DRX}) has come to an end. Grain growth (GG) is defined as the uniform coarsening of a material with a minimal dislocation content at a high temperature [1].

Although extensive efforts have been put on a wide range of materials, recrystallization during and following deformation is still not fully understood [2]. Experimentally, the softening fraction [3] during annealing of dynamically recrystallized microstructures was often used to differentiate recrystallization regimes, due to the fact that it is difficult to distinguish SRX and PDRX [4]. Researchers at McGill University were probably the first ones who investigated the post-dynamic softening. They proposed a mechanism involving three different restoration processes including recovery, PDRX, and SRX, based on metallographic examination on polycrystalline copper [5–7]. Later, Sakai et al. [8,9] performed further research on the subject using a nickel alloy and austenitic steels, providing a detailed description of the above restoration processes. The observed fractional softening is, however, a combined effect of recovery, recrystallization and (where applicable) precipitation contributions, making it hard to distinguish their separate influences. The different mechanisms acting after hot deformation have been further studied by Hodgson and co-workers [10–13], while the mechanisms of recrystallization during and after deformation have been carefully examined by Dehghan-Manshadi et al. [14,15] using 304 austenitic stainless steels.

Several models have been proposed to investigate the effect of the thermomechanical parameters on the softening kinetics during

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and after deformation, however, limited studies have been reported on the microstructural evolution in terms of recrystallized volume fraction and grain size. A large group of these models are based on the Johnson–Mehl–Avrami–Kolmogorov (JMAK) equation approach [15–21]. However, the ideal JMAK behavior is rarely exhibited by real materials. Such deviation from this ideal behavior is due to the presence of recovery, non-uniform distribution of stored strain energy, non-random distribution of recrystallized nuclei, and anisotropic growth of the recrystallized nuclei [22]. For this category of models, experimental validation is often lacking, and good agreement between numerical and experimental data in terms of grain size is rare. Beyond the JMAK model, the evolution of dislocation density populations can be discretely followed through the entire deformation process, e.g. by Roucoules et al. [23], based on the Sandstrom and Lagneborg approach [24,25]. However, in [23], the recrystallized grain size, which is of interest in most of the industrial applications, was not analyzed. It is furthermore assumed that the mechanisms which take place during dynamic and static recovery or during DRX, SRX or PDRX are the same. Kugler and Turk [26] developed a Cellular Automaton model for the simulation of multi-stage deformation and post-dynamic recrystallization for the case when DRX is initiated in the material during deformation. The model enables both quantitative and topological simulations of microstructural evolution before and during PDRX, and it allows the simulation of multi-stage deformation. However, the evolution of the recrystallized grain size was again not considered in the model. The explicit representation of microstructures includes much more information relying on the topological aspects, but when dealing with 3D microstructures with a statistical number of grains, these methods usually become computationally demanding.

Coupled models taking into account recovery, precipitation and recrystallization were also developed [27,28]. Numerical models [29–31] accounting for recrystallization during and after hot deformation for aluminum alloys were developed, such as the "Through Process Model" for the production processes of aluminum [32]. It should be noted that, different from austenitic stainless steels, aluminum alloys are of high stacking fault energy and recrystallization is characterized by the gradual formation and appearance of a new structure with no identifiable nucleation and growth stages.

In general, although some efforts have been reported in modeling recrystallization during multi-pass conditions for steels, the literature lacks accurate recrystallization models which are able to give quantitative agreements with experimental data (especially grain size) under multi-pass conditions. Most of these models either lack experimental validation or only provide qualitative agreement for selected deformation conditions. The connections between DRX, PDRX, SRX, and grain growth are usually oversimplified. Even though successful prediction of flow stress is usually obtained, the evolution of microstructure in terms of recrystallized fraction and grain size are mostly left unexploited. Furthermore, most of these models are not designed to operate under variable thermal and/or mechanical conditions, therefore making it difficult to use for industrial applications.

In the current work, a physically based numerical model was developed to predict the microstructural evolution during and after hot deformation at the grain scale. The framework of this model is based on a DDRX model [33] published by the current authors where the data structure is represented by a set of representative grains characterized by two state variables: grain size and dislocation density. Each representative grain is surrounded by two homogeneous equivalent media with high and low dislocation densities representing the average of recrystallized and non-recrystallized grains, respectively. The relative volume weights of the two media are related to their volume fractions, which represent a new way of introducing topological information into a DDRX model. The key phenomena like strain-hardening, recovery, nucleation of recrystallization occurring during deformation are described with traditional equations. The data structure varies with time due to nucleation and disappearance of grains until a steady-state is reached. This results in a two-site mean field model with automatic and accurate account of initial grain size effects.

In this paper, significant improvements and modifications have been made to the original DDRX model in order to account for the subsequent PDRX, making the model compatible with recrystallization after deformation. This is detailed in Section 2. The identification of model parameters is discussed in Section 3. The predictive capabilities of the model are then validated against 304L stainless steel experimental results in Section 4. The model predictions are in excellent quantitative agreement with the experimental observations under different conditions.

2. Model description

The model is presented as follows. Firstly, representation of the microstructure with two-site mean field media is described in Section 2.1. The general equations describing the key physical phenomena occurring during recrystallization are presented from Sections 2.2–2.4, covering the evolution of dislocation density, grain boundary migration and nucleation. Except the static recovery equation, these equations were used in our dynamic recrystallization model [33], the interested reader is referred to the original publication for more details. A more general expression of the critical dislocation for dynamic recrystallization is proposed in Section 2.5, still taking into account of the effect of dynamic recovery. The microstructure after deformation is reclassified according to the dislocation density of the grains, the details of which can be found in Section 2.6. A new formulation describing the interaction of the representative grains with the two surrounding Homogeneous Equivalent Medias (HEMs) is shown in Section 2.7, where the topological information can be incorporated due to the introduction of the two-site mean field media. Finally, the attractive features of this model and its limitation are listed in Section 2.8.

2.1. Microstructure representation

The framework is based on a mean field approach [33], where each representative grain G_i, defined by two state variables (the grain diameter D_i and the grain average dislocation density ρ_i), is immersed in two HEMs (see Fig. 1). A representative grain G_i accounts for a number N_i of identical spherical grains located at different positions in the microstructure. The neighbors of a given grain in a real recrystallizing microstructure (Fig. 1a) are replaced by two HEMs, respectively referring to the average of recrystallized (RX) and non-recrystallized (NR) grains (Fig. 1b).

The initial set of representative grains typically follows a log-normal distribution for the grain size and a Gaussian distribution for the dislocation densities. However, it has been tested that other distributions can also be used with negligible effect on the final result.

2.2. Modeling the evolution of the dislocation density and flow stress

The model makes use of the modified Kocks and Mecking equation [34–36] to describe the evolution of the dislocation density during deformation

$$\frac{\partial \rho}{\partial \varepsilon} = K_1 - K_2 \rho \tag{1}$$