

Modelling dynamic softening processes during hot working

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Abstract

This paper models the kinetics of dynamic recovery and recrystallization under hot working conditions. For doing so, the first-order kinetics equation is coupled with a thermo-viscoplastic finite element analysis to determine the kinetics of dynamic softening processes at different points of deforming metal. The proposed model can consider the effects of macro parameters, such as temperature and strain rate variations as well as the influences of microparameters as initial grain size on the rate of dynamic softening processes.

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1. Introduction

The modelling of dynamic softening mechanisms, such as dynamic recovery and dynamic recrystallization, is of great importance in controlling of the microstructure as well as the flow stress of material during hot deformation [1]. In this regard, several models have been proposed to assess the kinetics of dynamic recrystallization and recovery during hot forming for various engineering alloys especially steels [2]. Dynamic recrystallization of austenite in low alloy steels has been modelled by Medina and Hernandez [3]. They utilized single hit hot torsion tests to derive the kinetic parameters of dynamic recrystallization and then, by the aid of Avrami's equation the rate of this transformation for various kinds of alloy steels have been evaluated. Also, in other research works a similar trend has been employed to evaluate the recrystallization behavior for different kinds of steels [4–6]. Pussegona et al. [7] have studied dynamic recrystallization through physical modelling of a rolling line. In this work, flow behavior and developed microstructure of four kinds of alloy steel were taken into account by employing multi-stage hot torsion experiments. The effect of dynamic recovery and recrystallization on flow behavior during hot deformation processes

has been investigated in several research works [8–12]. In these works, two different approaches have been used. One concerns with utilizing hot torsion or hot compression experiments and direct observation of the developed microstructure and flow stress of deformed metal and then developing experimental relationships for describing dynamic recrystallization rate. The other approach deals with the mathematical modelling of dynamic recovery and recrystallization through the theories of phase transformations [9,11]. The main equations used in this category are Avrami and hyperbolic sine equations. It should be noted that in all published works, the derived equations are appropriate for the isothermal and constant strain rate conditions and the occurrence of dynamic softening processes and their progress have been assumed homogenous within the deforming metal. While in practice, both temperature and strain rate are varying as well as there are distributions of temperature and strain within the metal. So, the rate of dynamic recovery and recrystallization alter at different points of the metal.

In this work, by means of a thermo-viscoplastic finite element model and coupling it with a kinetic model based on the assumption of first-order reaction the kinetics of dynamic recovery and dynamic recrystallization are predicted. The model can be employed under real deformation conditions where temperature and strain rate vary as well as the effects of various process parameters, such as deformation speed,

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initial temperature and interface heat transfer coefficient, can be evaluated. To validate the modelling results, non-isothermal experiments have been conducted and in this way, load–stroke and time–temperature curves are determined and compared with predicted ones.

2. Mathematical model

For evaluating the deformation conditions at each time step, a finite element analysis is coupled with the phase transformation ones. In this method, the basic idea includes minimization of the energy functional of the deforming body [17,18]. The principle equations for determining temperature and velocity fields are described as follows:

$$\int \left(\frac{\partial W_i}{\partial x} k \frac{\partial T}{\partial x} + \frac{\partial W_i}{\partial y} k \frac{\partial T}{\partial y} + \frac{\partial W_i}{\partial z} k \frac{\partial T}{\partial z} - W_i \rho_w c \frac{\partial T}{\partial t} + W_i \dot{q} \right) dV - \int W_i q_n dA = 0 \quad (1)$$

$$\int \bar{\sigma} \delta \bar{\varepsilon} dV + \int K \dot{\varepsilon}_v \delta \dot{\varepsilon}_v dV - \int F_i \delta u_i ds = 0 \quad (2)$$

where ρ_w , c and k are density, specific heat and thermal conductivity of the metal, respectively, and W_i is weighting function. This function controls the form of error distribution over each element and is usually chosen to be the same as approximating function used to describe temperature field [18]. q_n is the heat flux at boundary surface, $\dot{q}$ represents the volumetric rate of heat of deformation, $\bar{\sigma}$ and $\bar{\varepsilon}$ are effective stress and effective strain rate, respectively. During hot working, dynamic recovery and recrystallization are possible softening mechanisms that can affect the flow behavior as well as the microstructure of the deforming body. In this work to determine the kinetics of dynamic recovery, the proposed equation by Kocks [13] for variation of dislocation density is employed.

$$\frac{d\rho}{d\varepsilon} = k_1 \rho^{1/2} - k_2 \rho \quad (3)$$

where ρ is the dislocation density, and k_1 and k_2 represent the rates of dislocation storage and recovery, respectively. Utilizing the classic relationship between stress and dislocation density, the variation of flow stress due to dynamic recovery during hot deformation can be expressed as follows:

$$2 \frac{d\sigma}{d\varepsilon} = k_1(\alpha G b) - k_2 \sigma, \quad \sigma = \sigma_0 \text{ at } \varepsilon = 0 \quad (4)$$

In this equation, k_1 can be evaluated as $2(\theta_{II}/G)(\alpha b)^{-1}$, where θ_{II} may be estimated as a function of temperature [13]. While k_2 is a function of deformation conditions (temperature and strain rate) [13] and can be determined through experiments. For doing so, one may use Eq. (2) when the flow stress reaches to the steady-state situation, $d\sigma/d\varepsilon = 0$, under this circum-

stance, k_2 can be determined as below:

$$k_2 = \frac{k_1(\alpha G b)}{\sigma_{\text{Rec}}} \quad (5)$$

Here, σ_{Rec} is the saturated flow stress due to dynamic recovery that can be assessed by the stress–strain curves. This parameter can be expressed by the following relationship [3]:

$$\sigma_{\text{Rec}} = A d_0^q z^m \quad (6)$$

where d_0 is the initial austenite grain size, A , q and m the material constants and z is the Zener–Hollomon parameter, i.e.

$$z = \dot{\varepsilon} \exp \left(\frac{Q_{\text{def}}}{RT} \right) \quad (7)$$

where T is absolute temperature, R the gas constant, Q_{def} the apparent hot deformation activation energy and $\dot{\varepsilon}$ is the applied strain rate.

Note that Eq. (4) is a differential equation that can be solved by the aid of numerical techniques as modified Newton scheme. On the other hand, to assess the kinetics of dynamic recrystallization, this process can be treated as a first-order transformation equation [14].

$$\frac{dX_d}{d\varepsilon} = k_d \varepsilon^{n_d-1} (1 - X_d), \quad X_d = 0 \text{ at } \varepsilon = \varepsilon_c \quad (8)$$

while its effect on the flow stress can be evaluated by:

$$\sigma = \sigma_{\text{Rec}} - X_d(\sigma_p - \sigma_{\text{Rex}}) \quad (9)$$

where X_d and k_d are volume fraction of recrystallized phase and rate parameter, respectively. σ_{Rex} and σ_p are the steady-state flow stresses due to dynamic recrystallization and peak stress, respectively. The above equation can be solved by the aid of a simple integration if the deformation conditions do not vary during recrystallization which, in this case, yields Avrami's equation [1]. However, in hot working conditions both temperature and strain rate are changing so that, k_d varies during hot deformation [15]. Under this circumstance, Eq. (8) is non-linear and a finite difference method can be employed to solve this equation. In this approach, using Taylor's expansion and difference approximation, the above ordinary differential equation can be reduced to an equation ignoring the high-order terms [16]:

$$x^{p+1}(\varepsilon_n) \cong x(\varepsilon_n - \Delta\varepsilon) + \frac{\Delta t}{2} [x(\varepsilon_n - \Delta\varepsilon) + x^p(\varepsilon_n)] \quad (10)$$

Here, $\Delta\varepsilon$ is the strain increment, $x(\varepsilon_n)$ and $x(\varepsilon_n - \Delta\varepsilon)$ the volume fractions at the n th and $(n-1)$ th steps, respectively, and p describes iteration number. To calculate the volume fraction at each new step an iterative procedure should be adopted because of the implicit form of the above equation.

Eqs. (1) and (2) should be solved simultaneously to calculate the temperature and strain fields. In addition, to determine flow stress of deforming metal and to evaluate the kinetics of dynamic recovery and recrystallization Eq. (4) (or Eq. (8) when $\varepsilon \geq \varepsilon_c$ should be coupled with Eqs. (11) and (12). For

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