Applied Mathematics and Computation 338 (2018) 164–174

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc

The collective behavior of shear strain localizations in dipolar materials

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ARTICLE INFO

Keywords:
Shear band
Strain localization
Self-organization
Numerical simulation
Differential equations

ABSTRACT

We study the collective behavior of shear bands in HY-100 steel and OFHC copper taking into account the dipolar effects. Starting from mathematical model, we present new numerical methodology that allows one to simulate the processes of shear strain localization in nonpolar and dipolar materials. The verification procedure was performed to prove the efficiency and accuracy of the proposed method. Using the proposed algorithm we investigate the statistical characteristics of the shear strain localization processes in dipolar materials and compare results with nonpolar case. In particular, we obtain the statistical distributions of the width of localization zones and distance between them.

1. Introduction

Understanding the mechanisms of materials failure, developing methods for predicting and preventing these processes are very important tasks. The problem is most acute in the manufacturing, nuclear, military and space industry, since all materials are used must satisfy the requirements of reliability, safety and durability for various methods of loading and exploitation.

In this regard, starting from 1980s the problem of shear strain localization in various materials has been actively studied since it turns out that this process is one of the mechanisms of materials failure under high speed shear deformations. Examples of such process can be found in various of physical experiments and technological processes like metal forming, high speed impact, shock loading, welding, exploitation of the nuclear power plants and even been the hypothesis of the space shuttle crash [1–6]. Nowadays this phenomenon is called adiabatic shear banding. In essence, the shear bands are narrow regions where the high temperatures and deformations are reached due to conversion of plastic work to heat in a short period of time. This process is enhanced at high strain rates because there is not enough time to heat diffusion prevent nonuniform stretching and as a result nonuniform heating of material is occur. Such distribution of heat significantly influence on plastic flow, which increases in hotter region and decreases in a colder one [7].

At the moment, there are a lot of analytical, numerical and experimental studies devoted to the adiabatic shear banding phenomena. Among them we highlight the works by Batra et al. [7–11], Walter and Wright [12–14], Zhou et al. [15,16], DiLellio et al. [17–19], Li et al. [20,21], Kudryashov et al. [22–24], Marchand and Duffy [25], Nesterenko et al. [26–28]. We also emphasize monographs by Bai and Dodd [29] and Wright [30] and the references there in. All of these works are concentrated on revealing the basic factors influencing on the initiation, growth and interaction of shear bands.

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https://doi.org/10.1016/j.amc.2018.06.005

One way to study the shear strain localization in materials undergoing deformations is to take into account the dipolar effects. It means that the strain gradient is considered as a new independent variable, since the process of shear banding accompanied by significant value of strains and strain-rates. Such approach was firstly suggested and applied in works [8,9,31,32]. Based on the dipolar theory of Green et al. [33] and modified it by means of rate effects authors obtained the mathematical model of shear bands formation in dipolar materials. Moreover, as it was mentioned in [8], authors also were motivated by work [34], where the dipolar effects considered as a hypothesis to describe interaction among dislocations in materials. Thus, in [31] authors have shown that in the case of single band evolution dipolar effects lead to decreasing in growth rate of central amplitudes of temperature, strain and strain-rate. Also in the case of dipolar material the formation of shear band is significantly delayed in time compared with nonpolar material and the region of localization becomes wider [9]. We note, that according to results of [35] shear bands initiated at flaws, pits, scratches and inhomogeneities in material. Relying on this fact, in works [7,8,32] the process of two shear bands evolution and interaction in nonpolar and dipolar material is studied. The inhomogeneity of initial temperature is used to generate the process of shear bands formation. It was shown that in the case of dipolar material the only one shear band is formed in the centerline of the specimen. Moreover, authors have shown that this process does not depend on strain-rate.

It is known that one of the important features during the plastic flow localization process is a collective behavior of shear bands. It turns out that to accommodate plastic deformations in response to external traction at high-strain-rate deformations the collective phenomenon of shear bands formation is observed, since the development of shear bands interconnected [26]. In experimental works by Nesterenko et al. [26–28] authors observed the formation of multiple shear bands spaced periodically through the specimen. Later, to model and initiate this process in different materials the inhomogeneity of initial stress was used, see [16,22]. However, in these theoretical works the processes of shear bands formation were studied in nonpolar materials. Thus, motivated by the results of works [8,9,31,32] and [16,22,26–28] we have studied the collective behavior of shear bands formation taking into account dipolar effects.

Our work is organized as follows. In Section 2 we give a brief description of mathematical model. In Section 3 we present new numerical approach that allows one two simulate shear bands formation in nonpolar and dipolar material. In Section 4 we perform a verification procedure of proposed numerical algorithm and in Section 5 we present results of numerical simulation of self-organization processes of shear bands formation in dipolar materials.

2. Mathematical model of the problem

We consider the processes of simple shearing of an isotropic, termo-visco-plastic block of material that occupies the region between two planes $0 \le y \le H$. The low plane is fixed and the upper plane is moving under the constant velocity v_0 along x axis. We suppose that motion is volume preserving and x axis is parallel to the direction of shear. In such suggestions, all thermomechanical parameters of material (such as velocity, stress, temperature, deformation and etc) depend just from the space variable y, and only one nonzero component of the Cauchy stress tensor exists. This is a tangent component, for which we use the notation $s = \tau_{xy}$.

According to the results of works [8,9,31–33] the mathematical model of the problem considered can be expressed by the following system of nonlinear equations

$$v_t = \frac{1}{\rho}(s - \sigma_y)_y, \tag{2.1}$$

$$s_t = \mu(v_y - \dot{\varepsilon}), \tag{2.2}$$

$$\sigma_t = l\mu\left(v_{yy} - \frac{1}{l}\dot{d}\right), \tag{2.3}$$

$$\psi_t = \frac{s_e\dot{\varepsilon}_e}{\kappa(\psi)}, \tag{2.4}$$

$$C\rho T_t = (kT_y)_y + s_e\dot{\varepsilon}_e, \tag{2.5}$$

where $v(y,t)$ is the velocity, $T(y, t)$ is a temperature of material, $\dot{\varepsilon}^p(y,t)$ is the plastic strain rate, $\psi(y, t)$ is a strain hardening variable, $\sigma(y, t)$ is a dipolar stress, $d(y, t)$ is a dipolar strain. Furthermore, l is a characteristic material property with the dimension of length corresponding to the dipolar effects which are taken into account, ρ is a mass density, µ, C and k – elastic shear modulus, specific heat and thermal conductivity, respectively. In (2.1)–(2.5) the following notations were used

$$s_e = \sqrt{s^2 + \sigma^2}, \qquad \dot{\varepsilon}_e = \sqrt{\dot{\varepsilon}^2 + \dot{d}^2}, \qquad \varepsilon_e = \int_0^t \dot{\varepsilon}_e(\tau)d\tau. \tag{2.6}$$

Here $s_e, \dot{\varepsilon}_e$ and ε_e are the effective stress, strain-rate and strain. Effective variables are connected by the plastic flow law $D(s_e, \psi, T) \ge 0$. We also suppose that the connection between the strain-rate and the gradient of strain rate from the stress components have the following form [8,9,31–33]

$$\dot{\varepsilon} = \frac{s}{s_e}\dot{\varepsilon}_e, \qquad \dot{d} = \frac{\sigma}{s_e}\dot{\varepsilon}_e, \qquad \dot{\varepsilon}_e = D(s_e, \psi, T). \tag{2.7}$$