Adiabatic shear bands localization in materials undergoing deformations

P N Ryabov, N A Kudryashov, R V Muratov

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe shosse 31, Moscow, Russia

E-mail: `nakudr@gmail.com`, `pnryabov31@gmail.com`

Abstract. We consider the adiabatic shear banding phenomenon in composite materials undergoing the high speed shear deformations. The mathematical model of adiabatic shear banding in thermo-visco-plastic material is given. New two step numerical algorithm which is based on the Courant-Isaacson-Rees scheme that allows one to simulate fully localized plastic flow from initial stage of localization is proposed. To test this numerical algorithm we use three benchmark problems. The testing results show the accuracy and efficiency of proposed algorithm. The features of adiabatic shear bands formation in composites are studied. The existence of characteristic depth of localization in composites is shown. Influence of initial temperature distribution on the processes of adiabatic shear bands formation in composites is considered.

1. Introduction

The study of the strength properties of different technologically important materials subjected to shear deformations is one of the most important sections of mechanics. One of the methods used for this purpose is the torsional Kolsky-bar method that loads the sample in high rate of simple shear [1,2]. In work [1] authors have shown that geometrical defects in the sample of material undergoing deformations leads to the plastic flow localization with subsequent formation of adiabatic shear bands (ASB) in the area of defect. The studying of the adiabatic shear bands formation processes is an extremely important task, since these processes lead to the failure of materials. The following phenomenon was observed in shock loading, metal forming, ballistic impact and etc [3-5].

The adiabatic shear bands are narrow regions where high temperature and deformations are exceeds in a short period of time. The reason of the ASB formation is a loss of stability of plastic flow occurs due to the thermal softening effect. In conditions close to adiabatic the work of plastic deformation converted into heat which causes thermal softening of material and leads to adiabatic shear bands farmation.

Besides the geometrical defects which leads to the ASB formation, it turned out that the following processes may take place if we have thermal heterogeneity in heating of material. However, most of the works devoted to study this effect, concentrated on the formation of ASB in simple material. Thus the studying the processes of ASB formation in composite material is of interest.

2. Mathematical model of ASB formation in composites

We consider the simple shear deformation of an infinite sample which consist of two thermo-visco-plastic materials. The height of the composite sample is H, where y_1 and y_2 are a heights of materials used in it. To convinience we define the following notations: y_1 mm – y_2 mm.

The governing equations that describe this physical process have the following form [6-9]

$$v_t = \frac{1}{\rho}\tau_y, \tag{1}$$

$$\tau_t - \mu v_y = -\mu \dot{\varepsilon}^p, \tag{2}$$

$$\tau = \Phi(T, \psi, \dot{\varepsilon}^p), \tag{3}$$

$$\psi_t = \frac{\tau \dot{\varepsilon}^p}{\kappa(\psi)}, \tag{4}$$

$$C\rho T_t = (kT_y)_y + \beta \tau \dot{\varepsilon}^p, \tag{5}$$

where y, t is the coordinate and time, τ is a stress, v is a velocity, T is a temperature, ψ is a strain hardening factor, ρ is the material density, μ is the shear module, C, k are the specific heat and thermal conductivity respectively and β is the Taylor-Quinney parameter.

The composite is free of strain at $t = 0$. Initial strain rate $\dot{\varepsilon}^p = \dot{\varepsilon}_0$. We use the following initial conditions

$$v(y,0) = v_0(y), \quad T(y,0) = T_0(y), \quad \tau(y,0) = \tau_0(y), \quad \psi(y,0) = \psi_0, \quad \varepsilon(y,0) = 0. \tag{6}$$

Velocity on the boundaries is used in the form

$$v(0,t) = 0, \quad v(H,t) = v_{up}. \tag{7}$$

We use two types of conditions on temperature on boundaries. The first one has the form

$$T(y=0,t) = 0, \quad T(y=H,t) = 0. \tag{8}$$

The second one is

$$T_y(y=0,t) = 0, \quad T_y(y=H,t) = 0. \tag{9}$$

The plastic flow (3) low is used in the following form

$$\tau = \kappa_0 g(T)\left(1 + \left(\frac{\psi}{\psi_0}\right)^n\right)\left(1 + \frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_y}\right)^m. \tag{10}$$

The thermal softening factor $g(T)$ is used in the form

$$g(T) = \exp(-aT) \quad \text{or} \quad g(T) = (1 - aT)^3, \tag{11}$$

depending on what material we use.

The boundary value problem (1)–(9) is solved numerically. The numerical algorithm consists of two stages. The first stage devoted to solution of mechanical part of the problem. For this purpose we use the Courant-Isaacson-Rees scheme with the Newton iterations to system (1)–(3), (6)–(8). The strain hardening is defining from the solution of Cauchy problem (4), (6) using the fourth order Runge-Kutta method. On the second stage, we solve thermal part of the problem, i.e. we define the temperature of composite solving mixed boundary value problem (5), (8), (9). The proposed numerical algorithm was tested on three benchmark problems. The results of testing prove its accuracy and efficiency.

3. Results of numerical simulation

We consider the composite which is made from steel and copper parts. The height of the steel is y_1 and the height on copper is y_2. Numerical experiments show that the evolution of stress, velocity and temperature on initial stage of localization does not depend on values of y_1, y_2 and $\dot{\varepsilon}_0$.

Since initial stress in steel more than in the copper approximately on ten times, there is a big gradient of stress in composite. This causes wave of initial disturbance, which moves to point $y = 0$. Than it reflects from the boundary $y = 0$ goes to the boundary between steel and copper. The velocity in steel oscillates. We can estimate the period and frequency of its oscillations using the following formulaes

$$T = 4y_1\sqrt{\frac{\rho_{st}}{\mu_{st}}}, \quad \omega = \frac{\pi}{2y_1}\sqrt{\frac{\mu_{st}}{\rho_{st}}}, \tag{12}$$

where μ_{st}, ρ_{st} – shear module and density of steel. After a while these oscillations are damped. The disturbance goes to copper part of composite and localized in it. The number of localization areas depends on the value of initial strain rate $\dot{\varepsilon}_0$ and y_1, y_2. We found that there is a characteristic depth ξ on which the plastic flow localized (see Fig. 1). The value of ξ inversely proportional $\dot{\varepsilon}_0$, that can be seen in Fig. 2.

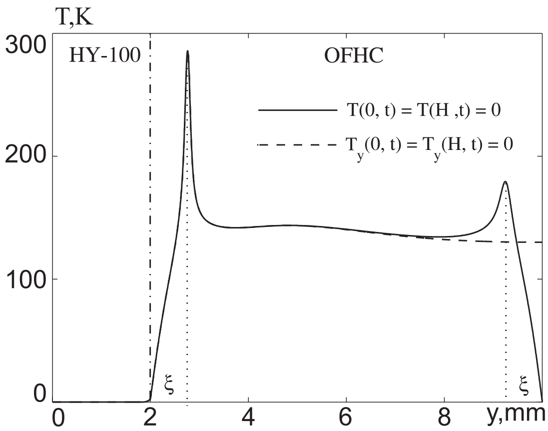

Figure 1. Distribution of temperature T through the sample. Solid line corresponds to (8) and doted line to (9).

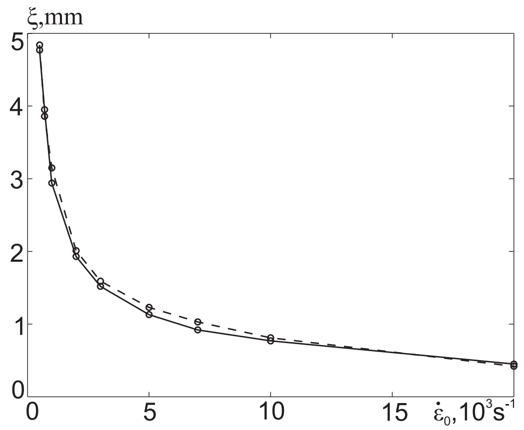

Figure 2. Dependence of depth ξ from $\dot{\varepsilon}_0$ in slab 2 mm - 8 mm. Solid line corresponds to (8) and doted line to (9).

In works [6-9] authors have shown that nonuniform distribution of temperature initiates the process of adiabatic shear bands formation. Here we consider the influence of initial temperature distribution on the ASB formation process in composite material. The initial temperature distribution was used in the form

$$T(y,0) = T_{max}\exp\left[-500\left(\frac{y}{H} - \delta\right)^2\right], \tag{13}$$

where T_{max} is a maximum of initial distribution, $y = \delta H$ is a point where this maximum is reached.

We consider the composite 3 mm - 3 mm with thermal isolated boundaries. The initial strain rate is equal to $\dot{\varepsilon}_0 = 10^4$ s^{-1}. If there is no initial disturbance ASB localized on the upper moving boundary [9]. If we place the initial disturbance in the point $\delta = 0.75$, at $T_{max} = 0.5 - 500$ K, the shear band formed in the point $y = 0.75H$. Increasing the value of T_{max} decries the

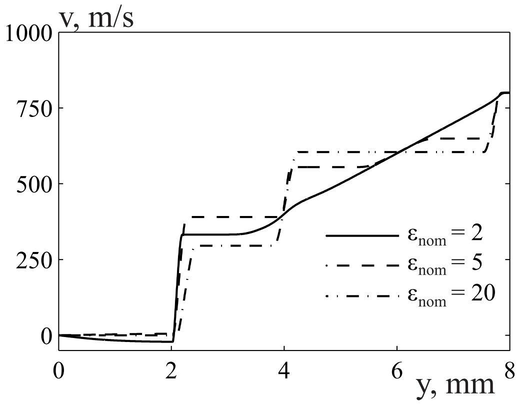

Figure 3. Velocity distribution in slab 2 mm - 6 mm at different time moments ($\dot{\varepsilon}_0 = 10^5$ s^{-1}).

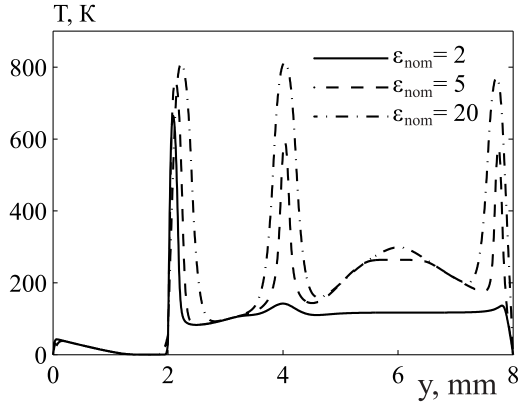

Figure 4. Temperature distribution in slab 2 mm - 6 mm at different time moments ($\dot{\varepsilon}_0 = 10^5$ s^{-1}.

localization time. If we move the maximum of initial disturbance to the boundary between materials ($\delta = 0.5$) the ASB formed near boundary between materials. At a high value of T_{max}, deformations localized on a boundary and then moves to the copper part of the composite.

If we change the height of the composite with zero temperature on the boundaries and consider 2 mm - 6 mm sample, the formation of two ASB is observed in the left and right boundary of copper [9]. The velocity distribution becomes stepwise (Fig. 3). If we place initial disturbance in the middle of the copper part of the sample, the third ASB formes in that area. Whatever disturbance we use, the shear bands on the boundaries of copper are observed (see Fig. 4).

4. Acknowledgments
This work was supported by the Grant for support of young Russian scientists 7207.2016.1.

References
[1] Marchand A and Duffy J 1988 *J. Mech. Phys. Solids* **36** 251
[2] Duffy J, Campbell J D and Hawley R H 1971 *J. Appl. Mech.* **38** 83
[3] Schneider J and Nunes J A 2004 *Metall. Mater. Trans.* B **35** 777
[4] Seidel T and Reynolds A 2001 *Metall. Mater. Trans.* A **32** 2879
[5] Rogers H C 1979 *Annu. Rev. Mater. Sci.* **9** 283
[6] Walter J W 1992 *Int. J. Plast.* **8** 657
[7] Wright T W and Batra R C 1985 *Int. J. Plast.* **1** 205
[8] Kudryashov N A, Ryabov P N and Zakharchenko A S 2015 *J. Mech. Phys. Sol.* **76** 180
[9] Kudryashov N A, Muratov R V and Ryabov P N 2016 *Model. Anal. Inf. Sys.* **23** 298 (in Russian)