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Effect of Nominal Strain-Rates on the Initiation and Growth of Adiabatic Shear Bands in Steels

R. C. Batra[1]

Adiabatic shear banding, i.e., the phenomenon of shear strain localization in high strain-rate deformations of ductile materials, has received considerable attention recently. We refer the reader to Clifton et al. (1984), Wright (1987), Batra (1987a), Fressengeas and Molinari (1987), and Grady and Kipp (1987) for references on various aspects of adiabatic shear bands. Herein we focus on studying the effect of the nominal strain-rate on the initiation and development of shear bands. For this purpose we use a special case of the thermoviscoplasticity theory which Wright and Batra (1987) derived by including the strain-rate effect in the general thermoplasticity theory due to Green et al. (1968).

Previous works (Clifton et al., 1984; Batra, 1987a) studied initial-boundary value problems that simulated a material defect by superposing a perturbation, usually in the temperature field, on the body previously deformed to a point on the stress-strain curve that was just before the peak stress. Here we add a temperature perturbation to the configuration of the body in which it just starts deforming plastically.

Formulation of the Problem

Referrring the reader to Wright and Batra (1987) for details, we note that equations, in nondimensional variables, that govern the simple shearing deformations of a semi-infinite viscoplastic body bounded by the planes $y = \pm 1$ are

$$\dot{v} = \frac{1}{\rho} s_{,y}, \ \dot{\theta} = k\,\theta_{,yy} + \Lambda s^2, \tag{1}$$

$$\dot{s} = \mu(v_{,y} - \Lambda s), \ \dot{\Psi} = \Lambda s^2 \Big/ \left(1 + \frac{\Psi}{\Psi_o}\right)^n, \tag{2}$$

$$\Lambda = \max\left[0, \left\{\left(\frac{s}{\left(1+\frac{\Psi}{\Psi_o}\right)^n (1-a\theta)}\right)^{\frac{1}{m}} - 1\right\}\right] / bs, \tag{3}$$

with boundary conditions

$$v(\pm 1, t) = \pm 1, \ \theta_{,y}(\pm 1, t) = 0, \tag{4}$$

and a suitable set of initial conditions. Equations $(1)_1$ and $(1)_2$ express, respectively, the balance of linear momentum and internal energy. Here v is the x-velocity of a material particle, ρ its mass density, s the shearing stress at a material particle, θ its temperature change from that in the unstressed reference configuration, μ is the shear modulus, parameters n and m describe the strain and strain-rate sensitivity of the material, a superimposed dot indicates material time differentiation, and a comma followed by a y signifies partial differentiation with respect to y. Of these nondimensional variables only ρ, b, and k depend upon the nominal strain-rate $\dot{\gamma}_o$; ρ varies as $\dot{\gamma}_0^2$, b is proportional to $\dot{\gamma}_o$, and k to $1/\dot{\gamma}_o$.

The constitutive relations (2) and (3) give one possible model of viscoplastic materials. Equations $(2)_1$ and (3) imply that the plastic part (Λs) of the strain rate vanishes when

$$|s| \le \left(1 + \frac{\Psi}{\Psi_o}\right)^n (1 - a\theta). \tag{5}$$

For the initial conditions we take

$$v(y,0) = y, \ s(y,0) = (1-\theta(y,0))(1+b)^m, \quad \theta(y,0) = 0.1(1-y^2)^9 e^{-5y^2}. \tag{6}$$

We seek solutions of equations (1)-(4) and (6) such that v is antisymmetric, and s and θ are symmetric in y. Thus the problem is to be studied over the spatial domain [0, 1] and the boundary conditions become

$$v(0,t) = 0, \ \theta_{,y}(0,t) = 0, \ v(1,t) = 1, \ \theta_{,y}(1,t) = 0. \tag{7}$$

Computation and Discussion of Results

The reader is referred to Batra (1987a) for details of integrating the preceding equations. We took the following values of various parameters that correspond to a typical hard steel when $\dot{\gamma}_o = 500\ s^{-1}$ in computing the numerical results presented and discussed below.

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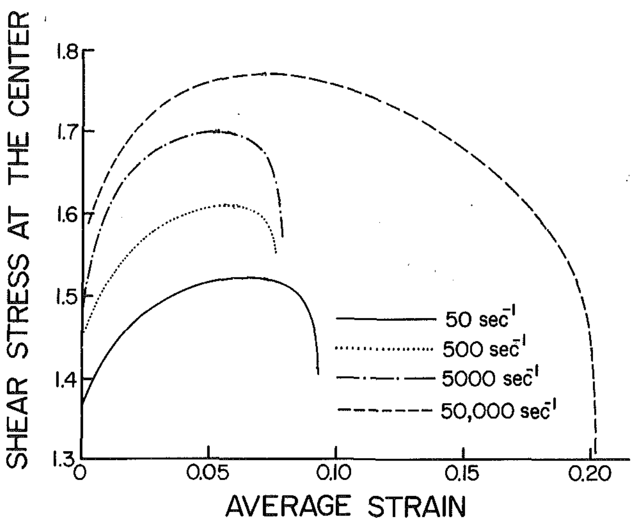

Fig. 1 Shear stress at the center versus average shear strain

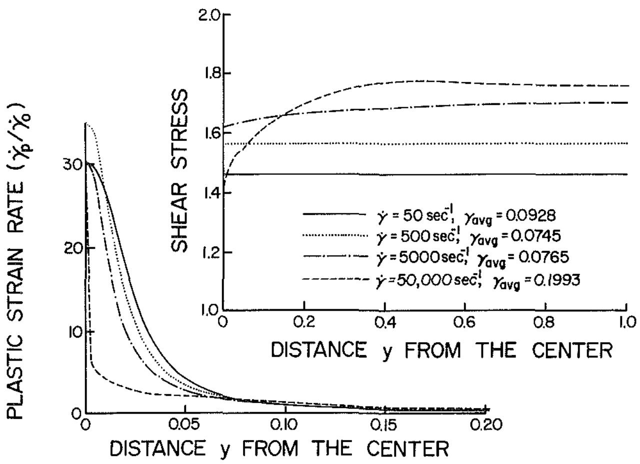

Fig. 2 Shear stress and plastic strain-rate versus distance from the center

$$\rho=3.928\times10^{-5},\ k=3.978\times10^{-3},\ a=0.4973,\ \mu=240.3$$

$$n=0.09,\ \psi_o=0.017,\ b=5\times10^{6},\ m=0.025$$

At other nominal strain-rates the values of ρ, b, and k were appropriately scaled.

Figure 1 depicts the shear stress at the center versus the average strain γ_o in the specimen for $\dot{\gamma}_o$ = 50 s^{-1}, 500 s^{-1}, 5000 s^{-1}, and 50,000 s^{-1}. Note that the peak in the stress-strain curve occurs at a lower value of the average strain as $\dot{\gamma}_o$ is increased from 50 s^{-1} to 5000 s^{-1} but occurs at a relatively larger value of γ_o when $\dot{\gamma}_o$ is increased from 5000 s^{-1} to 50,000 s^{-1}. Prior to the peak in the stress, the strain and strain-rate hardening predominate but beyond the peak these effects are overcome by the thermal softening. In Fig. 2 the distribution of the shear stress and the plastic strain-rate $\dot{\gamma}_o$ is plotted through the thickness of the slab at values of the average strain when the rate of change of plastic strain-rate at the center becomes 10^7 s^{-2} or higher. The values of average strains at which results are plotted in Fig. 2 are listed therein. For $\dot{\gamma}_o$ = 50 s^{-1} and 500 s^{-1} the shear stress is essentially uniform throughout the thickness of the slab but for $\dot{\gamma}_o$ = 5000 s^{-1} and 50,000 s^{-1}, the shear stress in the center is less than what it is in the interior of the slab. Since the nondimensional mass density is proportional to $\dot{\gamma}_o^2$, at high strain rates the inertia effects become more predominant. That the shear strain localization has occurred is clear from the plots of $\dot{\gamma}_p$ versus y in Fig. 2.

Following Wright (1987) we define the half band-width d as the distance from the center of the band to the point where the plastic strain rate has fallen to 1/10th of its central value. The values of d so determined from Fig. 2(*b*) equal 158 μm, 136 μm, 122 μm, and 9 μm at $\dot{\gamma}_o$ = 50 s^{-1}, 500 s^{-1}, 5000 s^{-1} and 50,000 s^{-1}, respectively. These values of d and those computed by Wright (1987) who studied the steady state problem are of the same order of magnitude and exhibit the same trend. As $\dot{\gamma}_o$ varies from 50 s^{-1} to 50,000 s^{-1} the value of k decreases from 3.978×10^{-2} to 3.978×10^{-5} and that of b increases from 5×10^5 to 5×10^8. Numerical computations described by Batra (1987b) who used the constitutive relations (2) and (3), kept $\dot{\gamma}_o$ = 500 s^{-1} but changed k and b by varying their dimensional values reveal that the values of the semi-band width d are unaffected for $0 \le k \le 0.063$ and $5 \times 10^2 \le b \le 5 \times 10^6$. Finally, we note that for $b = 5 \times 10^8$ and $\dot{\gamma}_o$ = 500 s^{-1} the value of d was computed to be 85 μm.

Conclusions

In the simple shearing of the viscoplastic block studied herein at $\dot{\gamma}_o$ = 50 s^{-1}, 500 s^{-1}, 5000 s^{-1}, and 50,000 s^{-1}, the inertia forces start playing a significant role at $\dot{\gamma}_o$ = 5000 s^{-1}. For other constitutive relations this may not be true. At lower strain rates the shear stress stays essentially uniform throughout the specimen. The computed velocity fields reveal that after the shear strain localization has occurred, most of the specimen away from the boundaries of the band moves as a rigid block at relatively low strain rates, but such is not the case at strain rates of 5000 s^{-1} or higher. Narrower bands are formed at higher strain rates.

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